Demand Prioritization for a Water Technology Company

by

Jennie May
Bachelor of Science in Supply Chain Management, Marketing, and Public Relations (Syracuse University, USA)

Xiaoyue Li
Bachelor of Science in Business, Information Systems, and Supply Chain Management (Indiana University Bloomington, USA)

SUBMITTED TO THE PROGRAM IN SUPPLY CHAIN MANAGEMENT
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF APPLIED SCIENCE IN SUPPLY CHAIN MANAGEMENT
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May 2022

Signature of Author: ____
Department of Supply Chain Management
May 6, 2022

Signature of Author: ____
Department of Supply Chain Management
May 6, 2022

Certified by: ____
Dr. Milena Janjevic
Research Scientist at the MIT Center for Transportation & Logistics
Capstone Advisor

Demand Prioritization for a Water Technology Company

by

Jennie May
Bachelor of Science in Supply Chain Management, Marketing, and Public Relations (Syracuse University, USA)

Xiaoyue Li
Bachelor of Science in Business, Information Systems, and Supply Chain Management (Indiana University Bloomington, USA)

Submitted to the Program in Supply Chain Management
on May 06, 2022 in Partial Fulfillment of the
Requirements for the Degree of Master of Applied Science in Supply Chain Management

ABSTRACT

With demand outpacing production capacity, increased variability in supply lead times and customers' conflicting requests to escalate orders, there is a demand prioritization debacle. This Water Technology Company is faced with inefficiently and manually prioritizing individual orders. To ensure the appropriate demand is fulfilled first, the Water Technology Company is seeking a standardized and repeatable demand prioritization process. This sustainable solution will allow for objective and immediate demand prioritization while taking into account all business stakeholder interests. By implementing a Multi-Criteria Decision Making (MCDM) model, the top criteria were identified. Along with MCDM, a hybrid approach to the Analytical Hierarchy Process (AHP) was applied to identify the weights for each of the six criteria. In order to normalize demand orders so the selected criteria could be compared to one another, value function patterns were applied to the criteria inputs. The MCDM demand prioritization model is expected to generate improvements in the key metrics of Profit Margin, Days to Delivery, and Days to Customer Want. The largest expected improvement is with the increase in Profit Margin, ranging from 75% to 250%. Simulation tests were conducted to review the robustness of the six criteria and the group aggregation methods of the criteria weights. This demand prioritization process can be customized and implemented to any industry in any country.

Capstone Advisor: Dr. Milena Janjevic
Title: Demand Prioritization for a Water Technology Company

ACKNOWLEDGEMENTS

We would like to extend gratitude to our advisor, Dr. Milena Janjevic, for her never ending assistance through the project exploration, analysis, and evaluation period.

We would also like to thank the help and support from the Class of 2022, MIT's Master of Supply Chain Management.

Table of Contents

List of Figures

List of Tables

1 Introduction 7
1.1 Current Industry State 7
1.2 Motivation 7
1.3 Problem Statement and Research Objective 8
1.4 Current Operations 8

2 Literature Review 10
2.1 Introduction 10
2.2 Demand Prioritization Methodologies 11
2.2.1 First Come First Serve 11
2.2.2 Multi-Criteria Decision Making 11
2.2.3 Machine Learning 12
2.2.4 Conclusion – Use of MCDM 13
2.3 Identification of Prioritization Criteria 13
2.4 Defining Value Functions 15
2.5 MCDM Tools 18
2.6 Methods for Aggregating Metrics 19
2.6.1 Aggregation of Individual Judgments (AIJ) 20
2.6.2 Reciprocal Method 20
2.6.3 Group Aggregation 20
2.6.4 Conclusion - Hybrid Approach 21

3 Methodology 22
3.1 Criteria Selection Process 23
3.1.1 Current Process Map 24
3.2.2 Preliminary Qualitative Interviews 25
3.2.1 Order Management 25
3.2.2 Sweden Factory 25
3.2.3 Commercial Sales Team – Country 1 26
3.2.4 Commercial Sales Team – Country 2 26
3.2.5 Commercial Sales Team – Country 3 26
3.3 Criteria Selection 27
3.4 Assigning Value Functions Patterns 29
3.5 Design of the AHP Analysis 30
3.5.1 Criteria Weight Exercise 30
3.5.2 AHP - Decision Maker Feedback Review 30
3.5.3 Decision Maker Aggregation - Arithmetic and Geometric 34
3.5.4 Current Criteria - Random Sampling of Four Methods 35
3.5.5 Extended Criteria - Random Sampling of Four Methods 35

3.6 Methodology conclusion 35

4 Results 36
4.1 Order Profit with Existing Metrics 36
4.2 Order Profit with Extended Criteria 41

5 Discussion 42
5.1 Communication feedback loops 43
5.2 Technology infrastructure 43
5.3 Limitations 44

6 Conclusion 45

References List 46

Appendix 47

List of Figures

Figure 1: Material and information flows within the Water Technology Company's stakeholders………………..…9
Figure 2: Outline of the current order process within the Water Technology Company……………..………………9
Figure 3: Online Order Prioritization Metric Diagram Tree from Yuanyuan & Qian (2014)...................................15
Figure 4: Equations of a) Weight Arithmetic Mean Method (WAMM) and b) Geometric Mean Method (GMM)....21
Figure 5: Three paths outlining demand prioritization methodology…………………………………………..22
Figure 6: Demand Prioritization Methodology……………………………………………………………………23
Figure 7: Current value stream process map outlining order receipt, escalation and delivery…………………...….24
Figure 8: Selection of criteria based on literature review and Water Technology Company preferences…………...28
Figure 9: Online AHP Priority Calculator……………………………………………………………………...…31
Figure 10: Comparison of profit margin when Current Criteria methodology is implemented in the demand prioritization process………………………………………………………………………………..……40
Figure 11: Comparison of Days to Delivery and Days to Customer Want when Current Criteria methodology is implemented in the demand prioritization process………………………...…………………..…………41

List of Tables

Table 1: Literature review of top demand prioritization criteria……………………………………………………..13
Table 2: Piecewise value functions for normalizing MCDM criteria from Rezaei (2018)...16
Table 3: Six selected criteria definitions………………………………………………………………………..28
Table 4: Matching of value function patterns to each criterion………………………………………...…………30
Table 5: Initial decision maker (DM) response to the criteria weight exercise……………………...……………32
Table 6: Heatmap of individual DM criteria weights for six extended criteria…………………………...…………32
Table 7: Heatmap of individual DM criteria weights for three current criteria…………………...…………………33
Table 8: Selected criterion weights without a value function applied……………………………………...……..33
Table 9: Scaled Weight on Existing Criteria and Metrics Performance - 4,000 Orders Capacity…...………………37
Table 10: Scaled Weight on Existing Criteria and Metrics Performance - 2,000 Orders Capacity…..…………...…37
Table 11: Only Consider Profit Margin and Metrics Performance - 4,000 Orders Capacity…………………….…38
Table 12: Random Order Allocation and Metrics Performance………………………………………...……...39
Table 13: Extended Criteria Weight and Profit Impact……………………………………………………………42

1 Introduction

1.1 Current Industry State

Supply chain is receiving a thorough evaluation in the press, in the boardroom, and on the factory floor. Motivation for any project in the supply chain field is derived from two key factors: 1) the need to decrease costs, and 2) the desire to increase profits. Essentially, supply chain is now known as the lever that companies can rely on to solve business issues.

Currently, there are many ongoing initiatives to improve the accuracy of forecasts and the efficiency of operation processes with the objective of building resilience against any potential supply chain disruptions. Such disruptions include a mismatched supply and demand scenario, which often ends with disappointed expectations, increased uncertainty in the supply chain, and a negative impact to the financial bottom line.

In the midst of a global pandemic, border lockdowns interrupted entire value chains through delayed materials movements and deliveries. During this time, many industries experienced shifts in customer demand. From the toy industry to the automotive industry, companies have grappled with erratic demand changes while staying on track to achieve financial recovery plans. With an everlasting supply-demand gap, uncertainty in demand will continue to incentivize companies to explore innovative technology and opportunities to prioritize existing demand with the available supply in such a way that maximizes revenue and growth in the long term (Shih, 2022).

1.2 Motivation

The global supply chain disruptions are having an impact on a Water Technology Company. This Water Technology Company is faced with manually selecting which orders to deliver first as its demand outpaces supply and standard lead times jumped up over 400% in 2021. The high demand for orders pertains to new water pumps with end customers scattered across the value stream and across international borders.

The Sweden factory (SF), two distribution centers (DCs), and the order management team (OMT) have honed skills in expediting, adjusting, and rearranging schedules. This manual intervention is an inefficient use of company resources. A data-driven set of prioritization criteria will assist the Water Technology Company in objectively identifying which orders to prioritize first. Along with increasing profits, this proposed prioritization process may increase customer satisfaction and lead to increased sales growth.

1.3 Problem Statement and Research Objective

With capped capacity in the production factory located in Sweden, surging demand from customers, and longer material lead times, the Water Technology Company's key problem is determining how to identify which water pump orders to prioritize (or deprioritize). In terms of identification, which criteria should the company review when prioritizing orders to ensure the constrained available material is delivered to the most appropriate order first. After selecting the criteria, this capstone offers recommendations on how to implement a demand prioritization process. Note that the prioritization process will focus only on orders for new pumps. Aftermarket sales for spare parts to existing water pumps in the field is out of scope.

A potential challenge is how to scale such a demand prioritization process in an objective, repeatable method. Another foreseen challenge is that the business leaders, within the Water Technology Company, are limited in the amount of data they receive from other internal teams due to differing business processes and enterprise resource planning (ERP) data fields.

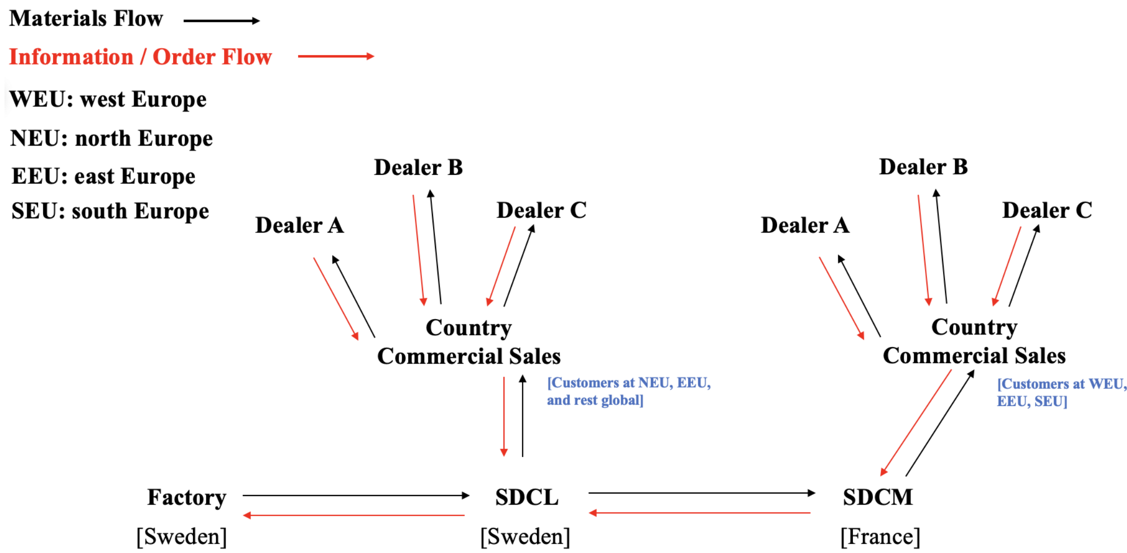
1.4 Current Operations

Existing demand prioritization methods are initially based on the customer's initial requested delivery date. If orders for multiple customers have the same initial requested delivery date, the second criterion, the date in which the Commercial Sales teams submitted the order(s), is reviewed through an interim escalation process for orders deemed urgent.

The process map in Figure 1 shows the Water Technology Company's materials and information process flow. Material is produced in the Swedish factory (SF) and then stored at the Swedish Distribution Center (SDCL) and either delivered to global customers, or transferred to the French Distribution Center (SDCM) to fulfill the major European orders.

Figure 1

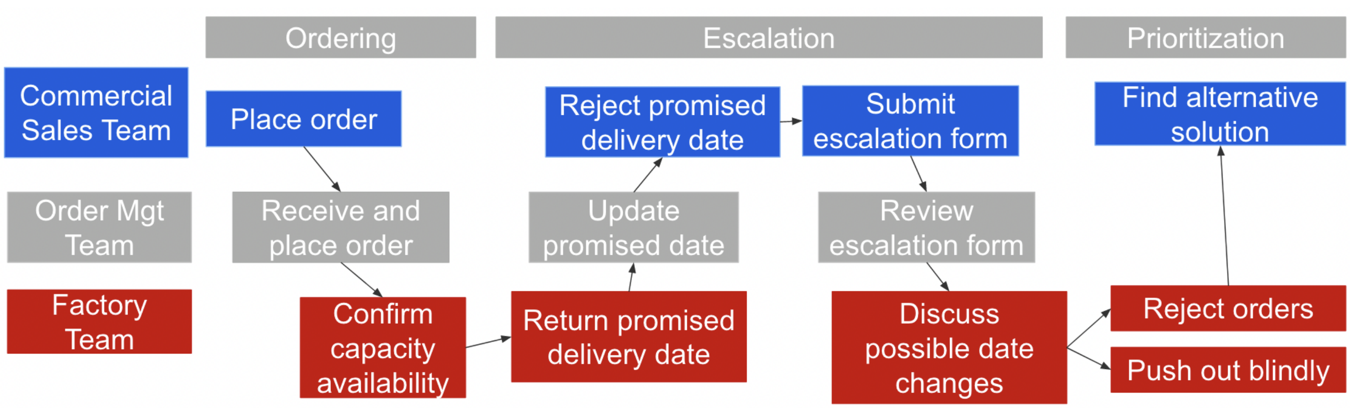
Material and information flows within the Water Technology Company's stakeholders



As Figure 1 indicates, the material and information flows between the country's commercial sales teams and the DCs. The commercial sales teams place orders for water pumps but are not able to designate which ones are for safety stock versus order stock. Currently, the end customer information is not automatically captured and shared through the value stream. This lack of data sharing leaves the enterprise wide business leaders and order management team (OMT) blind as to what order is truly the most important.

Figure 2

Outline of the current order process within the Water Technology Company.



The existing demand prioritization escalation process, outlined in Figure 2, only prioritizes orders in a local and individualized method, rather than regional or global level. With a short-term, narrow focus, the decision on which order to manufacture and deliver first does not account for the larger business view. This potentially leaves production capacity and materials unutilized while negatively impacting long-term revenue. The existing decision analysis process is housed on Microsoft's SharePoint site and managed by one individual.

The process begins with an order in which the internal published delivery date does not match the commercial sales team need. Once the SF team receives a pull-in request, they have two approaches. First, blindly escalate the requested order by delaying the existing order delivery. Or second, have the commercial sales team who wrote the escalation request rank all remaining unfulfilled orders in order of preference. The second option moves liability and decision making onto the individual Commercial Sales team to decide which orders to deprioritize in order to open up capacity. (R, Axelsson, Decision Makeral communication, November 4, 2021) These two approaches will be eliminated with a standardized demand prioritization process. To achieve this, the method of prioritization must be selected along with which criteria to measure.

2 Literature Review

In order to identify the best standardized and repeatable process for the Water Technology Company to prioritize its orders, an extensive literature covered methods of prioritization, process to select criteria, implementation practices, and normalization of data techniques.

2.1 Introduction

This literature review starts with a review of methodologies in which sales orders can be evaluated, such as first come first serve (FCFS), multi-criteria decision making (MCDM), and machine learning (ML). Then, after deciding on the MCDM method, we summarize the criteria most used in academic literature. As criteria will have various units of measures, a literature review on how best to normalize all sales order data was conducted, resulting in value function patterns being assigned to each criteria. With data normalized, MCDM tools are reviewed, each tool aggregating each individual decision maker (DM) preference in a unique way.

2.2 Demand Prioritization Methodologies

2.2.1 First Come First Serve

The traditional priority allocation method, First Come First Serve (FCFS), prioritizes the specific by time the orders are received. In FCFS, the order received first is completed first. FCFS does not take into account order urgency, capacity optimization, or customer need. Instead of using FCFS, Hu et al. (2015) proposes reviewing product revenue and holding costs in the scenario of reducing backlogs. A customized capacity model may be more aligned to feasible revenue management for a company (Hu et al., 2015). FCFS differs from MCDM and ML as the other methodologies consider multiple criteria, such as the order type and the end customer (Lečić-Cvetković et al., 2010).

2.2.2 Multi-Criteria Decision Making

MCDM, as its name conveys, allows for the consideration of multiple criterion when prioritizing orders. This is a large umbrella term, as it covers many potential decision-based analysis tools which all follow a similar three-step process: "1) Structuring the problem on hand; (2) Constructing the decision model; and (3) Analyzing the model" (Akyildiz et al., 2015). For group decision making, MCDM aligns well with a structured decision for a large problem while another option, social choice (SC) uses individual DM votes (Srdjevic, 2007). SC assumes homogeneity in the DM preference and opinions so MCDM is declared a better option for the Water Technology Company.

MCDM offers an expeditious method to aggregate results and prioritize orders (Muralidharan et al., 2002). For the purpose of this capstone, the Analytical Hierarchy Process (AHP) is described in 2.5 but additional MCDM tools, such as analytical network process (ANP), preference ranking organization method for enrichment evaluation (PROMETHEE), and technique for the order of prioritization by similarity to ideal solution (TOPSIS), can be seen in Akyildiz et al. (2015), Muralidharan et al. (2022), Ishal et al. (2019), and Sharma et al. (2018).

2.2.3 Machine Learning

Besides FCFS and MCDM, companies can utilize machine learning algorithms, such as a radial basis function (RBF) neural network or the hybrid harmony search algorithm of optimized support vector machines (HHS-SVM) to prioritize orders. Machine learning algorithms utilize additional data inputs such as customer segmentation which can be achieved through considering revenue, profit, development potential, requested service rate, and strategic partnership (Lečić-Cvetković et al., 2010). After customers are grouped into categories, several other variables need to be introduced to complete the algorithm. To avoid a company solely focusing on short-term profit generation, Lečić-Cvetković et al. (2010) recommend considering partition to reserve a certain quantity for small customers who have great sales growth potential. The algorithms also take days of sales outstanding into consideration, so any backorders from the previous cycle are prioritized first in the subsequent production allocation.

Tang and Cai (2008) highlight the radial basis function (RBF) neural network when applied to an evaluation index to prioritize customer orders. RBF factors in the evaluation index of a constrained supply chain when executing demand prioritization in a make-to-order business. The RBF three-degree system is similar to a Gauss Function design, which also has three layers. The first layer is the input data. The hidden section is the point in time at which the input data has the connection weight calculated between the indexes (in this case an index is the sales order criteria) to linearly normalize the input data. After normalization, the data is now in the output section. Tang and Cai (2008) specify 13 evaluation indexes that are expanded upon with a RBF algorithm while Yuanyuan and Qian (2014) use a similar approach, but with HHS-SVM. The RBF neural network requires training samples to review the evaluation criteria connection weights and then utilize computer programming to test machine learning on potential spreads of the network (Tang & Cai, 2008).

Both RBF and HHS-SVM require sample trial and test data; overall the complexity of machine learning over decision analysis ties back to the availability of data. For HHS-SVM, the online ordering environment evaluation index in Figure 2 outlines all criteria identified by Yuanyuan and Qian (2014). With raw data, a training set uses the harmony search algorithm to identify optimal support-vector machine parameters in order to build an evaluation model (Yuanyuan & Qian, 2014). Machine learning is not chosen for this capstone but is an option in years to come for future projects as the amount of data shared and available between all business groups increases.

As enterprise requirement planning (ERP) systems are updated with additional fields, this ML demand prioritization model can be created in the future to identify the optimal order.

2.2.4 Conclusion – Use of MCDM

The methodology to prioritize water pump sales orders will follow the MCDM framework. Out of FCFS and ML, MCDM allows for a group of DMs to input into criteria weights, it is reactive to changes in the industry but follows the business objectives, and is able to be performed with the least amount of technology. To tackle the Water Technology Company's demand prioritization challenge, the MCDM practice of an analytical hierarchy process, AHP, will be implemented first.

2.3 Identification of Prioritization Criteria

Scholars have utilized many different criteria to prioritize orders and demand. These criteria can be categorized into metrics which impact the order, the product, and the customer. In Table 1, the top nine metrics identified are Profit Margin, Delivery, Production Capacity, Product Category, Customer Relationship, Order Urgency, Product Quantity, Production Cost and Potential Sales Growth. Each cell with a Y highlights that that specific author discusses the respective prioritization criteria.

Table 1

Literature review of top demand prioritization criteria.

Author	Profit Margin	Delivery	Production Capacity	Product Category	Customer Relationship	Order Urgency	Product Quantity	Production Cost	Potential Sales Growth
Zhu et al. (2014)	Y	Y	Y	Y	Y	Y	Y	Y	Y
Tang & Cai (2008)	Y	Y	Y	Y		Y	Y	Y	
Balakrishnan et al. (1996)	Y	Y		Y					
Yuanyuan & Qian (2014)	Y	Y	Y	Y	Y	Y	Y	Y	Y
Akyildiz et al. (2015)	Y		Y		Y				Y
Total Count	**5**	**4**	**4**	**4**	**3**	**3**	**3**	**3**	**3**

Within the top nine criteria mentioned in the literature aggregated in Table 1, additional background was provided in terms of customer relationships and the accompanying customer segments. If customers are segmented, Carr and Duenyas (2003) argue that each unique demand signal can also decipher if the order is a contractual order with penalties or a transactional order with no penalties. Companies can utilize order segmentation to accept or reject orders to reduce backlog impacts (Carr & Duenyas, 2,000). In the event of limited capacity, Lečić-Cvetković et al. (2010) summarize that companies should leverage Available-To-Promise (ATP) and Capable-To-Promise (CTP) logic imbedded with customer segmentation to determine order fulfillment priority, increasing probability of realizing higher income, as orders with low priority will be rejected or deprioritized.

When identifying and selecting metrics, make-to-order supply chains revolve around customer priorities and require a "cooperation alliance" to share information (Tang & Cai, 2008). As information is freely shared throughout the company, the time between order receipt and placement allows the factory to initiate production due to make-to-order business structures that must wait for a tangible record of order acceptance. Make-to-order companies can utilize the acceptance of orders and negotiation of contracts to create additional levers to proactively address capacity constraints through tight deadlines and dynamic pricing (Mestry et al., 2011).

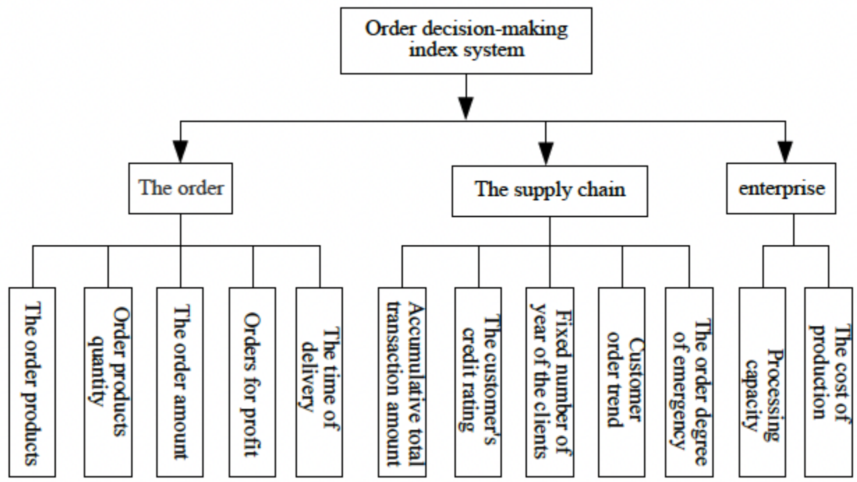
In contrast to a make-to-order environment, make-to-stock businesses plan for on-hand inventory to satisfy orders, but with unstable downstream demand, demand prioritization is still an issue. Lečić-Cvetković et al. (2010) support that a make-to-stock business model should be equipped with a robust and efficient algorithm. A robust algorithm would need to consider multiple factors, such as strategic customer relationships, future potential growth of a customer, and the profit margin. An efficient system of allocation is critical to operating efficiency to balance sales volume and profit.

The Water Technology Company straddles both environments, make-to-stock and make-to-order. Make-to-stock orders are satisfied by pumps on shelf in Sweden or France, whereas the make-to-order pumps do not begin production until a real customer order is received. Unfortunately, the current process does not facilitate end-to-end inventory data sharing. This lack of communication is a symptom of archaic ERP systems mixed with a multitude of different Commercial Sales teams operating with their own data.

After selecting metrics, aggregating them starts with a graphical index system, as Yuanyuan and Qian (2014) show in, Figure 3. Similar index evaluation systems are also identified by Tang and Cai (2014), Saaty (2008), and Akyildiz et al. (2015).

Figure 3

Online Order Prioritization Metric Diagram Tree from Yuanyuan & Qian (2014)



This type of indexing criteria is critical when demand outpaces supply. Capacity rationing is another term for describing this scenario, defined by Balakrishnan et al. (1996) as restricting a portion of capacity to only be available for high-priority orders. Products with price sensitivity (such as airplane seats within the airline industry) follow this approach, whereas a manufacturing environment can utilize the order categorization to ensure optimum capacity plans are derived from key metrics (Balakrishnan et al., 1996).

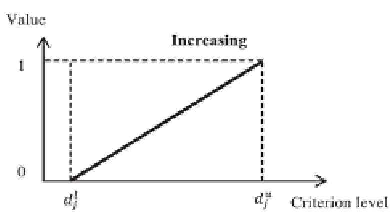
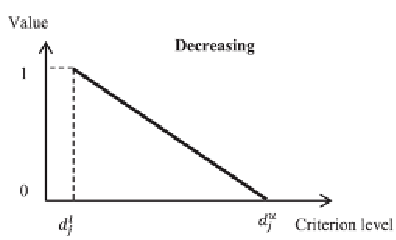
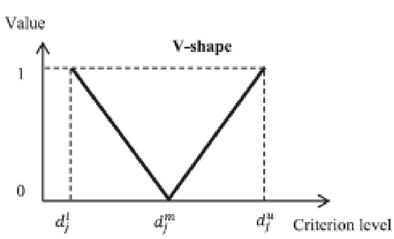
2.4 Defining Value Functions

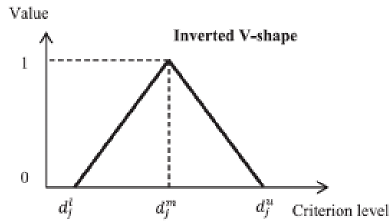
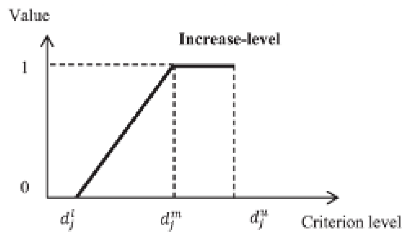
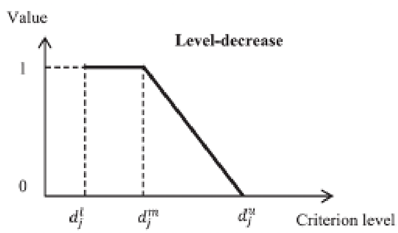
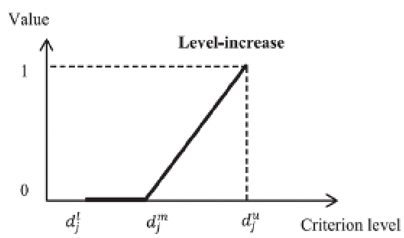
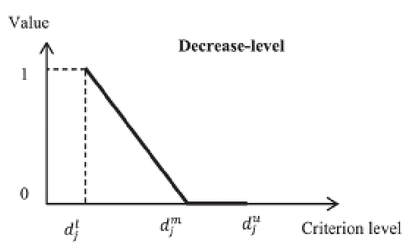
The final selection of criteria do not have the same units of measure. In order to compare and prioritize orders, the criteria data inputs must be normalized in advance of any MDCM tool implementation. Value function patterns are a method to normalize the water pump order data. Each function takes the criterion input and transforms it into a normalized value based on predefined upper and lower domains. Value function patterns assume that all criteria follow monotonic-linear value functions, either increasing or decreasing, thus overly simplifying business rules from the real world. For non-linear value functions, additional information is researched by scholars Kirkwood (1997) and Pratt (1964). To define a value function, the business owner identifies the pattern which more important or less important orders follow.

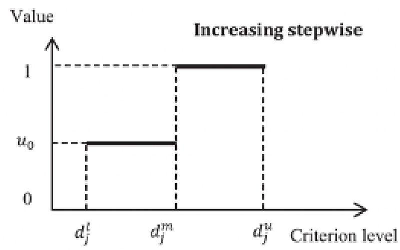
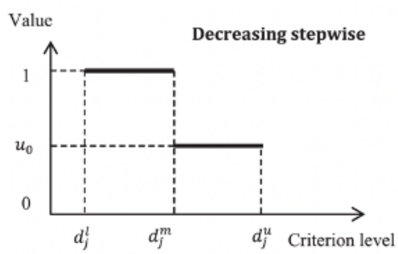
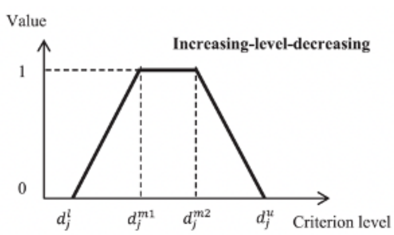
For an overview of all value functions, 11 piecewise value functions and several exponential value functions represent various business scenarios for decision makers (Rezaei, 2018). Essentially, a defined domain $[d^l_j, d^u_j]$ or $[d^l_j, d^m_j, d^u_j]$, depending on the type of value functions, needs to be identified first to calculate value. Table 2 presents all 11 piecewise value functions, including the function figure, a brief explanation, and the formula. Exponential value functions are not included here due to their complexity.

Table 2

Piecewise value functions for normalizing MCDM criteria from Rezaei (2018).

Function Figure	Function Concept	Function Formula
	**Increasing:** value u_{ij} increase as x_{ij} increase	$u_{ij} = \begin{cases} \frac{x_{ij} - d^l_j}{d^u_j - d^l_j}, & d^l_j \leq x_{ij} \leq d^u_j, \\ 0, & \text{otherwise.} \end{cases}$
	**Decreasing:** value u_{ij} decrease as x_{ij} increase	$u_{ij} = \begin{cases} \frac{d^u_j - x_{ij}}{d^u_j - d^l_j}, & d^l_j \leq x_{ij} \leq d^u_j, \\ 0, & \text{otherwise.} \end{cases}$
	**V-shape:** value u_{ij} decrease as x_{ij} reach a certain level then u_{ij} increase	$u_{ij} = \begin{cases} \frac{d^m_j - x_{ij}}{d^m_j - d^l_j}, & d^l_j \leq x_{ij} \leq d^m_j, \\ \frac{x_{ij} - d^m_j}{d^u_j - d^m_j}, & d^m_j \leq x_{ij} \leq d^u_j, \\ 0, & \text{otherwise.} \end{cases}$

	**Inverted V-shape:** value u_{ij}increase as x_{ij} reach a certain level then u_{ij} decrease	$u_{ij} = \begin{cases} \frac{x_{ij}-d_j^l}{d_j^m-d_j^l}, & d_j^l \le x_{ij} \le d_j^m, \\ \frac{d_j^u-x_{ij}}{d_j^u-d_j^m}, & d_j^m \le x_{ij} \le d_j^u, \\ 0, & \text{otherwise.} \end{cases}$
	**Increase-level:** value u_{ij} increase as x_{ij} reach a certain level then u_{ij} remain at the maximum level	$u_{ij} = \begin{cases} \frac{x_{ij}-d_j^l}{d_j^m-d_j^l}, & d_j^l \le x_{ij} \le d_j^m, \\ 1, & d_j^m \le x_{ij} \le d_j^u, \\ 0, & \text{otherwise.} \end{cases}$
	**Level-decrease:** value u_{ij} remain at the maximum level until x_{ij} reach a certain point then value u_{ij} decrease	$u_{ij} = \begin{cases} 1, & d_j^l \le x_{ij} \le d_j^m, \\ \frac{d_j^u-x_{ij}}{d_j^u-d_j^m}, & d_j^m \le x_{ij} \le d_j^u, \\ 0, & \text{otherwise.} \end{cases}$
	**Level-increase:** value u_{ij} remain at 0 until x_{ij} reach a certain point then value u_{ij} increase	$u_{ij} = \begin{cases} 0, & d_j^l \le x_{ij} \le d_j^m, \\ \frac{x_{ij}-d_j^m}{d_j^u-d_j^m}, & d_j^m \le x_{ij} \le d_j^u, \\ 0, & \text{otherwise.} \end{cases}$
	**Decrease-level:** value u_{ij} keep decreasing until x_{ij} reach a certain point then value u_{ij} remain at 0	$u_{ij} = \begin{cases} \frac{d_j^m-x_{ij}}{d_j^m-d_j^l}, & d_j^l \le x_{ij} \le d_j^m, \\ 0, & d_j^m \le x_{ij} \le d_j^u, \\ 0, & \text{otherwise.} \end{cases}$

	**Increasing stepwise:** value u_{ij} remain the same as x_{ij} reach a certain, then u_{ij} jump to and remain the next level as x_{ij} continue increase	$u_{ij} = \begin{cases} u_0, & d_j^l \le x_{ij} \le d_j^m, \\ 1, & d_j^m \le x_{ij} \le d_j^u, \\ 0, & \text{otherwise.} \end{cases}$
	**Decreasing stepwise:** value u_{ij} remain the same as x_{ij} reach a certain, then u_{ij} jump down to and remain the next level as x_{ij} continue increase	$u_{ij} = \begin{cases} 1, & d_j^l \le x_{ij} \le d_j^m, \\ u_0, & d_j^m \le x_{ij} \le d_j^u, \\ 0, & \text{otherwise.} \end{cases}$
	**Increasing-level-decreasing:** value u_{ij} increase as x_{ij} reach a certain, then u_{ij} remain the next level as x_{ij} continue increase, then u_{ij} decrease as x_{ij} continue to move on	$u_{ij} = \begin{cases} \frac{x_{ij} - d_j^l}{d_j^m - d_j^l}, & d_j^l \le x_{ij} \le d_j^{m1}, \\ 1, & d^{m1} \le x_{ij} \le d^{m2}, \\ \frac{d_j^u - x_{ij}}{d_j^u - d_j^m}, & d^{m2} \le x_{ij} \le d_j^u, \\ 0, & \text{otherwise.} \end{cases}$

2.5 MCDM Tools

MCDM tools include Analytic Hierarchy Process (AHP), a simple heuristic that applies decision makers (DM) knowledge on critical factors. It is a quantifiable method that offers a cost-value approach, allowing the business to review tradeoffs, when faced with conflicting goals, in order to maximize quality, minimize cost, and decrease delivery times (Karlsson & Ryan, 1997). AHP scales selected metrics based on importance with a four-step process to 1) define the problem, 2) structure the objectives of the program in low, intermediate, and high levels, 3) compare levels with those immediately below using pairwise matrices, and 4) weigh the priorities for each element in each level to review all options (Saaty, 2008).

AHP first selects a core team of DMs to rank and weighs the order of importance for each criterion (May et al., 2014). The AHP process elicits the DM's judgment of elements in a hierarchy and mathematically manipulates them to obtain the final preference weights of the decision alternatives with respect to the overall goal (Srdjevic, 2007).

A supporting reason to implement the AHP process is the potential for higher profit contributions. Higher profits is an outcome observed from the 1996 study by Balakrishnan et al. AHP is also deemed a less complicated MCDM tool because it utilizes expert opinion and human judgements when knowledge and experience are more readily available than quantitative data (Zhu et al., 2014). A pairwise comparison outputs an ultimate score for each criteria. Saaty (2008) stated that the ability for AHP to use pairwise comparisons to quantify importance could be subjected to human judgment.

As weights are provided for each selected criterion with the AHP methodology, each criterion data normalized value is multiplied by the criterion weight factor. With all values summed together, this final output would not provide an objective list prioritizing which orders to be manufactured and delivered first. It is critical to understand that each criterion has different ranges and patterns. In the case of the Water Technology Company, Profit Margin numbers in dollars are quite different from a Days to Delivery value.

2.6 Methods for Aggregating Metrics

When utilizing MCDM and AHP, the decision maker (DM) survey responses can be aggregated in a variety of methods. The aggregation of individual judgments (AIJ), aggregation of individual priorities (AIP), and reciprocal methods are expanded in this section. Additional methods such as the loss function approach (LFA) which utilizes the consistency ratio (CR) to calculate the expected loss between criteria and Group AHP which reviews the aggregation of criteria based on preferential differences and rankings are reviewed in Ossadnik et al. (2016). Ossadnik et al. (2016) also reviews the aggregation of individual priorities (AIP) method which was a high contender. This AIP method is applicable when group members try to optimize different goals. Once ranking from an individual is received, final group preference can be calculated through a (weighted) arithmetic or a (weighted) geometric mean method (Ossadnik et al., 2016), however, all projects or sales orders must also be reviewed as an alternative.

2.6.1 Aggregation of Individual Judgments (AIJ)

The synergistic AIJ method applies when participants are from the same team or achieving the same goal. The result can be aggregated through calculating the geometric mean by considering voting power and criterion weight. However, it does not apply to the Water Technology Company's situation as many DMs reside in different departments. The commercial sales teams, factory team, and order management team all have conflicting interests and inherently will be misaligned when providing criterion importance rankings. Additionally, AIJ has limitations that include a DM group size should be smaller than five individuals (Ossadnik et al., 2016).

2.6.2 Reciprocal Method

In addition to the aforementioned methodologies, results can also be aggregated through methods which do not require a ranking of all alternatives and, instead, provide each DM an individual weight. First, the significance of a DM comes into play. DMs can equally receive the same weight (1/n where n=the number of DMs) or where a DM's individual weight is the reciprocal of their consistency ratio (Janković & Popović, 2019). There are other methods that are reviewed, such as social choice, where DMs provide votes for other DMs, each vote is considered an interval judgment (Srdjevic, 2007). The social choice weight takes into account the decision maker's knowledge, skill, years, attitude, and experience (Muralidharan et al., 2002). Individuals can provide rankings of DMs following the AHP approach while the aggregation of responses is calculated in a unique method. Of the various options, the reciprocal method utilizes the DM's personal consistency ratio value and the weight of the individual is the reciprocal.

To highlight what the CR is, it is a calculation provided by the AHP Priority Calculator (n.d) to measure a DM's consistency in their ranking of criteria importance. The logic of CR follows that if an apple is better than an orange, and an orange is better than a banana, a banana cannot be better than an apple. As individual responses are provided, a CR is calculated and should be less than or equal to 10%.

2.6.3 Group Aggregation

With the selection of AHP as the MCDM tool and the reciprocal of the CR to serve as each DM's individual weight, the prioritization criteria weights must be aggregated. There are two primary methods, the Weight Arithmetic Mean Weight Method (WAMM) and the Geometric Mean Method (GMM) outlined in Figure 4.

Figure 4

Equations of a) Weighted Arithmetic Mean Method (WAMM) and b) Geometric Mean Method (GMM)

$$w_i^{(g)} = \sum_{k=1}^{m} w_i^{(k)} \alpha_k$$

a)

$$w_i^{(g)} = \prod_{k=1}^{m} \left(w_i^{(k)} \right)^{\alpha_k}$$

b)

The WAMM is the sumproduct of all the DM's weight and their corresponding weight to the prioritization criteria (Janković & Popović, 2019). For these equations in Figure XX, w_i^g stands for the aggregated prioritization criteria weight, w_i^k stands for the individual DM's prioritization criteria weight. For this project, $alpha_k$ is seen as the individual DM's weight compared to the other DMs. By calculating the sumproduct of individual skill weight and its corresponding weight rating for each supplier, the aggregated weights for each of the prioritization criteria (three for the Current Criteria and six for the Extended Criteria) are objectively provided. The GMM individually takes the DM's criteria weight to the power of the DM's individual weight. For this project, there are seven DMs, the GMM is the product of those values multiplied together.

2.6.4 Conclusion - Hybrid Approach

When DMs are aligned with common objectives, all MCDM aggregation methods are applicable. However, the methodologies applicable to the Water Technology Company situation is limited as the DMs have conflicting objectives. The individuals are scattered across the entire order management process and have different interpretations of what is important for each criteria. If DMs have diverging or conflicting objectives, AIJ is not recommended. Therefore, by utilizing and implementing a hybrid approach of MCDM tools and a reciprocal method, the Water Technology Company will be able to take advantage of all available capacity while improving long-term financial revenue.

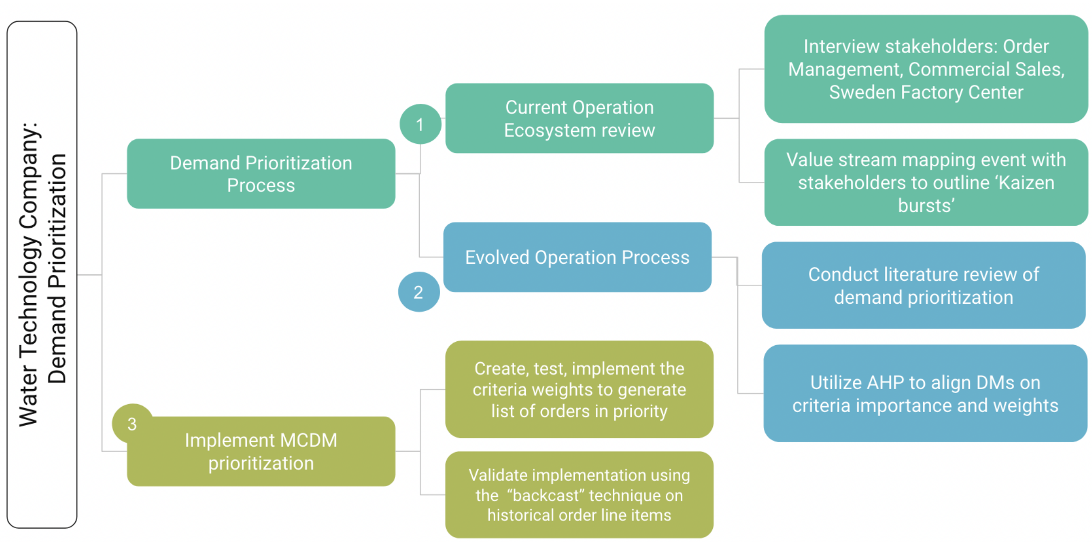
The number of DMs and alternatives impacts the ability for MCDM implementation options. In this research paper, alternatives are viewed as the sales orders. Unfortunately, as the number of sales orders can easily be over 1,000, asking DMs to individually rank each one is out of scope. Thus, the literature review includes methods to aggregate results of criteria importance where decision makers come from different backgrounds. The objective of this literature review was to identify which standardized criteria are most important in academia and then orchestrate a feasible implementation process for the sales orders of water pumps. The capstone will provide an official ranking of sales orders utilizing the top criteria, such as profit margin and order delivery date. Such information enhances the team's understanding of available levers to identify and satisfy the most important demand first.

3 Methodology

With a two-part research question, 1) what criteria can assist in prioritizing sales order demand; and 2) how can such criteria be implemented, the methodology in Figure 5 was constructed. There are three paths involved with this project; Path 1 focuses on the interviews which define the current process map, Path 2 focuses on the future process and the critical key factors to input into a MCDM, and Path 3 uses a hybrid approach to implement the Analytical Hierarchy Process (AHP) process. This project will utilize interviews, process mapping, MCDM, specifically, a hybrid approach to AHP.

Figure 5

Three paths outlining demand prioritization methodology

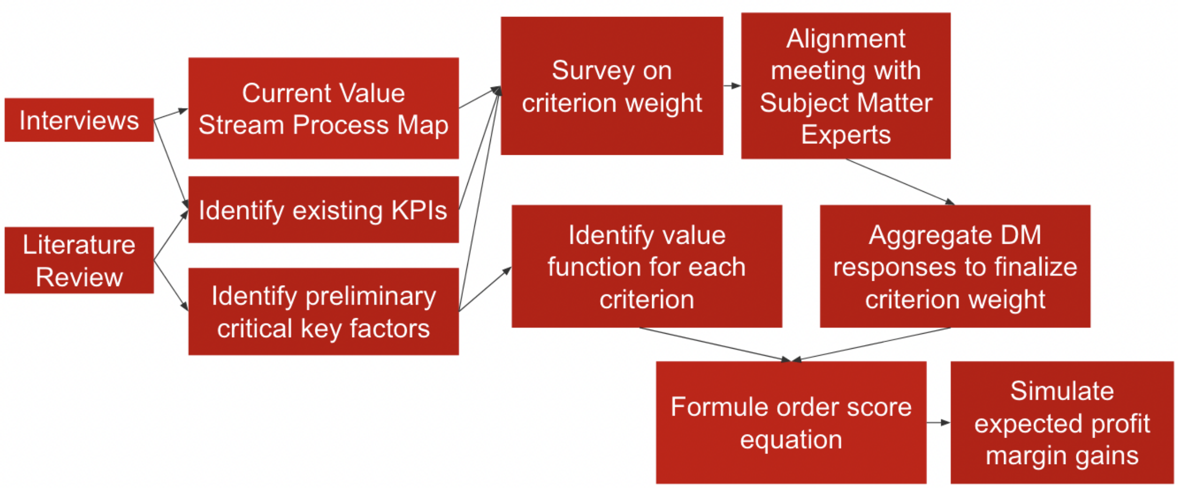


While the final deliverable is a list ranking orders to optimize a balance between profit margin and customer relationships, the methodology begins with identifying key criteria. Then, selecting and applying a value function pattern to each of the chosen criteria, and calculating an assigned weight based on the chosen DM aggregation method.

In execution of this project, the first alignment meeting raised interest and awareness for a standardized and repeatable prioritization process, however, the second alignment meeting with DMs identified their conflicting point of views on the chosen criteria. With DM inputs, Figure 6 highlights the chronological methodology of the project. The hybrid AHP process approach allows each DM to have an assigned weight, in terms of the reciprocal of their CR. With criteria weights identified, the weight can be applied to the normalized, sales order information.

Figure 6

Demand Prioritization Methodology



3.1 Criteria Selection Process

To select criteria, the current business structure had to be mapped out as Decision Makers (DMs) reside in different countries and departments. Interviews with DMs were conducted to outline the current process and gain insight into what order criteria are most important for each team.

3.1.1 Current Process Map

Virtual interviews were conducted with all DMs. As no existing process maps exist and none have been shared across the involved stakeholders, the process map was created from the virtual interviews and reviewed with all key stakeholders. Figure 7 is the computer-generated process map outlining the current process map for placing water pump orders and escalating orders.

Figure 7

Current value stream process map outlining order receipt, escalation and delivery.

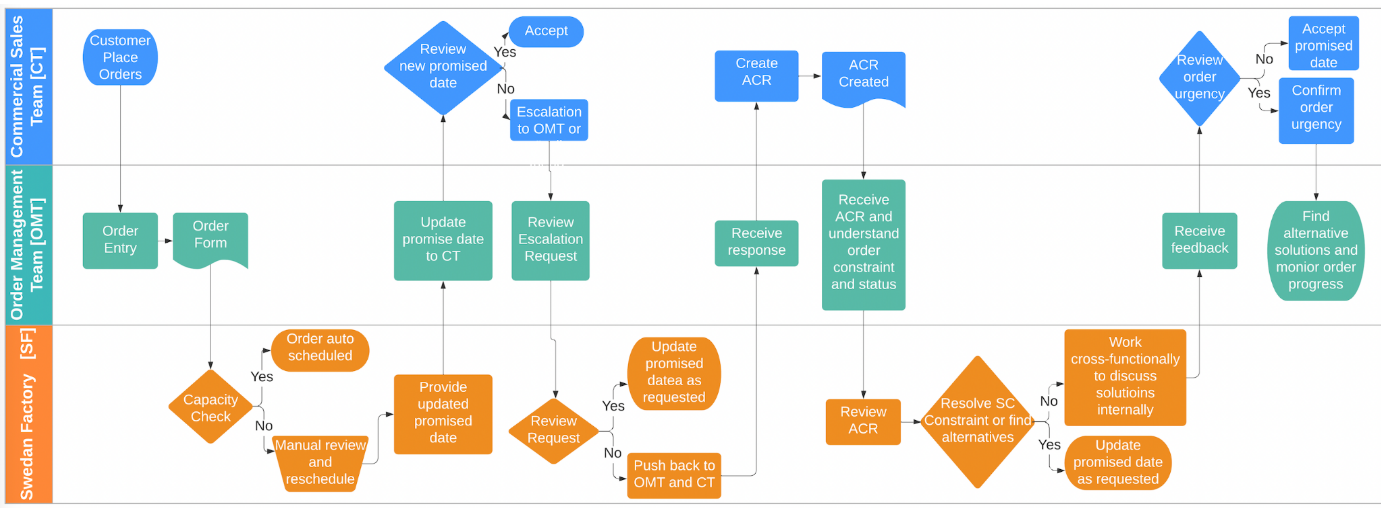


Figure 7 outlines the DMs involvement with the order management process, the first swim lane highlights how the Commercial Sales Team (CST) initiates the order placement and is the mediator between the end customer's needs and the Water Technology Company's central order management team (OMT). The OMT sits in between the CSTs and the Sweden factory (SF) team. The overall process highlights the automatic scheduling process of water pump orders if there are no constraints, however, when multiple orders request similar products for the same delivery date, the escalation process is kicked off. Creating this value stream process map highlighted the number of turnbacks during the process, and the amount of email requests for acceptance or approvals.

3.2.2 Preliminary Qualitative Interviews

Five virtual interviews were conducted with the Order Management team (OMT), the Sweden Factory (SF) team, Commercial Sales Team – Country 1, Commercial Sales Team – Country 2, and Commercial Sales Team – Country 3 with the purpose of identifying the current state environment and receiving internal suggestions to a solution for the problem statement.

3.2.1 Order Management

The order management team's (OMT) involvement in the escalation process is to review and respond to the accelerated conversion request (ACR). The ACR is submitted by the commercial sales team and is situated to escalate orders based on the end customer request date and dollar value. The OMT raised concern that the delivery delays from the Sweden Factory (SF) are not communicated through to the end customer causing missed expectations.

All escalation requests are very manual and conducted over Microsoft Sharepoint and email. Currently, the order management prioritization is only at the individual line item level and there is a lack of support with the current ERP system. The OMT requests that the deliverable prioritizes orders at business level and, hopefully, at global level in the future. Suggested solutions included setting an escalation budget for each commercial sales team and having KPI ownership such as on time delivery (OTD) and on time performance (OTP), scheduling rate, rescheduling rate and order placement speed.

3.2.2 Sweden Factory

The SF team is involved in the escalation process as they receive escalation orders through the ACR from the order management team. About 30% of escalation requests are accepted and cause the blind push out of other orders while ~70% of ACR requests are rejected. When a request is rejected, it is returned to the commercial sales team to determine prioritization within the team's individual order list. Main concerns with the current process include the lack of a formal process to manage the demand priority and no associated point of contact. Everything is conducted through Sharepoint with no standardized logic or algorithm to determine demand priority. The SF team asks that the final deliverable considers order volume, order margin, and the customer strategic relationship in the process of demand priority. Similar to the OMT, the SF team reviews OTD and OTP but also reviews the total order value and the backlog of existing orders.

3.2.3 Commercial Sales Team – Country 1

Sales team 1 is involved with the escalation process by proactively collecting demand expectations from customers and sharing forecasts to the SF. The team also has transparent communications with end customers by sharing lead times and placing stock orders for high turnover parts. ACRs are only submitted when there are urgent breakdown orders. For the current process, having good ordering practices, such as placing orders at lead time, does not correlate to having this sales team 1 receive any advantage in the order allocation prioritization. To them, it is concerning that the order delivery date can be pushed out again and again within one to two weeks of a confirmed delivery. A resulting effect of this change in delivery date is an increased customer dissatisfaction and potential loss of sales. This team looks for a reliable order delivery date. Overall, the sales team is concerned about customer backorders as this location is an emerging market and failing delivery could lead to customers walking away from the Water Technology Company.

3.2.4 Commercial Sales Team – Country 2

Sales team 2 shared that their orders include real customer orders and stock orders on high turnover parts. However, only customer orders receive escalations. Escalation happens based on customer needs, not considering strategic relationships or market segments. Their concerns with the current process include that demand forecasts are not collected or shared with the factory due to the number of individual SKUs. An order would be escalated when the initial promise date is unacceptable or the promise date is pushed out again and again. Sales team 2 looks for a reliable order delivery date and shares the order type information. While sales team 2 requested various items, some are out of scope of this demand prioritization project.

3.2.5 Commercial Sales Team – Country 3

Sales team 3 tracks orders but does not forecast potential orders, instead sales team 3 only places orders once demand is confirmed. The team shares the concern of sales team 1 in that stated delivery date commitments change at the last minute. The key request is to also have increased communication to share the existing and expected constraints to the commitment dates as soon as possible. As communication increases between the production factory and the sales teams, the sales team can then respond to end customers in a faster manner.

3.3 Criteria Selection

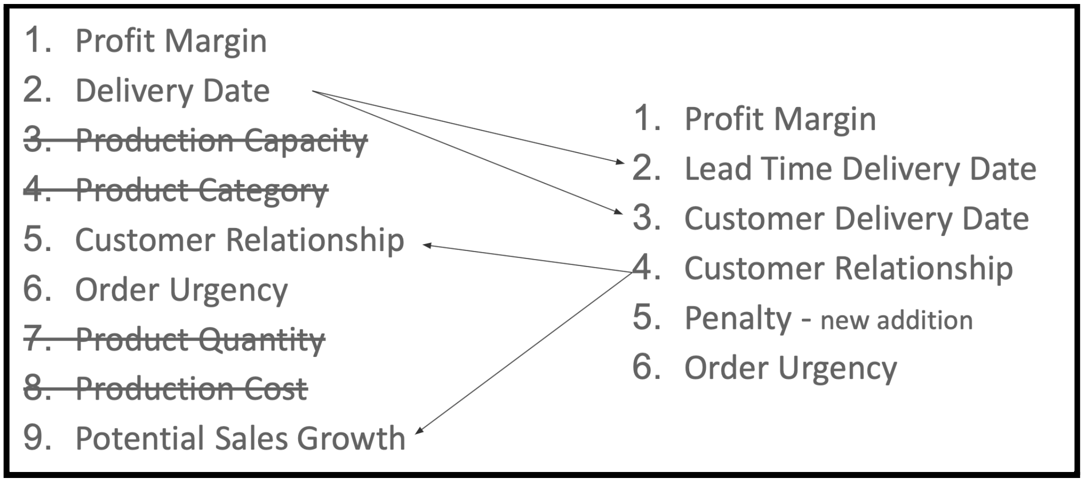
In order to select which criteria to include in the Water Technology Company's prioritization process, the first step is to identify the top criteria metrics and then cross-reference the literature review criteria with the available data from the company and the stakeholder input. Figure 8 identifies the nine criteria supported through the most literature pieces reviewed. However, the Water Technology Company only has existing data available for three of the nine criteria: Delivery, Production Capacity, and Production Cost. The criteria with existing data will be referred to as Current Criteria while the remaining three criteria will be added in when the Extended Criteria is discussed.

Production capacity and product category were not selected because the Water Technology Company specified that this project should not factor in or consider production planning. Product quantity was not considered in the demand prioritization process due to the wide range of product categories as fast and slow moving products do not align or correlate to all business goals. Product cost is reflected in profit margin, so it is taken out to avoid duplication. Potential sales growth is merged into customer relationships, as it is one of the most important factors to acknowledge when segmenting customers.

Delivery date is divided into two types - lead time delivery date and customer delivery date. The first one reflects production lead time and the latter shows the ideal delivery date requested by customers. From interviews with internal stakeholders, we understand that customers do not always respect standard production lead time when placing orders, therefore both delivery dates should be considered in demand prioritization to reward customers who place orders early and take care of customer needs.

Figure 8

Selection of criteria based on literature review and Water Technology Company preferences



The literature review gave less consideration to penalty as a criteria. However, multiple stakeholders brought up the significance of penalty during order allocations, thus this criteria is added in the final list. In the end, the final criteria are profit margin, lead time delivery date, customer delivery date, customer relationship, penalty, and order urgency. This initial and final list is presented in Figure 8. The detailed explanation of each criteria is available in Table 3.

Table 3

Six selected criteria definitions.

Criterion	Definition
Absolute Profit Margin	Sales price - MFG cost, absolute dollar value difference
Days to Delivery	Standard Leadtime Date - Current date, how many days until finished goods are committed based on published standard lead times
Days to Customer Want	Customer's Requested Delivery Date -Current Date, how many days until the customer wants the order to be delivered
Customer Relationships	Categorical Variable, assumed to be 1-Least to 5-Most Important Based on total sales, growth, etc
Financial Penalty	Binary, 0-no contract penalty or 1-yes contract penalty
Order Urgency	Categorical Variable, assumed to be 1-Least to 5-Most Important Based on order type (safety stock, work stop, scheduled order)

With five interviews and two alignment meetings with DMs, the interpretation and definition of the six criteria evolved. The initial attempt at a full consensus was not achieved due to the decision makers having conflicting objectives. Armed with criteria, a method to aggregate group responses in terms of the order of importance was identified. Finally, the implementation of the prioritization process is simulated with the Current and Extended Criteria utilizing assumptions for any missing data. The implementation is divided into two sections, the immediate, short term plan using available information for the Current Criteria while the longer term, Extended Criteria will require additional company leadership consensus.

3.4 Assigning Value Functions Patterns

With 11 different value function patterns, each of the six selected criteria in Table 3 requires its own value function pattern. After discussing all criteria with business leaders, each criterion was matched to its appropriate value function pattern based on a set of questions:

1. If there is one, what is the expected minimum value of this criterion?
2. If there is one, what is the expected maximum value of this criterion?
3. Does the criterion become more important the bigger the input value, or the smaller the input value?
4. Would you split the potential input values into buckets? If so, what range would those buckets be?
5. Do you have any additional thoughts on these criteria or the implementation of these criteria?

With responses specific to the Water Technology Company, the six criteria were assigned value function patterns as seen in Table 4. As profit margin increases, its value increases, therefore it is assigned the increasing value function pattern. Customer relationship, order urgency, and penalty are all categorical variables and align with an increasing step-wise function, the higher the input number, the more important the customer, order, or financial penalty would impact the overall business. Days to Delivery and Days to Customer Want are the only two criteria which follow a decreasing stepwise function, as the days are smaller (or negative) this raises the level of urgency as the orders are backlogged and missing external, customer want dates or internally set, production standard lead time dates.

Table 4

Matching of value function patterns to each criterion.

Value Function Pattern	Criterion/Criteria	Implementation
Increasing	Profit Margin	Input normalized between the minimum and maximum profit margin
Increasing stepwise	Customer Relationship Order Urgency Penalty	Categorical variable, 1-important to 5-very important, importance increases as data input increases
Decreasing stepwise	Days to Delivery Days to Customer Want	Categorical variable, 1-important to 5-very important, importance decreases as data input increases

3.5 Design of the AHP Analysis

The AHP analysis for this project revolved around a criteria weight exercise, an aggregation of the individual decision makers (DMs), a review of each DM's consistency ratio, and a group aggregation method.

3.5.1 Criteria Weight Exercise

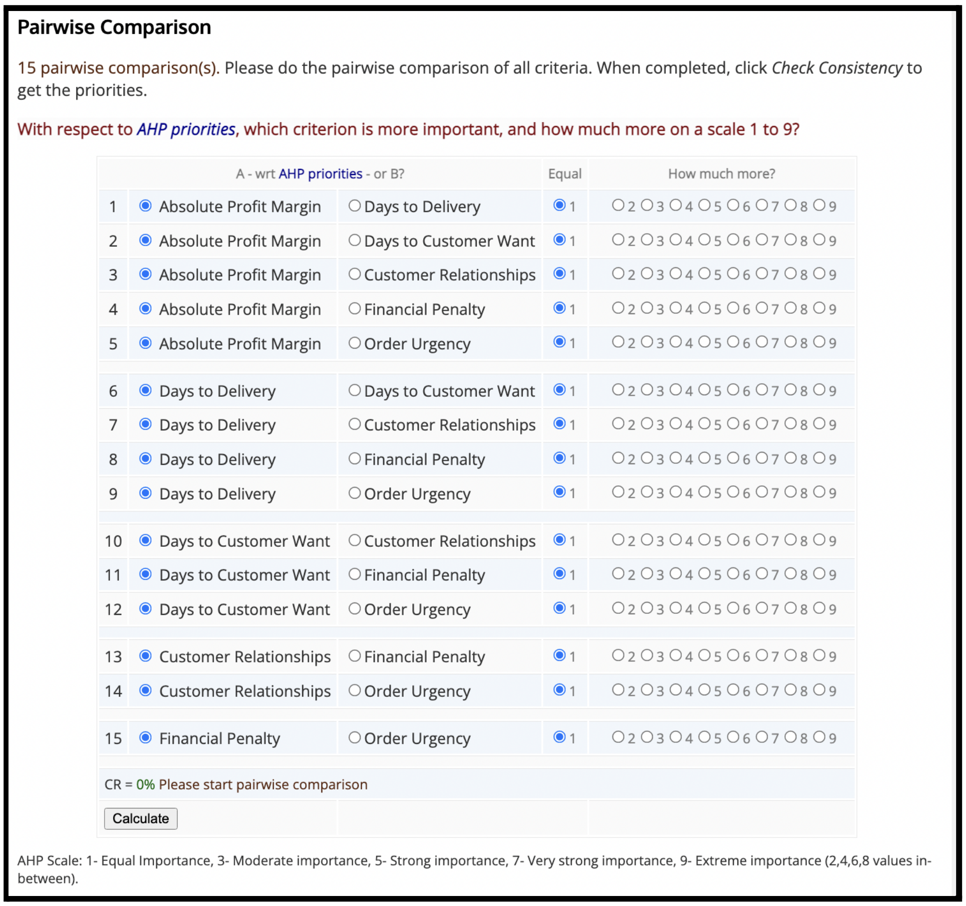
The design of the AHP analysis in the project began with an exercise activity for all DMs. By utilizing the DMs knowledge to compare the six criteria against each other. This survey was constructed on the universal used software, Microsoft Excel, and utilized three separate tabs. Appendix A highlights the first tab, which includes a set of instructions on how to fill out the form and the definitions of the six criteria. The second tab in this criteria weight exercise is shown in Appendix B, each DM provided the respective level of importance between the 15 permutations of the six criteria. An accompanying instructional video was also shared with all DMs to review before completing the criteria weight exercise.

3.5.2 AHP - Decision Maker Feedback Review

The criteria activity exercise responses from each DM were received and reviewed. This review utilized the AHP priority calculator, seen in Figure 9, which performs a pairwise comparison and offers suggestions in which the consistency ratio (CR) can be improved (*AHP Calculator - AHP-OS*, n.d.). The consistency ratio is the key threshold trigger for an AHP analysis. As the CR is a threshold, one of the eight respondents was an extreme outlier and removed from future calculations, moving forward, seven DMs responses are used.

Figure 9

Online AHP Priority Calculator



Pairwise Comparison

15 pairwise comparison(s). Please do the pairwise comparison of all criteria. When completed, click *Check Consistency* to get the priorities.

With respect to *AHP priorities*, which criterion is more important, and how much more on a scale 1 to 9?

	A - wrt AHP priorities - or B?		Equal	How much more?
1	Absolute Profit Margin	Days to Delivery	1	2 3 4 5 6 7 8 9
2	Absolute Profit Margin	Days to Customer Want	1	2 3 4 5 6 7 8 9
3	Absolute Profit Margin	Customer Relationships	1	2 3 4 5 6 7 8 9
4	Absolute Profit Margin	Financial Penalty	1	2 3 4 5 6 7 8 9
5	Absolute Profit Margin	Order Urgency	1	2 3 4 5 6 7 8 9
6	Days to Delivery	Days to Customer Want	1	2 3 4 5 6 7 8 9
7	Days to Delivery	Customer Relationships	1	2 3 4 5 6 7 8 9
8	Days to Delivery	Financial Penalty	1	2 3 4 5 6 7 8 9
9	Days to Delivery	Order Urgency	1	2 3 4 5 6 7 8 9
10	Days to Customer Want	Customer Relationships	1	2 3 4 5 6 7 8 9
11	Days to Customer Want	Financial Penalty	1	2 3 4 5 6 7 8 9
12	Days to Customer Want	Order Urgency	1	2 3 4 5 6 7 8 9
13	Customer Relationships	Financial Penalty	1	2 3 4 5 6 7 8 9
14	Customer Relationships	Order Urgency	1	2 3 4 5 6 7 8 9
15	Financial Penalty	Order Urgency	1	2 3 4 5 6 7 8 9

CR = 0% Please start pairwise comparison

Calculate

AHP Scale: 1- Equal Importance, 3- Moderate importance, 5- Strong importance, 7- Very strong importance, 9- Extreme importance (2,4,6,8 values in-between).

Initial exercise activity results are shown in Table 5 from the interactive exercise activity with the stakeholders show an inconsistency in the Consistency Ratio (CR) in terms of importance. There is inconsistency in each DM's weighing of the selected criterion. For example, Decision Maker 1 equally rated Profit Margin, Order Urgency, and Penalty, however, Profit Margin was then rated as 'strongly more important' than order urgency. DM5 is highlighted as the CR is an order of magnitude above the 10% threshold, thus DM5 is removed from further calculations and the remaining seven DM data points are reindexed to DM 1-7 used.

Table 5

Initial decision maker (DM) response to the criteria weight exercise

	DM 1	DM 2	DM 3	DM 4	DM 5	DM 6	DM 7	DM 8
Lambda Max	7.23	7.86	7.39	8.18	12.11	7.55	7.24	6.15
Consistency Index (CI)	0.25	0.37	0.28	0.44	1.22	0.31	0.25	0.03
Random Index (RI)	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24
Consistency Ratio	19.8%	30.1%	22.4%	35.1%	98.6%	25.0%	19.9%	2.4%

Top two challenges faced during the two alignment meetings included: 1) respondents cannot fully understand Customer Relationship, Order Urgency, and Penalty; and 2) respondents have trouble understanding the mechanism of AHP and are unable to compare Profit Margin to Days to Delivery. The differences in weight for all six extended criteria are seen in Table 6. While there are differences in assigned weights, there are common themes, Customer Relationship and Order Urgency received the top order of importance.

Table 6

Heatmap of individual DM criteria weights for six extended criteria

	Customer Relationships	Order Urgency	Profit Margin	Penalty	Days to Delivery	Days to Customer Want
DM1	34.30%	7.60%	7.90%	7.60%	31.20%	11.40%
DM2	20.20%	42.00%	9.20%	15.00%	4.50%	9.00%
DM3	49.40%	21.80%	8.80%	11.10%	3.80%	5.20%
DM4	23.90%	27.80%	3.70%	18.00%	6.50%	20.00%
DM5	50.10%	22.00%	8.00%	13.70%	2.80%	3.40%
DM6	16.20%	6.50%	34.40%	9.90%	21.50%	11.50%
DM7	10.10%	17.40%	31.10%	16.40%	19.00%	6.10%

The individual DM assigned weights follow unique patterns that correlate with the Water Technology Company. The customer focused mission of the company drives individuals to accommodate end customer requests and work to alleviate any and all concerns or escalation requests. However, with the limited information in the existing ERP system, Table 7 shows the heatmap for the individual DM criteria weights for just the three current criteria. This smaller heatmap shows a mix of the green, yellow, and red colors with Profit Margin receiving the highest overall score.

Table 7

Heatmap of individual DM criteria weights for three current criteria

	Profit Margin	Days to Delivery	Days to Customer Want
DM1	15.64%	61.78%	22.57%
DM2	40.53%	19.82%	39.65%
DM3	49.44%	21.35%	29.21%
DM4	12.25%	21.52%	66.23%
DM5	56.34%	19.72%	23.94%
DM6	51.04%	31.90%	17.06%
DM7	55.34%	33.81%	10.85%

The two heatmaps identify generalized patterns and provide seven sets of criteria weights. These criteria weights cannot be directly applied to a demand line item from a sales order. As days are different from dollars and dollars are different from categorical variables, the data input will need to be normalized and Table 8 shows an example of comparing selected criteria without normalizing data.

Table 8

Selected criterion weights without a value function applied

Without Applying Value Function			
Factor	Order 1	Order 2	Criteria Weight
Absolute Profit Margin	100	110	0.07
Days to Delivery	2	2	0.08
Days to Customer Want	-3	-3	0.05
Customer Relationships	2	2	0.49
Financial Penalty	20	20	0.21
Order Urgency	5	1	0.10
Total Value	12.76	13.06	

As an example, and using numbers from Table 8, a weight factor for Profit Margin criterion is 0.07 and Order Urgency is 0.10. Order urgency is weighted higher than Profit Margin. Ideally, the sales order output would prioritize an order with much higher urgency and slightly lower Profit Margin. Take an example, if two orders have all criteria being equal except Profit Margin and Order Urgency, the Profit Margin for Order 1 is 10% lower than Order 2. Meanwhile, Order Urgency for Order 1 is five times higher than Order 2. Order 1 should be prioritized in this example. However, as the range of Profit Margin is wider than Order Urgency, comparing hundreds of dollars in profit to just a categorical variable of 5 for Order Urgency. In this example, the total value of Order 2 is higher than Order 1, suggesting Order 2 should be produced first, this discrepancy can be identified in Table 8.

All but one DM had a CR less than 10% so adjustments were recommended to the remaining six DMs. Adjustments were recommended based on supply chain knowledge and expertise. These individual adjustments were approved by the DMs and the consistency ratio of <10% was achieved. At this point, each DM has an individual weight for each criteria. The next hurdle is to implement the most appropriate group aggregation method to combine all DMs.

3.5.3 Decision Maker Aggregation - Arithmetic and Geometric

With the approval of the criteria importance adjustments, the individual DM weights are calculated. The next step in this process is to utilize the individual DM weight for each criterion and aggregate all seven DM weights together. In order to achieve this, a table of four methods were established to align the options for DM weights and the method of aggregating the data:

1. Method 1 - DMs receiving the weight of the reciprocal of their CR and aggregated using the WAMM
2. Method 2 - DMs receiving equal weight (1/7 for each DM) and aggregated using the WAMM
3. Method 3 - DMs receiving the weight of the reciprocal of their CR and aggregated using the GMM
4. Method 4 - DMs receiving equal weight (1/7 for each DM) and aggregated using the GMM

To select the best method for implementation, a random sampling event was constructed to identify which method provides the greatest profit margin growth.

3.5.4 Current Criteria - Random Sampling of Four Methods

A random sampling was conducted for each of the four methods, 1-equal DM weight aggregated via WAMM, 2-reciprocal CR weight for each DM aggregated via WAMM, 3-equal DM weight aggregated via GMM, 4-reciprocal CR weight for each DM aggregated via GMM, for 10 times. For each random sample round, a random selection of 1,000, 2,000, 3,000, or 4,000 water pump demand order line items were chosen from the ~8000 line items file provided by the Water Technology Company. With the selection of capacity of the demand order line items, each line item received its individual Profit Margin, Days to Delivery and Days to Customer Want criteria calculations which factor into the final prioritization implementation. This process was repeated for each of the four group aggregation methods.

3.5.5 Extended Criteria - Random Sampling of Four Methods

The extended criteria, where all six of the prioritization criteria are used to evaluate demand prioritization, was tested in the same methods described in the previous section, 4.3.4. The random selection of 1,000, 2,000, 3,000 or 4,000 water pump sales order line items were used to calculate all six of the chosen criteria: the Profit Margin, Days to Delivery, Days to Customer Want, Customer Relationships, Penalty, and Order Urgency. With the data inputs to the demand prioritization criteria, the outputs are then multiplied to the respective criterion weight according to each of the four group aggregation methods.

3.6 Methodology conclusion

The final step of this methodology focuses on the long-term implementation of the demand prioritization allocation method. AHP can assign numerical values to each order in the form of a utility weight, however it does not show the Water Technology Company how to implement this. To ensure there is no single-source failure, it is recommended that an inhouse team author an algorithm to input orders, assign values, and output a list of orders in order of priority.

4 Results

As previously mentioned in Section 3.5.3, applying geometric and arithmetic aggregation methods under two different sets of individual decision maker weights generated a total of four sets of criteria weight. The data and numbers behind this group aggregation can be found in Appendix C for the arithmetic evaluation and Appendix D for the geometric evaluation. The total outcomes between profits and other qualitative categories under those four scenarios are evaluated and used as critical factors when finalizing the official criteria weight recommendations to the Water Technology Company. Considering the main purpose is to create a standardized and repeatable quantitative demand prioritization process to maximize profit margin, profit margin is discussed the most. A simulation on the current demand prioritization process was conducted, in order to understand and estimate the potential and additional profit generated by adopting the new approach.

4.1 Order Profit with Existing Metrics

With the existing data, available in the Water Technology Company's ERP data system, three of the six criteria are able to be calculated: Profit Margin, Days to Delivery, and Days to Customer Want. The scaled weight for these Current Criteria is calculated and presented in Table 9. The rank of criteria is consistent with Profit Margin taking the number one spot, followed by Days to Delivery then Days to Customer Want. However, the weight of each criteria has a wide range between those four methods. For Days to Customer Want, there is a 8.95% difference between Method 1 and Method 4. The range for Days to Delivery is from 31.24% to 34.49% and for Profit Margin is from 39.44% to 45.14%.

Table 9

Scaled Weight on Current Criteria and Metrics Performance - 4,000 Orders Capacity

4000 Orders Capacity	Total Profit from Scaled Weight on Existing Criteria			
Method	Method 1	Method 2	Method 3	Method 4
Profit Margin	**45.14%**	39.81%	43.95%	39.44%
Days to Delivery	34.49%	34.48%	33.11%	31.24%
Days to Customer Want	20.37%	25.71%	22.95%	29.32%
Total Order Profits	**$ 41,729,184**	$ 41,632,678	$ 41,638,948	$ 41,638,948
Days to Delivery	-60	-60	-60	-60
Days to Customer Want	-68	-68	-68	-68

To simulate the real world supply chain situation, a capacity constraint of 4,000 orders is assumed. The Water Technology Company provided blinded sales order data, sales orders from May to August of 2021 were used in the randomized simulation. With all order lines, over 8,000, the total possible profit is over $50M. For orders exceeding the 4,000 line item threshold, it is assumed there is no excess production capacity and thus order profit cannot be realized. Profit Margin was the criteria ranked highest, thus when it receives the highest allocated weight, 83% of profit is captured. The resulting total profits captured for all four methods have a difference of $96,506 between maximum and minimum methods.

The consistency in criteria ranking and total profit supports the robustness of this methodology. When capacity is reduced from 4,000 orders to 2,000 orders, there are only slight changes for each criteria. The number of days for Days to Delivery and Days to Customer Want increase slightly. However, the simulation with a smaller order capacity leads to less profits officially captured, as seen in Table 10.

Table 10

Scaled Weight on Current Criteria and Metrics Performance - 2,000 Orders Capacity

2000 Orders Capacity	Total Profit from Scaled Weight on Existing Criteria			
Method	Method 1	Method 2	Method 3	Method 4
Profit Margin	45.14%	39.81%	43.95%	39.44%
Days to Delivery	34.49%	34.48%	33.11%	31.24%
Days to Customer Want	20.37%	25.71%	22.95%	29.32%
Total Order Profits	$ 34,331,797	$ 34,331,797	$ 34,331,797	$ 34,331,797
Days to Delivery	-61	-61	-61	-61
Days to Customer Want	-70	-70	-70	-70

The final simulation reflected the mindset of the business leaders, who value profit margin most. With Profit Margin being the one and only criteria, the total profit increases to $45M, but this happens at the expense of Days to Delivery and Days to Customer Want. Table 11 highlights the increased profits but shows that when the orders being completed are more recent, the average drops down almost 10 full days, this can be interpreted that customers with older or backlogged orders should expect multiple and extended delays. While the financial bottom line increases within the company the customer relationships will be negatively impacted.

Table 11

Only Consider Profit Margin and Metrics Performance - 4,000 Orders Capacity

4000 Orders Capacity	Criteria Weight and Performance
Profit Margin	100%
Days to Delivery	0%
Days to Customer Want	0%
Total Order Profits	$ 45,220,420
Days to Delivery	-53
Days to Customer Want	-62

Currently, the Water Technology Company does not have a demand prioritization process. Customers are able to escalate orders and make phone calls. Initially, the SF will try to push out requests. If customers insist on having orders produced, Factory would choose to randomly push out existing scheduled orders to free up capacity or materials. With that being said, to simulate the current process, assuming the capacity cap is still 4,000 orders, 10 simulation rounds are performed. The average of simulation rounds profit is shown in Table 12 at $23.7M, the maximum profit is at $24.4M, and the minimum is at $23M. Compared to Method 1, when three existing criteria are taken into consideration, the resulting profit is $41.7M. Therefore, the potential profit generation could be up to $18.7M in a four-month order window. For the other two metrics, in those 10 simulation rounds, Average Days to Delivery is -54.3 days and Average Days to Customer Want is -61.5. Compared to using criteria weight to allocate orders, the two metrics are -60 and -68 days consistently among all methods. This means that aged customer orders are given the priority to produce first.

Table 12

Random Order Allocation and Metrics Performance

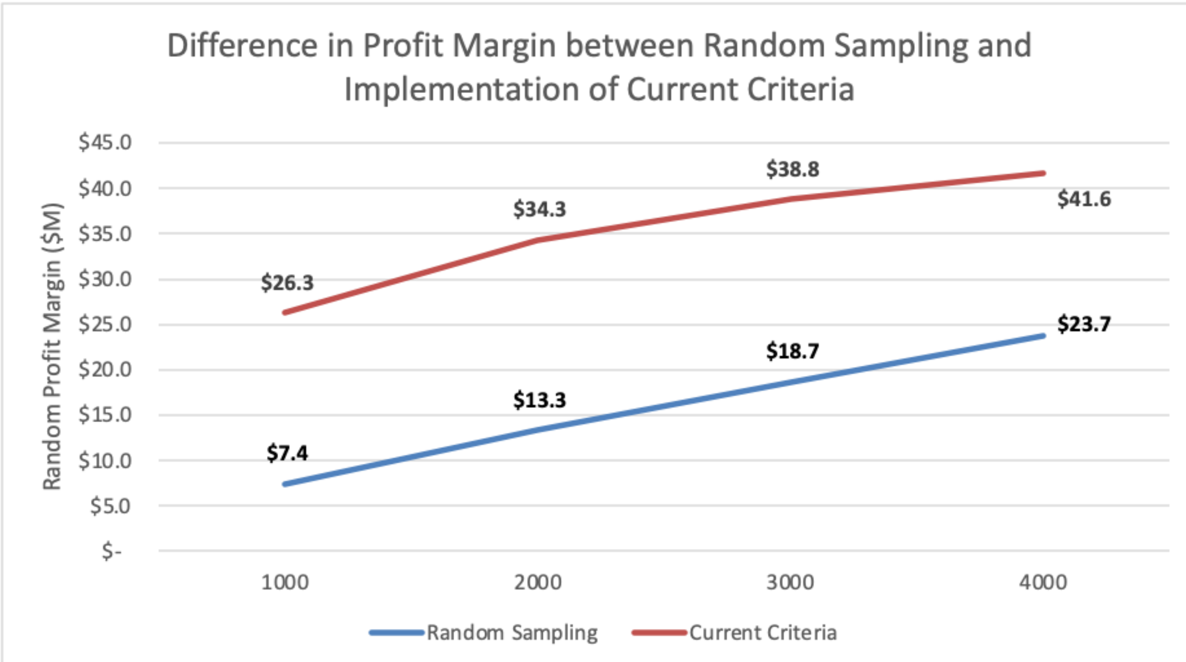
Simulation Round	Orders Profit	Average Days to Delivery	Average Days to Customer Want
R1	$ 23,607,291	-54	-62
R2	$ 22,958,417	-53	-61
R3	$ 23,250,287	-54	-61
R4	$ 23,629,658	-54	-61
R5	$ 24,365,907	-54	-61
R6	$ 23,838,405	-55	-62
R7	$ 23,746,224	-55	-62
R8	$ 24,266,320	-55	-62
R9	$ 23,939,748	-55	-62
R10	$ 23,700,140	-54	-61
Min	$ 22,958,417	-55	-62
Max	$ 24,365,907	-53	-61
Average	**$ 23,730,240**	**-54.3**	**-61.5**

In addition to the discussion of the simulation assuming a capacity of 4,000 line items, two scenarios are reviewed when comparing the overall expected Profit Margin, first, a simulation running the current, random demand prioritization process and second, a simulation running the proposed current criteria methodology. To monitor the real world business challenges, all simulations are performed under the assumption of limited capacity, which could come from labor, materials, or machines. The results of these simulations are shown in Figure 10 where current criteria demand prioritization is consistently exhibiting a higher profit margin.

When simulated with a capacity of 1,000, 2,000, 3,000, and 4,000 line items, Profit Margin is expected to increase between 75%-250%. Note that the smaller the assumed capacity, the larger the expected benefit of the current criteria. One key observation is that a scientific-based demand prioritization process would consistently generate higher Profit Margin than current practice at the Water Technology Company, which randomly pushes out orders. Additionally, the shrinked gap between two lines in Figure 10 indicates that the higher the capacity constraint, the more impact a scientific-based order allocation process can bring.

Figure 10

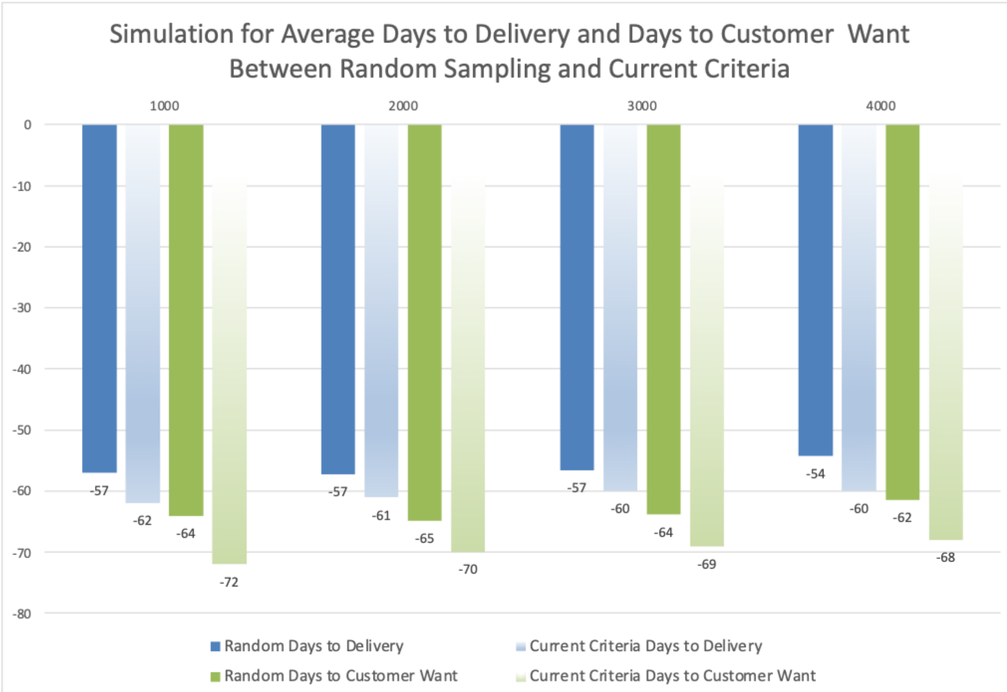
Comparison of profit margin when Current Criteria methodology is implemented in the demand prioritization process



When reviewing the Days to Delivery and Days to Customer Want criteria, the current criteria demand prioritization process will effectively ensure that older and needed orders are delivered first. In a simulation, structured the same as the profit margin simulation, the two scenarios are compared with the capacity limits of 1,000, 2,000, 3,000, and 4,000 line items in Figure 11. For Days to Delivery, the age of orders decreases between 5.7% to 9.5%, the age decrease is good, as these are the orders that have standard lead times furthest in the past. For Days to Customer Want, the current criteria improves the selection of orders as the criteria decreases an additional 7.3% to 11%.

Figure 11

Comparison of Days to Delivery and Days to Customer Want when Current Criteria methodology is implemented in the demand prioritization process



When running the simulation over a variety of capacity constraints, the range of improvement for Profit Margin ranged from 75% to 250%. The orders selected using the current criteria logic also had a Days to Delivery criteria averaging 6%-10% days older than a randomized process. Days to Customer Want were 7%-11% days older. This standardized and repeatable process eliminates the time intensive and manual selection of orders based on emails and calls between multiple decision maker groups.

4.2 Order Profit with Extended Criteria

With three more criteria introduced into the order allocation process, the overall rank and weight of each criterion has changed drastically, impacting total order profit captured. Customer Relationship is the number one criterion in Table 13 while Profit Margin is ranked 3rd or 4th with weight ranges from 13.26% to 19.2%. Among four methods, Method 1 results in the highest profit. It is important to recognize that with more considerations introduced into the demand prioritization process, the weight allocated to Profit Margin would diminish, thus the final captured order profit would decrease as well.

Table 13

Extended Criteria Weight and Profit Impact

	Total Profit from All Criteria			
	Method 1	Method 2	Method 3	Method 4
Customer Relationships	23.78%	29.17%	23.40%	30.39%
Order Urgency	19.69%	20.73%	20.64%	20.86%
Profit Margin	**19.20%**	14.73%	17.47%	13.26%
Penalty	14.03%	13.10%	16.20%	15.12%
Days to Delivery	14.67%	12.76%	13.16%	10.51%
Days to Customer Want	8.66%	9.51%	9.12%	9.86%
Capacity - 4000 Orders	**$ 26,528,737**	$ 25,817,698	$ 26,575,706	$ 25,396,509

When creating the MCDM demand prioritization model, dummy values for the extended criteria Order Urgency, Penalty, and Customer Relationship were implemented in order to evaluate the final impact of the MCDM recommended model. Thus, the extended criteria model does not accurately reflect the true business scenario and the current criteria model is further reviewed and recommended for immediate implementation.

5 Discussion

This recommended MCDM demand prioritization process objectively takes in demand information and generates a prioritized list which the Water Technology Company can follow. This approach, which is industry agnostic, supports the hypothesis that prioritization of demand based on a select group of key criteria would increase profit and strengthen customer relationships. The contribution of this project offers a standardized demand prioritization system, promotes alignment between global teams, offers a tool which the company can make better informed, timely decisions, and finally, increases the efficiency of the overall order management process.

Of the six selected criteria, the limitations of available data caused the recommended process to be adjusted from six criteria, down to just three criteria (current criteria). These current criteria include Profit Margin, Days to

Delivery, and Days to Customer Want. With the adoption of a MCDM demand prioritization process, even with just three criteria, the resulting magnitude of the improvement was unexpected. After conducting simulations under four different levels of capacity constraints, all tests resulted in a higher profit margin and strengthened customer relationships. The customer relationships are considered being strengthened as the demand prioritization process fulfills the customer orders that are relatively aged and most needed first.

As many companies face similar supply chain challenges from constrained materials, delayed standard lead times or increased customer demand, researchers and industry professionals can adjust and customize the methodology within this paper. And, for this discussion, the decision maker interviews and data analysis from the simulations led to a list of key findings. These key findings can be grouped into communication feedback loops and technological infrastructure.

5.1 Communication feedback loops

During the interview with DMs, it was apparent that the individual departments within the Water Technology Company operate independently and utilize different criteria. It was surprising that, while several DMs reviewed the six selected criteria, the DMs differed in overall ranking. To align on demand prioritization decisions, one enterprise wide definition of each of the six criteria would ensure communication alignment within the demand prioritization process. This consensus will promote the alignment between the global teams. Change management communication is recommended so the Water Technology Company can raise awareness of this new demand prioritization process. The communications approach should follow a top-down flow, starting with leadership consensus.

5.2 Technology infrastructure

For the Water Technology Company, and others looking to implement such a demand prioritization model, the willingness to accept technological enhancements and projects should be a requirement. This corresponding implication to the leadership team in the Water Technology Company is to facilitate the implementation of the current criteria demand prioritization process. A successful technology enhancement will maximize Profit Margin and strengthen customer relationships in the long-term while allowing better informed, timely decisions to be made. This differs from the current, short-term approach the Water Technology Company is following. Such implementation efforts will require technological enhancements to enhance existing ERP systems and data fields. Setting up the foundation for such technological infrastructure will allow all stakeholders within the Water Technology Company to provide information to best prioritize orders.

An existing pain point, uncovered during the interviews, is the lack of a technological demand prioritization feedback loop. To alleviate this pain, the technology systems and fields should be connected and utilize the same ERP software, including matching fields and column names. This enhancement will expand the usability of the MCDM model to include the extended criteria but will require leadership business championships and buy-in from internal stakeholders .

5.3 Limitations

The options for methodology applied in this MCDM demand prioritization approach were limited due to the quantity of alternatives. An alternative is viewed as the potential options which are being ranked in order of importance. In a typical decision making scenario, there may be three to five project options, but in the scenario of a list of demand, there are hundreds or thousands of sales orders.

In terms of solutions to the demand prioritization problem, an early method to solve the demand prioritization question was to categorize orders into buckets. These buckets could be stock order, scheduled order, urgent order, or government order. Not only was this an academic idea, brought up by four articles listed in Table 1, but also brought up and requested during the commercial sales team interviews. While this categorization approach would increase the visibility for the Water Technology Company to allocate constrained materials to the most urgent and pressing order, the available ERP systems would require customization along with all commercial sales teams agreeing on a global understanding of categorizing orders.

Another request was to include an indicator within the existing sales order tracking system to allow automatic prioritization logic to execute in the background. This would effectively eliminate some, if not all, escalation meetings and provide visibility to the true demand for an order, i.e., a natural disaster, a paying customer, or DC safety stock. However, the creation and implementation of such an order categorization fell outside the scope of this capstone due to time and financial requirements.

6 Conclusion

The implementation of this demand prioritization MCDM method is expected to provide financial and customer relationship benefits to the Water Technology Company. This increases efficiency of the order management process by standardizing the demand prioritization. Selecting six criteria and formulating an implementation plan is the first step in the right direction. In the future, the current criteria will evolve into all six of the extended criteria (Profit Margin, Days to Delivery, Days to Customer Want, Customer Relationship, Penalty, and Order Urgency) being implemented, allowing the Water Technology Company to factor in additional, unique customer needs. This feasible, standardized, repeatable demand prioritization process that is ready to be implemented tomorrow, starting with the current criteria Profit Margin, Days to Delivery, and Days to Customer Want.

With this research conducted on how to prioritize demand, future researchers are encouraged to review opportunities to automate demand prioritization tools in order to remove all manual intervention. An additional suggestion is to research appropriate methods to categorize Customer Relationships and Order Urgency. While these were out of scope for this project, the MCDM demand prioritization will be enhanced with a defined Customer Relationship and Order Urgency application.

References List

AHP calculator—AHP-OS. (n.d.). Retrieved April 18, 2022, from https://bpmsg.com/ahp/ahp-calc.php

Akyildiz, B., Kadaifci, C., & Topcu, I. (2015). A decision framework proposal for customer order prioritization: A case study for a structural steel company. *International Journal of Production Economics*, *169*, 21–30. https://doi.org/10.1016/j.ijpe.2015.07.004

Balakrishnan, N., Sridharan, V., & Patterson, J. W. (1996). Rationing Capacity Between Two Product Classes*. *Decision Sciences*, *27*(2), 185–214. https://doi.org/10.1111/j.1540-5915.1996.tb00850.x

Carr, S., & Duenyas, I. (2,000). Optimal admission control and sequencing in a make-to-stock/make-to-order production system. *Operations Research*, *48*(5), 709–720. Scopus. https://doi.org/10.1287/opre.48.5.709.12401

Hu, X., Li, Y., Byon, E., & Barry Lawrence, F. (2015). Prioritizing regular demand while reserving capacity for emergency demand. *European Journal of Operational Research*, *247*(2), 472–487. https://doi.org/10.1016/j.ejor.2015.06.020

Janković, A., & Popović, M. (2019). Methods for assigning weights to decision makers in group AHP decision-making. *Decision Making: Applications in Management and Engineering*, *2*(1), 147–165. https://doi.org/10.31181/dmame1901147j

Karlsson, J., & Ryan, K. (1997). A cost-value approach for prioritizing requirements. *IEEE Software*, *14*(5), 67–74. https://doi.org/10.1109/52.605933

Lečić-Cvetković, D., Atanasov, N., & Babarogić, S. (2010). An Algorithm for Customer Order Fulfillment in a Make-to-Stock Manufacturing System. *International Journal of Computers, Communications and Control*, *5*(5), 783–791. http://dx.doi.org/10.15837/ijccc.2010.5.2238

May, A., Anslow, A., Wu, Y., Ojiako, U., Chipulu, M., & Marshall, A. (2014). Prioritisation of performance indicators in air cargo demand management: An insight from industry. *Supply Chain Management*, *19*(1), 108–113. http://dx.doi.org/10.1108/SCM-07-2013-0230

Mestry, S., Damodaran, P., & Chen, C.-S. (2011). A branch and price solution approach for order acceptance and capacity planning in make-to-order operations. *European Journal of Operational Research*, *211*(3), 480–495. https://doi.org/10.1016/j.ejor.2011.01.002

Muralidharan, C., Anantharaman, N., & Deshmukh, S. g. (2002). A Multi-Criteria Group Decisionmaking Model for Supplier Rating. *Journal of Supply Chain Management*, *38*(3), 22–33. https://doi.org/10.1111/j.1745-493X.2002.tb00140.x

Ossadnik, W., Schinke, S., & Kaspar, R. H. (2016). Group Aggregation Techniques for Analytic Hierarchy Process and Analytic Network Process: A Comparative Analysis. *Group Decision and Negotiation*, *25*(2), 421–457. https://doi.org/10.1007/s10726-015-9448-4

Rezaei, J. (2018). Piecewise linear value functions for multi-criteria decision-making. *Expert Systems with Applications*, *98*, 43–56. https://doi.org/10.1016/j.eswa.2018.01.004

Saaty, T. L. (2008). Decision making with the analytic hierarchy process. *International Journal of Services Sciences*, *1*(1), 83. https://doi.org/10.1504/IJSSCI.2008.017590

Srdjevic, B. (2007). Srdjevic, B.: Linking analytic hierarchy process and social choice methods to support group decision-making in water management. Decision Support Systems in Emerging Economies 42(4), 2261-2273. *Decision Support Systems*, *42*, 2261–2273. https://doi.org/10.1016/j.dss.2006.08.001

Tang, L., & Cai, X. (2008). RBF Neural Network for the Priority of Buyer Order in Supply Chain. *2008 4th International Conference on Wireless Communications, Networking and Mobile Computing*, 1–6. https://doi.org/10.1109/WiCom.2008.1526

Yuanyuan, Z., & Qian, C. (2014). Online Order Priority Evaluation Based on Hybrid Harmony Search Algorithm of Optimized Support Vector Machines. *Journal of Networks*, *9*(4), 972–978.

Zhu, L., Ma, Y., & Zhang, L. (2014). *Ensemble model for order priority in make-to-order systems under supply chain environment*. 321–328. https://doi.org/10.1109/ICMSE.2014.6930247

Appendix

Appendix A: Criteria Weight Exercise, tab 1

Appendix B: Criteria Weight Exercise, tab 2

Appendix C: Group Aggregation using Arithmetic method

Appendix D: Group Aggregation using Geometric method

Appendix A: Criteria Weight Exercise, tab 1

Welcome
Goal: Your participation in this exercise will help create a standardized, repeatable order prioritization process that will be implemented.
Ask: First, review the 6 selected criterion. Second, using your expert opinion, select criteria importance levels on the tab: Criteria Importance.

(blue)	Existing Data
(red)	Current field not available - Dummy values to be used for project implementation

Key criterion	Definition (as of February 2022)	Team	Criteria Value Observations	Please provide any notes/opinions
Absolute Profit Margin	Sales price - MFG cost, absolute dollar value difference	Order Mgt	1) Constant increase: higher the dollar value, the more important	
Days to Delivery	"Standard Leadtime Date - Current date, how many days until finished goods are committed based on published standard lead times"	Production	2) Decrease Stepwise: Orders with lower values are more urgent	
Days to Customer Want	Customer's Requested Delivery Date -Current Date, how many days until the customer wants the order to be delivered	Commercial Sales	2) Decrease Stepwise: Orders with lower values are more urgent	
Customer Relationships	Categorical Variable, assumed to be 1-Least to 5-Most Important Based on total sales, growth, etc	Leadership Team	1) Increase Stepwise: higher the categorical variable, more important	
Financial Penalty	Binary, 0-no contract penalty or 1-yes contract penalty	Commercial Sales	1) Increase Stepwise: higher the dollar penalty, the more important	
Order Urgency	Categorical Variable, assumed to be 1-Least to 5-Most Important Based on order type (safety stock, work stop, scheduled order)	Leadership Team	1) Increase Stepwise: higher the categorical variable, more urgent	

Appendix B: Criteria Weight Exercise, tab 2

Objective: Gather expert opinion on criteria importance in order to identify criteria weights to be used in the standardized, repeatable order prioritization process.
Ask: Using your expert opinion, select the appropriate importance level when comparing Criterion A to Criterion B. After selection, you can read the Final Statement in Column F.

Criterion A	Select:	Criterion A is ____ important to Criterion B	Criterion B	Final statement
Profit Margin	1/9	extremly less important	Days to Delivery	Profit Margin is extremly less important than Days to Delivery
Profit Margin	1/9	extremly less important	Days to Customer Want	Profit Margin is extremly less important than Days to Customer Want
Profit Margin	1/9	extremly less important	Customer Relationships	Profit Margin is extremly less important than Customer Relationships
Profit Margin	1/9	extremly less important	Penalty	Profit Margin is extremly less important than Penalty
Profit Margin	1/9	extremly less important	Order Urgency	Profit Margin is extremly less important than Order Urgency
Days to Delivery	1/4	moderatly plus less important	Days to Customer Want	Days to Delivery is moderatly plus less important than Days to Customer Want
Days to Delivery	1/9	extremly less important	Customer Relationships	Days to Delivery is extremly less important than Customer Relationships
Days to Delivery	1/9	extremly less important	Penalty	Days to Delivery is extremly less important than Penalty
Days to Delivery	1/9	extremly less important	Order Urgency	Days to Delivery is extremly less important than Order Urgency
Days to Customer Want	1/9	extremly less important	Customer Relationships	Days to Customer Want is extremly less important than Customer Relationships
Days to Customer Want	1/9	extremly less important	Penalty	Days to Customer Want is extremly less important than Penalty
Days to Customer Want	1/9	extremly less important	Order Urgency	Days to Customer Want is extremly less important than Order Urgency
Customer Relationships	1/9	extremly less important	Penalty	Customer Relationships is extremly less important than Penalty
Customer Relationships	1/9	extremly less important	Order Urgency	Customer Relationships is extremly less important than Order Urgency
Penalty	1/9	extremly less important	Order Urgency	Penalty is extremly less important than Order Urgency

Importance Legend

Value	Description
9	extremly more important
8	very, very strongly more important
7	very strongly or demonstrated more important
6	strongly plus more important
5	strongly more important
4	moderatly plus more important
3	moderatly importance
2	weak or slightly more important
1	Equally Important
1/2	weak or slightly less important
1/3	moderatly less importance
1/4	moderatly plus less important
1/5	strongly less important
1/6	strongly plus less important
1/7	very strongly or demonstrated less important
1/8	very, very strongly less important
1/9	extremly less important

Appendix C: Group Aggregation using Arithmetic method

		Arithmetic Mean					
		Criterion Weights - DM weight adjusted by CR - Method 1					
DM	DM Weight	Customer Relationships	Order Urgency	Profit Margin	Penalty	Days to Delivery	Days to Customer Want
DM1	11.02%	34.30%	7.60%	7.90%	7.60%	31.20%	11.40%
DM2	9.94%	20.20%	42.00%	9.20%	15.00%	4.50%	9.00%
DM3	9.24%	49.40%	21.80%	8.80%	11.10%	3.80%	5.20%
DM4	10.89%	23.90%	27.80%	3.70%	18.00%	6.50%	20.00%
DM5	10.64%	50.10%	22.00%	8.00%	13.70%	2.80%	3.40%
DM6	10.16%	16.20%	6.50%	34.40%	9.90%	21.50%	11.50%
DM7	38.11%	10.10%	17.40%	31.10%	16.40%	19.00%	6.10%
Total Composite Weight		23.78%	19.69%	19.20%	14.03%	14.67%	8.66%
Rank		1	2	3	5	4	6

		Criterion Weights - DM equal weight - Method 2					
DM	DM Weight	Customer Relationships	Order Urgency	Profit Margin	Penalty	Days to Delivery	Days to Customer Want
DM1	14.29%	34.30%	7.60%	7.90%	7.60%	31.20%	11.40%
DM2	14.29%	20.20%	42.00%	9.20%	15.00%	4.50%	9.00%
DM3	14.29%	49.40%	21.80%	8.80%	11.10%	3.80%	5.20%
DM4	14.29%	23.90%	27.80%	3.70%	18.00%	6.50%	20.00%
DM5	14.29%	50.10%	22.00%	8.00%	13.70%	2.80%	3.40%
DM6	14.29%	16.20%	6.50%	34.40%	9.90%	21.50%	11.50%
DM7	14.29%	10.10%	17.40%	31.10%	16.40%	19.00%	6.10%
Total Composite Weight		29.17%	20.73%	14.73%	13.10%	12.76%	9.51%
Rank		1	2	3	4	5	6

Appendix D: Group Aggregation using Geometric method

		Geometric Mean					
		Criterion Weights - DM weight adjusted by CR - Method 3					
DM	DM Weight	Customer Relationships	Order Urgency	Profit Margin	Penalty	Days to Delivery	Days to Customer Want
DM1	11.02%	88.88%	75.28%	75.60%	75.28%	87.95%	78.72%
DM2	9.94%	85.30%	91.74%	78.88%	82.81%	73.47%	78.71%
DM3	9.24%	93.69%	86.87%	79.89%	81.62%	73.92%	76.10%
DM4	10.89%	85.57%	86.99%	69.84%	82.97%	74.26%	83.92%
DM5	10.64%	92.91%	85.13%	76.44%	80.94%	68.37%	69.79%
DM6	10.16%	83.11%	75.75%	89.72%	79.05%	85.54%	80.27%
DM7	38.11%	41.74%	51.35%	64.07%	50.21%	53.10%	34.44%
Total Composite Weight		19.59%	17.28%	14.62%	13.56%	11.02%	7.63%
Scaled Weight		23.40%	20.64%	17.47%	16.20%	13.16%	9.12%
Rank		1	2	3	4	5	6

		Criterion Weights - DM weight adjusted by CR - Method 4					
DM	DM Weight	Customer Relationships	Order Urgency	Profit Margin	Penalty	Days to Delivery	Days to Customer Want
DM1	14.29%	85.82%	69.20%	69.59%	69.20%	84.67%	73.33%
DM2	14.29%	79.57%	88.34%	71.12%	76.26%	64.21%	70.89%
DM3	14.29%	90.42%	80.44%	70.67%	73.05%	62.68%	65.55%
DM4	14.29%	81.51%	83.29%	62.44%	78.27%	67.67%	79.46%
DM5	14.29%	90.60%	80.55%	69.71%	75.28%	60.00%	61.69%
DM6	14.29%	77.10%	67.67%	85.86%	71.87%	80.28%	73.42%
DM7	14.29%	72.07%	77.89%	84.63%	77.24%	78.88%	67.06%
Total Composite Weight		25.34%	17.39%	11.06%	12.61%	8.76%	8.22%
Scaled Weight		30.39%	20.86%	13.26%	15.12%	10.51%	9.86%
Rank		1	2	4	3	5	6