INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH & DEVELOPMENT

ISSN 2278 – 0211 (Online)

Qualitative and Quantitative Analysis in Comparing Prospective CWCs

Pradeep J. S. Bhavaraju
Scientist, Indian Maritime University, Visakhapatnam Campus, Visakhapatnam, India

Abstract:
Qualitative analysis either involves traditional deductive logic beginning with assumptions and carefully deducing an outcome from them, or, a holistic approach in which all the factors and criteria involved are laid out in advance in a hierarchy or in a network system that allows for dependencies. Quantitative analysis involves estimating Life Cycle Costs to arrive at an economic equitable assessment of competing design alternatives considering total expenditures over its-entire economic life.
The paper applies Qualitative and Quantitative concepts to choose prospective designs of two configurations of the CWC i.e, the Vertical and the Horizontal orientations. Solutions are proposed to evaluate overall performance of the CWC.

Keywords: *Circulating Water Channel (CWC), Life Cycle Costing (LCC), Failure Modes and Effect Analysis (FMEA), Multiple Criteria Decision Making (MCDM), FMECA (Failure Modes, Effects and Criticality Analysis)*

1. Introduction

Indian Maritime University Visakhapatnam Campus (IMUV), erstwhile National Ship Design and Research Centre (NSDRC), was established in 2008 under the Act of Parliament for the purpose of conducting research activities in maritime industry, providing consultancy works in ship design, and imparting education & training through short term courses and programs. During the past five years, IMUV has been awarded 17 research projects sanctioned by the Ministry of Shipping, one such being 'Study of Flow around Ships in a Hydrodynamic Test Facility"

The first phase of the research project is to build a 1:4 scaled model test facility called the Circulating Water Channel (CWC). The CWC generates a controlled flow environment for the purpose of conducting various hydrodynamic research activities such as resistance test, manoeuvring test, studies for fish nets, sediment flow studies, etc. While the experimental facilities such as towing tank facility, sea keeping and manoeuvring basin are expensive, a relative low cost CWC, recognized by the International Towing Tank Conference (ITTC) community, is designed to facilitate academic and research activities. The 1:4 scaled model of the CWC is fabricated and is currently being tested within IMUV and the full scale facility would be established as a part of the second phase. Due to the limited availability of test facilities for a large variety of shipping related experiments in India, an economically viable CWC configuration is preferred to industry operators, developers and academia.

1.1. Existing CWCs [1]

Data for 26 existing CWCs categorized into Country and Year established, orientation, working section, maximum speed and motor power is obtained from the "Catalogue of Facilities" published by International Towing Tank Conference, ITTC as shown in Table 1.

A study of the existing channels shows that CWCs with vertical circuits are more popular and are evidently preferred to those with the horizontal circuits because of lesser impeller cavitation on itself [2] (to due high hydrostatic pressure), better and easily obtainable quality of flow in the working section [3] (the part of the CWC in which experiments are carried out) and lesser floor space occupation, despite higher power consumption (~25%greater).

However, a study of the layout drawings of these channels also show that to obtain high quality flow, it is necessary to incorporate additional features such as surface flow accelerators, air bubble extractors and vacuum systems in the vertical circuits(which are not required in the horizontal circuit).

As both circuits have their respective merits and demerits, better CWC configuration choice is possible if such analysis includes qualitative decision making process involving ranking desired attributes, and, quantitative decision making technique estimating capital, operation and maintenance costs for the entire life cycle.

2. Qualitative Analysis

2.1 Qualitatively, What Attributes are Desired?

An attribute is an entity which can be verified or measured when the final product is used in real conditions. Grouping of attributes produces a quality or function desired. [4]

To start with, the desired attributes are borrowed from ISO/IEC 9126, a standard for the evaluation of software quality. The fundamental objective of ISO/IEC 9126 standard is to address human biases that can adversely affect the delivery and perception of a product. These biases include changing priorities after the start of a project or not having any clear definitions of "success." By clarifying, then agreeing on the project priorities and converting to measurable values, ISO/IEC 9126 tries to develop a common understanding of the project's objectives and goals.

Based on ISO 9126, the desired attributes are stated, some of which are observable at runtime and some that are desirable during the product life. The lists of attributes are decided and grouped at functional and sub characteristics as shown in Table 2.

2.2 Multiple-Criteria Decision Making methods (MCDM) [5]

MCDM is concerned with structuring and solving decision-and-planning-problems involving multiple criteria. Given the attributes, the CWCs are evaluated for "success" with the objective of generating uniform flow across the working section of the CWC minimizing financial expenditures.

The desired characteristics/attributes and their pair-wise judgments are written in a matrix form and the normalized principle Eigen vector is calculated. The highest Eigen value indicates top priority attribute desired to fulfill the objective. The same technique is applied to the sub-characteristics and is ranked according to their relative importance. Multiplying the characteristic and sub characteristic gives the global priority of the importance of the criteria in achieving the objective. The priority matrix, shown in Figure 1 below**,** shows 'maintainability' as the top desired objective.

Matrix		Performance (Responsiveness)	Reliability	Add. services required	Availability	Maintainability	Competitive power	Enhance ability	Capital & Operating Expenditures	Limitations Risks	Portability	**Normalized Principal Eigen Vector indicating priorities**
	#	1	2	3	4	5	6	7	8	9	10	
Performance(Responsiveness)	1	1	1	3	1	1	9	9	1	1	7	**0.1451**
Reliability	2	1	1	7	1	1	9	9	1	3	9	**0.1808**
Add. services required	3	1/3	1/7	1	1/5	1/9	1	1	1/3	1/5	3	**0.0296**
Availability	4	1	1	5	1	1	9	9	1	3	7	**0.1705**
Maintainability	5	1	1	9	1	1	9	9	1	3	9	**0.1854**
Competitive power	6	1/9	1/9	1	1/9	1/9	1	1	1/7	1/9	1/9	**0.0152**
Enhance ability	7	1/9	1/9	1	1/9	1/9	1	1	1/5	1/9	1	**0.0196**
Capital & Operating Expenditures	8	1	1	3	1	1	7	5	1	5	7	**0.1568**
Limitations Risks	9	1	1/3	5	1/3	1/3	9	9	1/5	1	1/7	**0.0634**
Portability	10	1/7	1/9	1/3	1/7	1/9	9	1	1/7	7	1	**0.0336**

Table 1: Priority Matrix

Global priorities for the desired attributes are obtained and ranked according to the CWC alternatives. Four MCDM methods are used namely Technique for the Order of Prioritization by Similarity to Ideal Solution (TOPSIS), Weighted Sum Model, Weighted Product model and Analytical Hierarchal Process in analyzing attributes. The results of all four methods, shown in Tables 3-6 favor choosing the Vertical Circulating Water Channel.

3. Quantitative Analysis

"Cost is a universal language understood by engineers without ambiguity."

As previously stated, while the Vertical CWCs (high power consumed, additional components required, less risk of impeller cavitation, less space) are preferred compared to Horizontal CWC (less power consumed, no additional components, high risk of impeller cavitation, more space), an economic comparison of the alternatives is made to see whether replacing the impeller (high cost, less availability of manufacturers) for the Horizontal CWC could be justified over higher power consumption maintenance of additional components in the Vertical CWC.

A study period of 5760 hours (3hrs/day x 2 days/week x 4 weeks/month x 6 months/ year x 40 years) is considered taking in view of the academic semester laboratory usage interests. Cost elements like initial cost, annual operating and maintenance cost, power costs and expected salvage value are obtained from various vendors and experience of maintenance engineers and evaluated for life. Two approaches are used to estimate expenditures i.e., cash outflows using Present & Annual Worth methods and opportunity costs using Cost-based FMEA.

3.1. Life Cycle Costs [6]

The Present Worth method, converts all the costs to the present values and is less keen on future actual costs. Annual worth method, amortizes all costs over the life of the item or project and is used where there is no difficulty in finding funds for initial investments. Both methods are arithmetically identical and which method to choose depend on the psychology of management of the institute. The initial data includes capital cost, replacement costs, maintenance, salvage costs is tabulated as shown below. To predict failure of equipment in analyzing capital replacement costs, Weibull Analysis is carried out and compared based on experience of the maintenance engineers, and is detailed in Annexure 1 separately.

	Vertical CWC (in Lakhs of rupees)	**Horizontal CWC (in Lakhs of rupees)**
Impeller	0.67	0.67
Water lubricated bearing	0.04	0.04
Propeller shaft	0.03	0.03
Stuffing box	0.11	0.11
Thrust bearing	0.06	0.06
Coupling	0.06	0.06
Motor	4.00	3.20
Bubble extractor	0.05	-
Surface flow accelerator	0.02	-
Paints	0.05	0.05
Glass plates for working section	0.08	0.08
Material steel	2.28	2.28
Total capital costs	6.65	6.58
Expected salvage value at the end of 40 years	0.66	0.66
Economic life	40 years	40 years
Single expenditures due to capital repairs at the end of year:		
~-Year 28(Impeller)	-	0.67
~-Year 13,26,39(WLB)	0.04	0.04
~-Year 20(Propeller Shaft)	0.03	0.03
~-Year 10,20,29(Stuffing Box)	0.11	0.11
~-Year 11,22,33(Thrust Bearing)	0.06	0.06
~-Year 31 (Coupling)	0.06	0.06
~-Year 20(Motor winding)	0.50	0.25
~-Year 11,22,33(Bubble Extractor)	0.05	0.05
~-Year 11,22,33(Surface Flow Accelerator)	0.02	0.02
~-Year 2,4,6,…38(Paints)	0.05	0.05
Operating costs	Rs 5 per kWh	Rs 5 per kWh
Rate of escalation for operating and maintenance costs	5% per year	5% per year

Table 2: Data for Life Cycle Costing

The equivalent worth is calculated as follows:

- Present Worth= –Initial cost – Replacement cost x (P/F, 12%, n) $_{\text{at end of 'n'th year}}$ + Salvage (P/F, 12%, 40) – Base electrical cost (P/A, 12%, 40) – increased electrical gradient cost (P/G, 12%, 40)
- Annual Worth = Present Worth x (A/P, 12%, 40)

Putting the values of different compound interest factors in the above expression, the estimated values of equivalent worth are tabulated below:

	Vertical CWC (in Lakhs of rupees)	**Horizontal CWC (in Lakhs of rupees)**	**% Difference**
Present Worth	-9.19	-9.07	1.29
Annual Worth	-1.11	-1.10	1.29

Table 3

It is observed that the cash outflows for the Horizontal CWC is minimal and can be chosen. However, as the percent difference for cash outflows is 1.29% between the alternatives, the management can decide if any additional amount can be spend in choosing the Vertical CWC based on the vision planning and financial goals of the institute. Also, the above calculations do not include land occupation costs, which when included, clearly favors the Vertical CWC (due lesser floor space occupied).

3.2. Cost-Based FMEA

FMEA mitigates risk during the design phase before they occur. The risk mitigation proposals [7] can be distinguished by the way they reduce either the Occurrence (Prevention) or the Severity (Protection) of the failure modes, and also by the phase of the development of the system they relate to (Design, Test, Operation or Maintenance) of which few of them are shown below:

	Prevention (decreases Occurrence)	**Protection (decreases Severity)**
Design	Implement redundancy to reduce the risk of losing the function	Implement risk-containment provisions to avoid cascading failures
Test	Apply specific tests in simulated operating conditions to check reliability of a component	Apply specific tests to ensure maintainability of components that require a long time to repair
Operation	Interlock operation of sensitive components with a safety check to avoid damage	Prepare specific training and procedures to allow falling back to a safe degraded mode in an emergency
Maintenance	Increase the frequency of inspections and preventive maintenance operations	Keep spares on-site so that time to repair is shortened

Table 4

As the traditional FMEA ends with the calculation of Risk Priority Number and does not consider the consequences of the failures in terms of costs, a new methodology called "Life Cost-based FMEA" [8] measures risk of failure in terms of cost. Risk contains two basic elements (1) chance, measured by probability, and (2) consequence, measured by cost. Expected failure cost is defined as the product of the probability of a particular failure and the cost associated with that failure. The lifetime costs associated with each component failure is calculated as explained below.

Calculate Expected Failure Costs

Labour Cost =F x { [Detection Time x L x N]+[Fixing Time x L x N] + [Delay Time x L x N] }
Material Cost =F x Quantity x Cost of Part
Opportunity cost =Recovery time x Hourly costs
where, F =Frequency of failure occurrence
L =Labour rate (Rs/day)
N =Number of operators

Opportunity cost, which is the cost incurred when a failure inhibits the main function of a system and prevents any creation of value. Simply stated, it is the cost of a missed opportunity.

Table 5

Using failure rate from Weibull data and based on experience of our Maintenance Engineers, the labor, material and opportunity costs over life of both alternative CWC configurations are estimated. The results shown in Table 7 indicate higher opportunity costs for the Vertical CWC which is undesirable. (Recommendations are provided in the same table considering equipment design in the last column.)

4. Discussions

The paper discusses Qualitative and Quantitative methodologies to choose prospective Circulating Water Channel i.e., Vertical or Horizontal circuit.

As part of Qualitative analysis, a list of desired characteristics are selected based ISO 9126 and grouped into characteristic and sub-characteristic features. Using four Multi Criteria Decision Making techniques, namely TOPSIS, Analytical Hierarchy Process, Weighted Product Model and Weighted Sum Model, pair wise judgments are done against the attributes and ranked based on their priority. The analysis concludes choosing Vertical CWC than its other alternative. However a sensitivity analysis should be made to study the effects of variations in judgments on the stability of the final outcome.

As part of Quantitative analysis, Life Cycle Costs were estimated based on BIS 13174 using equivalent worth analysis methods. Weibull analysis serves as a preliminary failure rate prediction tool to estimate capital replacement costs. Present Worth and Annual Worth methods show a 1.29% difference between the two alternatives, the Horizontal CWC resulting in minimum cash outflows. Since the costs do not include the land occupation costs, the vertical CWC is favorable when it is included.

Cost-based FMEA described here considers the consequences of the failures in terms of costs i.e., whether costs involving design changes for avoiding failures are less than the failures themselves. However, to calculate the probability of failure over the project life, suitable eta (characteristic life, hours) and beta (shape parameter, hours)values for various component of the CWC are chosen based on Weibull data available with suitable precautions and assumptions. Cost based FMEA is carried out and opportunity costs are predicted which favors choosing Horizontal CWC.

5. Conclusion

To conclude, a Vertical CWC can be used if it can be used for a commercial purpose in the long run as it has an advantage of easily obtaining uniform flow, minimum space required and higher availability despite greater initial capital costs and cash outflows. A Horizontal CWC is useful for academic purpose in the long run as it requires lesser capital costs and generates reasonably good uniform flow despite large space requirements.

6. Assumptions

1. Considering MCDM, the judgments used to perform the comparisons are the preferences of the author and also based on experience of the maintenance engineers. They represent their best understanding of the influences involved from the different points of view taken from the literature and by consulting themselves.
2. The reliability analysis methods used in the design stage are qualitative, depending on comparison with data from similar systems and on Weibull data, whereas after several years of operation, reliability analysis can become more quantitative, depending on statistical data.
3. The impeller cavitation number for the Horizontal CWC is about 10% below from the Burill's limiting value while it is 40% below for the Vertical CWC. It is safely assumed that the impeller cavitates atmost once during its life time for the Horizontal CWC.
4. Only one labor is assumed to maintain for all individual components and the costs do not consider skill level. Opportunity cost for life is estimated as: no. of failures x total loss time x Rs 2000 per day.

7. Acknowledgements

I thank our Director I/c Shri. U.S.Ramesh and Prof (Dr) RPGokarn (IIT, Kharagpur) for their valuable support and contributions during the initial phases of the project and for encouraging us to present this paper. I also thank our Head of Finance, Shri M V Ramana Murty for giving his views on the financial aspect of the project and Maintainance Engineers Dr Ravichandran and Shri Saravanan for sharing their experiences with machinery maintenance.

8. References

i. Concept Design Document, Aarnav Shipping Technological Research Sanstha-Mumbai
ii. Practical Ship Hydrodynamics, Belkar Vortram, Pg54, Elsevier Publication
iii. CFD Application on the Development of Circulating Water Channel (2006), Zuogang Chen, Yumi Kurokawa and Hitoshi Nishimoto, Proceedings of the Sixteenth International Offshore and Polar Engineering Conference
iv. Decision making with the analytic network process, Saaty and Vargas, Springer Publication
v. http://en.wikipedia.org/wiki/Multiple-criteria_decision_analysis
vi. BIS 13174(Part 2), Life Cycle Costing
vii. ITER RAMI Analysis Program (28WBXD), Van Houtte D ,Okayama K , Sagot F
viii. S.J.Rhee, K.Ishii, "Life Cost-Based FMEA Incorporating Data Uncertainty", Proc. ASME Design Engineering Technical Conf, Montreal, 2002
ix. Bloch, Heinz P. and Fred K. Geitner, 1994, Practical Machinery Management for Process Plants, Volume 2: Machinery Failure Analysis and Troubleshooting, 2nd Edition, Gulf Publishing Company, Houston, TX. (or) http://www.barringer1.com/wdbase.htm
x. http://reliabilityanalyticstoolkit.appspot.com/
xi. Pump User's Handbook by Allan R. Budris and Heinz P Bloch

Annexure 1

WEIBULL ANALYSIS

The Weibull distribution can be used to model many different failure distributions. Given a shape parameter (β) and characteristic life (η) the reliability can be determined at a specific point in time (t). The two-parameter Weibull distribution probability density function, reliability function and hazard rate are given by:

$f(t) = \left(\frac{\beta}{\eta}\right)\left(\frac{t}{\eta}\right)^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^{\beta}}$ Probability Density Function

$h(t) = \left(\frac{\beta}{\eta}\right)\left(\frac{t}{\eta}\right)^{\beta-1}$ Reliability Function

$R(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}}$ Hazard Rate

Using the information based on Weibull Database [9], the frequencies for different types of failure are predicted with the help of software tool [10] as shown in the below table. The failure rates for sealing, bearing, coupling and shaft are verified with a pump user handbook [11] and are found to be in close proximity.

Precautions in using Weibull data [9]:

Weibull's beta (slope of the Weibull line which is a shape factor) and eta values (a location parameter known as the characteristic value) are frequently viewed by experienced end users of the data as proprietary information. Experienced practioneers of Weibull technology do not widely publish or disseminate their expensive data.

The Weibull characteristics may vary for different industries because of the way it is installed, maintained, and operated. Hence precautions may be taken to choose the correct values for based on experience and operating conditions. The database is intended for educational purposes only.

		INPUTS			OUTPUTS						
http://www.barringer1.com/wdbase.htm	Equipment	beta (shape param)	eta(scale param, characteristic life)	time of interest (hours) (t)	PDF, f(t) e-05	Reliability R	mean life (hours)	Failure rate h(t), e-05	MTBF (hours)	time consumed upto 90% reliability (hours)	time consumed upto 90% reliability (years)
Gas turbines blades/vanes	Impeller	0.9	125000(V) , 50000(H)	5760 (40 years)	0.920V) , 1.94(H)	0.9392(V) , 0.8668(H)	131451(V), 52580(H)	0.979(V) , 2.230(H)	102098, 44748(H)	10256(V), 4103(H)	71.225 (V), 28.49 (H)
Sleeve bearing	WLB	0.7	50000		2.15	0.8023	63352	2.68	37351	2008	13.945
Shafts, centrifugal pumps	Prop Shaft	0.8	50000		2.06	0.8374	56650	2.47	40567	3001	20.843
Seals, mechanical	Stuffing box	0.8	25000		3.15	0.7342	28325	4.29	23299	1501	10.421
Ball bearings	Thrust bearing	0.7	40000		2.42	0.7729	50681	3.13	31950	1607	11.156
Couplings, gear	Coupling	0.8	75000		1.57	0.8796	84975	1.78	56110	4502	31.264
DC Motor	DC motor	0.8	50000		2.06	0.8374	100000	2.47	40567	3001	20.843
joints, mechanical	Bubble Extractor	0.5	150000		1.40	0.8220	300000	1.70	58788	1665	11.563
joints, mechanical	Surface Flow Accelerator	0.5	150000		1.40E	0.8220	300000	1.70	58788	1665	11.563
	Paints										2

Table 1

List of Existing Circulating Water Channels						
Sl.NO	**Laboratory**	**Year**	**Orientation**	**Working Section(L*B*D4)**	**Max Speed(m/s)**	**Motor Power(kw)**
1	Berlin,Germany	1957	V	7*1.7*1.5	2.4	40
2	Nagasaki,Japan	1965	V	2.35*0.80*0.60	2	7.5
3	Tokyo,Japan	1966	H	3*1.20*0.75	2	19
4	Tokyo,Japan	1970	V	?	2	75
5	Osaka,Japan	1972	H	6.55*1.50*1.0	2.3	37
6	Osaka,Japan	1973		3.5*1.6*1.0	1	22
7	Kobe,Japan	1973	H	?	2	30
8	Berlin,Germany	1974	V	11.0*5.0*3.0	4	2*2000
9	Nantes,France	1978		10.0*2.0*1.25	1.7	135
10	Rome,Italy	1978	V	10.0*3.6*2.25	5	2*435
11	Isatnbul,Turkey	1978	V	6.0*1.50*7.0	2	35
12	Genova,Italy	1979	H	*2.4*1.70	1.5	160
13	Wuhan,China	1981	H	6.0*1.80*		
14	Harbin,china	1982	H	7.0*1.70*1.50	2.4	40
15	Shanghai,China	1982	H	6.0*1.50*1.20	2.5	18
16	Hiroshima,Japan	1982	V	4.0*1.4*0.90	1.2	2*5.5
17	Yokohama,Japan	1983	V	4.70*1.80*0.90	2.8	2*22
18	Ulsan,korea	1984	V	5.5*2.0*1.30	2	44
19	Kyushu,Japan	1986	V	4.40*1.50*1.30	1.3	2*22
20	Ibaragi,Japan	1989	V	8.0*2.80*1.40	3	2*90
21	Daeduk,korea	1990	V	2.0*?*?	1	15
22	Pusan,Korea	1991	V	?	2	44
23	Pohang,Korea	1991	V	4.45*?*?	2	10.33
24	Yokohama,Japan	1991	V	3.0*?*?	1	5.5
25	Taejon,Korea	1993	V	6.0*2.0*1.20	3	2*37
26	coanda,Canada	?	V	10.0*1.50*1.0	0.09444	22.371
27	Tsu,Japan	?	V	9.0*2.50*1.50	2.5	110

Table 2: Catalogue of Facilities

Characteristics	**Sub-characteristics (Generate uniform flow minimizing costs)**	**Max/Min**	***Definitions***
Performance	Latency	Minimize	*Measure of the time delay experienced by a system*
	Accuracy	Maximize	*Degree of closeness of measurements of a quantity to that quantity's actual (true) value*
	Range of load	Maximize	*Difference between Minimum and maximum operable load*
Reliability	MTBF	Maximize	*Predicted elapsed time between inherent failures of a system during operation*
	MTTR	Minimize	*Average time required to repair a failed component (the time from when the failure occurs until it is detected)*
	Impeller reliability	Maximize	*Ability of a system or component to perform its required functions under stated conditions for a specified period of time.*
	Fault tolerance	Maximize	*Property that enables a system to continue operating properly in the event of the failure of (or one or more faults within) some of its components.*
Add services required	Material required(direct and indirect)	Minimize	*Fabrication steel, civil structure*
	Add. components(direct and indirect)	Minimize	*Surface flow accelerators, vacuum pumps*
	Power consumed (direct and indirect)	Minimize	*Motor, internal lighting, add. component*
	Performance tuning	Maximize	*Ability of system to handle a higher load(velocity, rpm, test section water height)*
Availability	Uptime	Maximize	*Measure of time a machine is available without needing for maintenance purpose, etc.*
	Robustness	Maximize	*Ability of a system to continue operating despite abnormalities in input (or) ability to resist change without adapting its initial stable configuration*
Maintainability	Testability	Maximize	*Ease with which a product can be maintained in order to isolate/correct defects or their cause, repair or replace faulty or worn-out components without having to replace still working parts, prevent unexpected breakdowns, maximize a product's useful life, efficiency, reliability, and safety, make future maintenance easier, or cope with a changed environment.*
	Changeability	Maximize	
	Monitoring	Maximize	
			j
Competitive power	Competitive power	Maximize	*Factors that influence the competitive position in an industry or market*
Enhance-ability	Guaranteed performance	Maximize	*Ability to perform at higher loads*
	increase system's ability	Maximize	*Ability to improve system without changing systems component(upgrade)*
C&O expenditure	Capital expenditure	Minimize	*Capital costs: civil, fabrication, electrical, machinery ,instrumentation*
	Required Space	Minimize	*Space: floor area, roof height*
	Installation time	Minimize	*Time required to install and commission*
	Operating expenditures	Minimize	*Operating costs: Motor, add. components, internal lighting*
Limitations/Risks	Ease of operation	Maximize	*Minimizes the need for manual activities such as frequent checks, impeller monitoring, ergonomically easy*
Portability	Install-ability	Maximize	*Maximize ease: minimize personnel, machinery and tools*
	Adaptability	Maximize	*Ability of a system to adapt itself to changed environment*

Table 3: List of attributes

Attribute	**Global priority**	**VCWC**	**HCWC**	**sqrt**	**VCWC**	**HCWC**	**VCWC**	**HCWC**	**A***	**VCWC**	**HCWC**	**A'**	**VCWC**	**HCWC**
		rating		**sqrt(a^2+b^2)**	**a/d**	**b/d**	**e/z**	**f/z**	**max ideal score (g,h)**	**separation from ideal (g-p)^2**	**separation from ideal (h-p)^2**	**min ideal score (g,h)**	**separation from ideal (g-s)^2**	**separation from ideal (h-s)^2**
	z	a	b	d	e	f	g	h	p	q	r	s	t	u
Latency	0.0290	4	6	7.2111	0.5547	0.8321	0.0161	0.0241	0.0241	0.0001	0.0000	0.0161	0.0000	0.0001
Accuracy	0.0726	7	3	7.6158	0.9191	0.3939	0.0667	0.0286	0.0667	0.0000	0.0015	0.0286	0.0015	0.0000
Range of load	0.0435	4	6	7.2111	0.5547	0.8321	0.0241	0.0362	0.0362	0.0001	0.0000	0.0241	0.0000	0.0001
MTBF	0.0271	6	4	7.2111	0.8321	0.5547	0.0226	0.0150	0.0226	0.0000	0.0001	0.0150	0.0001	0.0000
MTTR	0.0271	4	6	7.2111	0.5547	0.8321	0.0150	0.0226	0.0226	0.0001	0.0000	0.0150	0.0000	0.0001
Impeller reliability	0.0904	7	3	7.6158	0.9191	0.3939	0.0831	0.0356	0.0831	0.0000	0.0023	0.0356	0.0023	0.0000
Fault tolerance	0.0362	5	5	7.0711	0.7071	0.7071	0.0256	0.0256	0.0256	0.0000	0.0000	0.0256	0.0000	0.0000
Material required(direct and indirect)	0.0024	4	6	7.2111	0.5547	0.8321	0.0013	0.0020	0.0020	0.0000	0.0000	0.0013	0.0000	0.0000
Add. components(direct and indirect)	0.0046	3	7	7.6158	0.3939	0.9191	0.0018	0.0043	0.0043	0.0000	0.0000	0.0018	0.0000	0.0000
Power consumed (direct and indirect)	0.0106	3	7	7.4686	0.4418	0.8971	0.0047	0.0095	0.0095	0.0000	0.0000	0.0047	0.0000	0.0000
Performance tuning	0.0120	6	4	7.2111	0.8321	0.5547	0.0100	0.0067	0.0100	0.0000	0.0000	0.0067	0.0000	0.0000
Uptime	0.0682	6	4	7.2111	0.8321	0.5547	0.0567	0.0378	0.0567	0.0000	0.0004	0.0378	0.0004	0.0000
Robustness	0.1023	7	3	7.6158	0.9191	0.3939	0.0940	0.0403	0.0940	0.0000	0.0029	0.0403	0.0029	0.0000
Testability	0.0742	4	6	7.2111	0.5547	0.8321	0.0411	0.0617	0.0617	0.0004	0.0000	0.0411	0.0000	0.0004
Changeability	0.0742	3	7	7.6158	0.3939	0.9191	0.0292	0.0682	0.0682	0.0015	0.0000	0.0292	0.0000	0.0015
Monitoring	0.0371	3	7	7.6158	0.3939	0.9191	0.0146	0.0341	0.0341	0.0004	0.0000	0.0146	0.0000	0.0004
Competitive power	0.0152	8	2	8.2462	0.9701	0.2425	0.0147	0.0037	0.0147	0.0000	0.0001	0.0037	0.0001	0.0000
Guaranteed performance	0.0118	8	2	8.2462	0.9701	0.2425	0.0114	0.0029	0.0114	0.0000	0.0001	0.0029	0.0001	0.0000
increase system's ability	0.0078	4	6	7.2111	0.5547	0.8321	0.0043	0.0065	0.0065	0.0000	0.0000	0.0043	0.0000	0.0000
Capital expenditure	0.0470	3	7	7.4686	0.4418	0.8971	0.0208	0.0422	0.0422	0.0005	0.0000	0.0208	0.0000	0.0005
Required Space	0.0314	8	2	8.2462	0.9701	0.2425	0.0304	0.0076	0.0304	0.0000	0.0005	0.0076	0.0005	0.0000
Installation time	0.0314	3	7	7.6158	0.3939	0.9191	0.0124	0.0288	0.0288	0.0003	0.0000	0.0124	0.0000	0.0003
Operating expenditures	0.0470	3	7	7.4686	0.4418	0.8971	0.0208	0.0422	0.0422	0.0005	0.0000	0.0208	0.0000	0.0005
Ease of operation	0.0634	4	6	7.2111	0.5547	0.8321	0.0352	0.0528	0.0528	0.0003	0.0000	0.0352	0.0000	0.0003
Install-ability	0.0235	7	3	7.6158	0.9191	0.3939	0.0216	0.0093	0.0216	0.0000	0.0002	0.0093	0.0002	0.0000
Adaptability	0.0101	7	3	7.6158	0.9191	0.3939	0.0093	0.0040	0.0093	0.0000	0.0000	0.0040	0.0000	0.0000
										VCWC	HCWC		VCWC	HCWC
								sum(separation)		0.0041	0.0079		0.0079	0.0041
								S* =sqrt(sum)		0.0642	0.0890	S'	0.0890	0.0642
					Relative closeness to ideal sol = S'/(S*+S')				VCWC	58%				
									HCWC	42%				

Table 4: TOPSIS

					TABLE 5 - WEIGHTED SUM MODEL		**TABLE 6 - WEIGHTED PRODUCT MODEL**	**TABLE 7 - ANALYTICAL HIERARCHY PROCESS**	
Attribute		**VCWC**	**HCWC**		**VCWC**	**HCWC**	**VCWC/HCWC**	**VCWC**	**HCWC**
	Global priority	rating							
	k	a	b		a*k	b*k	(a/b)^k	a*k	b*k
Latency	0.0290	4	6						
Accuracy	0.0726	7	3		0.1161	0.1741	0.9883	0.1161	0.1741
Range of load	0.0435	4	6		0.5079	0.2177	1.0634	0.5079	0.2177
					0.1741	0.2612	0.9825	0.1741	0.2612
MTBF	0.0271	6	4						
MTTR	0.0271	4	6		0.1627	0.1085	1.0111	0.1627	0.1085
Impeller reliability	0.0904	7	3		0.1085	0.1627	0.9891	0.1085	0.1627
Fault tolerance	0.0362	5	5		0.6328	0.2712		0.6328	0.2712
					0.1808	0.1808	1.0000	0.1808	0.1808
Material required(direct and indirect)	0.0024	4	6						
Add. components(direct and indirect)	0.0046	3	7		0.0094	0.0142	0.9990	0.0094	0.0142
Power consumed (direct and indirect)	0.0106	3	7		0.0139	0.0325	0.9961	0.0139	0.0325
Performance tuning	0.0120	6	4		0.0349	0.0709	0.9925	0.0349	0.0709
					0.0721	0.0481	1.0049	0.0721	0.0481
Uptime	0.0682	6	4						
Robustness	0.1023	7	3		0.4092	0.2728	1.0280	0.4092	0.2728
					0.7161	0.3069	1.0905	0.7161	0.3069
Testability	0.0742	4	6						
Changeability	0.0742	3	7		0.2966	0.4450	0.9704	0.2966	0.4450
Monitoring	0.0371	3	7		0.2225	0.5191	0.9391	0.2225	0.5191
					0.1112	0.2596	0.9691	0.1112	0.2596
Competitive power	0.0152	8	2						
					0.1216	0.0304	1.0213	0.1216	0.0304
Guaranteed performance	0.0118	8	2						
increase system's ability	0.0078	4	6		0.0941	0.0235	1.0164	0.0941	0.0235
					0.0314	0.0470	0.9968	0.0314	0.0470
Capital expenditure	0.0470	3	7						
Required Space	0.0314	8	2		0.1552	0.3152	0.9672	0.1552	0.3152
Installation time	0.0314	3	7		0.2509	0.0627	1.0444	0.2509	0.0627
Operating expenditures	0.0470	3	7		0.0941	0.2195	0.9738	0.0941	0.2195
					0.1552	0.3152	0.9672	0.1552	0.3152
Ease of operation	0.0634	4	6						
					0.2536	0.3804	0.9746	0.2536	0.3804
Install-ability	0.0235	7	3						
Adaptability	0.0101	7	3		0.1646	0.0706	1.0201	0.1646	0.0706
					0.0706	0.0302	1.0086	0.0706	0.0302
					sum(a*k)/sum(b*k)		sum((a/b)^k)	Greater [sum(a*k) , sum(b*k)]	
					1.0662		1.0018	5.1602	4.8398

Table 5: Weighted Sum Model / Table 6: Weighted Product Model / Table: 7 Analytical Hierarchy Process

RESULTS FOR VERTICAL CWC																
Equipment	**Expected Life (Yr)**	**Replacement Req.at end of year**	**No Of Failures Over Life**	**Detection Time (Days)**	**Fixing Time (Days)**	**Delay Time (Days)**	**Loss Time (Days)**	**Qty**	**Parts Cost (Rs)**	**Labor Rate (Rs/Day)**	**No of Labor**	**Labor Cost**	**Material Costs**	**Total Maintenance Costs**	**Opportunity Costs**	Design For :
												costs over 40 year period life				
Impeller	40	71.23	0	2	2	90	94	1	0.67	0.020	1	-	-	-	-	Reliability
WLB	40	13.95	3	2	2	30	34	2	0.02	0.020	1	2.04	0.13	2.17	2.04	Serviceability
Prop Shaft	40	20.84	2	2	2	60	64	1	0.03	0.020	1	2.56	0.06	2.62	2.56	Serviceability
Stuffing Box	40	10.42	4	2	2	30	34	1	0.11	0.020	1	2.72	0.45	3.17	2.72	Diagnostic Capability
Thrust Bearing	40	11.16	4	2	2	30	34	1	0.06	0.020	1	2.72	0.22	2.94	2.72	Diagnostic Capability
Coupling	40	31.26	2	2	2	30	34	1	0.06	0.020	1	1.36	0.11	1.47	1.36	Serviceability
DC Motor	40	20.84	2	2	2	60	64	1	0.25	0.020	1	2.56	0.50	3.06	2.56	Serviceability
Bubble Extractor	40	11.56	4	2	2	30	34	1	0.05	0.020	1	2.72	0.20	2.92	2.72	Serviceability
Surface Flow Accelerator	40	11.56	4	2	2	30	34	1	0.02	0.020	1	2.72	0.08	2.80	2.72	Serviceability
Steel Paint	40	11.56	19	0.5	30	30	60.5	1	0.01	0.020	1	22.99	0.19	23.18	22.99	Serviceability
											Totals:	42.39	1.95	44.34	42.39	Serviceability

RESULTS FOR HORIZONTAL CWC																
Equipment	**Expected Life (Yr)**	**Replacement Req.at end of year**	**No Of Failures Over Life**	**Detection Time (Days)**	**Fixing Time (Days)**	**Delay Time (Days)**	**Loss Time (Days)**	**Qty**	**Parts Cost (Rs)**	**Labor Rate (Rs/Day)**	**No of Labor**	**Labor Cost**	**Material Costs**	**Total Maintenance Costs**	**Opportunity Costs**	Design For :
												costs over 40 year period life				
Impeller	40	28.49	1	2	2	90	94	1	0.674	0.020	1	1.88	0.95	2.83	1.88	Reliability
WLB	40	13.95	3	2	2	30	34	2	0.022	0.020	1	2.04	0.13	2.17	2.04	Serviceability
Prop Shaft	40	20.84	2	2	2	60	64	1	0.028	0.020	1	2.56	0.05	2.61	2.56	Serviceability
Stuffing Box	40	10.42	4	2	2	30	34	1	0.112	0.020	1	2.72	0.43	3.15	2.72	Diagnostic Capability
Thrust Bearing	40	11.16	4	2	2	30	34	1	0.056	0.020	1	2.72	0.20	2.92	2.72	Diagnostic Capability
Coupling	40	31.26	2	2	2	30	34	1	0.056	0.020	1	1.36	0.07	1.43	1.36	Serviceability
Dc Motor	40	20.84	2	2	2	60	64	1	0.250	0.020	1	2.56	0.48	3.04	2.56	Serviceability
Bubble Extractor	-	-	-	-	-	-	-	-	-	-	-		-	-	-	Serviceability
Surface Flow Accelerator	-	-	-	-	-	-	-	-	-	-	-		-	-	-	Serviceability
Steel Paint	40	42.59	19	0.5	30	30	60.5	1	0.010	0.020	1	22.99	0.01	23.00	22.99	Serviceability
											Totals:	38.83	2.32	41.15	38.83	

Table 8: Cost Based FMEA (All Prices in Lakhs of Rupees)