

Selection of maintenance strategy, using Analytical Hierarchy Process

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Abstract—Selection of appropriate maintenance strategy is key to economic viability of aviation and manufacturing industries.

The study discusses and presents an approach to facilitate the selection of the most appropriate maintenance strategy on the basis of the cost–benefit analysis by using Analytical Hierarchical Process (AHP). The goal is to select the most cost-effective alternative, among Run-To-Failure (RTF), Preventive Maintenance (PM), incorporating Prognostic Health Management (PHM) capability, or any possible Design-Out Maintenance (DOM) strategies, which positively affects on aircraft operational availability.

In this paper we proposed a stepwise algorithm to guide the selection process, based on two criteria of operational availability (benefit) and cost of failure.

Keywords: Maintenance strategy, Preventive Maintenance, Prognostic Health Management (PHM), Analytical Hierarchical Process (AHP), Cost–Benefit Analysis, Availability.

1. INTRODUCTION AND BACKGROUND

In aviation industry, Reliability Centered Maintenance (RCM) is a systematic methodology used to identify the PM tasks that are necessary to realize the inherent reliability and safety of equipment at the lowest possible cost. Developing a scheduled maintenance program by means of RCM consists of identifying the maintenance strategies that are both applicable (technically feasible) and effective (worth doing) [1-4]. In addition, designed maintainability characteristics also influence selection of maintenance strategies.

However, the effectiveness of the maintainability allocation and designed asset availability can be improved by establishing the RCM analysis as early as possible in system design and development phases, to influence necessary design changes of the technical system and in order to get the most applicable and cost-effective solution. Using RCM as part of the design process allows early identification of failure modes often resulting in expensive or complicated preventive maintenance tasks which may results in longer periods of maintenance downtime and higher operation

cost. However, it will identify design shortfalls, areas for the use of applicable technologies such as incorporation of diagnosis/prognosis and Built In Test (BIT) capability, or identification of design features, such as automated identification of PM tasks, modularity, easy accessibility, easy inspection, and interchangeability, which would lead to a higher availability performance, and lower life cycle costs. In addition, such capabilities will allow maintenance engineers to predict accurately future health status and to identify operational problems and required maintenance actions in advance. The ability to predict future health status and required maintenance actions are key enablers to any Condition Based Maintenance (CBM) programs [5]. This can be achieved through implementation of an effective PHM system.

1.1 PROGNOSTIC HEALTH MANAGEMENT (PHM) AND ITS BENEFIT

PHM is the name given to the capability being developed by Joint Strike Fighter (JSF) to enable the vision of Autonomic Logistics and so meet the overall affordability and supportability goals. [6]

Several protective and diagnostic/prognostic devices and systems are available for integration into an item’s design. State-of-the-art PHM systems are capable of detecting potential failure conditions and are also able to monitor the progression of chosen failure mode indicators, e.g., heat, vibration, etc., to predict when functional failures will occur. Through automated monitoring, a “prognosis” of the “health” of the component can be made. Item degradation is monitored automatically as it progresses to a defined potential failure condition, at which time some maintenance action is warranted. PHM systems may essentially perform “automatic” on-condition inspections at predefined intervals, which often are extremely short or nearly continuous. This is achieved by the use on-board sensors, algorithms, and diagnostic indicators (or indices) that are sensitive and accurate enough to detect or predict the potential failure condition [4].

A modern and comprehensive PHM system needs to interface with the Logistic Information System to trigger: (1) the activities of the Supply Chain Management System

promptly to provide required replacement parts; (2) planning needed to perform the required maintenance; and (3) training of the maintainer. Typical Turn-Around-Time (TAT) to perform any required depot level maintenance action is significantly reduced over that of legacy aircraft as a result of the advanced notification of maintenance requirements, and readily available tools and replacement parts.

Some of the benefits of a PHM system could be stated as using On-Condition maintenance which facilitates opportunistic maintenance, and reduces scheduled mission interruption. It also results in reducing test and support equipment for failure detection and rectification, on different level. [4]

PHM enables the control of the performance status of technical systems [4, 12], provides information on system health, and facilitates remaining useful life (RUL) estimation. With the advantage of identifying potential failures in advance, it reduces the number of irrelevant scheduled maintenance and avoids premature removal of items that are still in satisfactory condition. Adding planning horizon to PHM, it facilitates decision about implementation of opportunistic maintenance policy for components and system. It also contributes towards elimination of interruptions in scheduled mission due to failure, and avoids unplanned maintenance. It will help maintenance engineers to take action to eliminate the secondary damage, which would be cause of another failure. These possibilities will contribute to increase uptime (decrease down time) and affect the Mean Time Between Maintenance (MTBM) positively. [7.8.9]

Furthermore, the cost of correcting potential failure is often far less than the cost of correcting functional failures. This not only reduces the associated cost of repair, but also reduces the related downtime required for corrective action. Warning of failure provides time either to shut down the item before the situation becomes dangerous, or to move people out of harm's way. Moreover, the information on impending errors and failures makes it possible to optimize the logistics for replacement of components, i.e. by pre-order of the device that is about to fail and prepare for personnel requirement. This can limit the spare-part inventory and further reduce the down-time of the system in question.

In fact, a highly developed ability to use aircraft components and systems optimally is advantageous in order to achieve market competitiveness. This requires that degradations and impending faults are identified before they cause a failure and that the RUL can be estimated by using prognostic methods. The prognostic ability enables optimal Condition-Based Maintenance (CBM) and offers the possibility to prolong RUL. Altogether, this gives the operator a higher potential of increasing the aircraft operational availability.

As illustrated in Figure 1, system design attributes and system support elements influence both engineering and economic aspects. In addition, a projected Life Cycle Cost (LCC) for a system often stems from the consequences of decisions made during the early design phases. These decisions pertain to the utilization of new technologies, the selection of components and materials, and the selection of manufacturing process, incorporation of diagnostic routines, prognostics, and maintenance support policies [6]. Therefore, design tradeoff plans and processes should be in place to ensure that such technologies are evaluated for life cycle cost effectiveness by the use of suitable optimization models or algorithms.

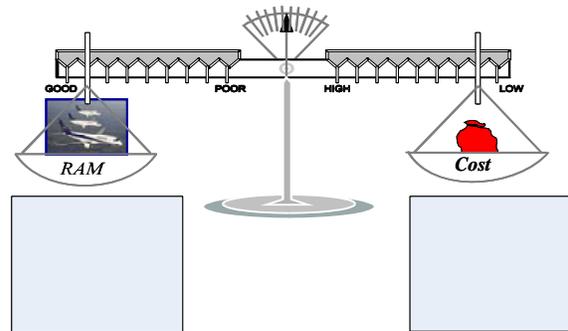


Figure 1. System effectiveness and LCC

The study presents an approach using the cost-benefit analysis for selecting the most appropriate maintenance alternatives among Run to Failure (RTF), Preventive Maintenance (PM), Prognostic Health Management (PHM). In addition Design-Out Maintenance (DOM) solutions are also considered in our study while selecting maintenance strategies for the aircraft systems. Recently, lot of emphasis has been made on either designing out maintenance need or design for maintenance considering the total operational and business risks.

Exact quantification and assessment of the cost-benefit analysis of alternatives for specific failure is a challenge in the early design phase, due to a long list of contributory factors, e.g. inadequacy in required information & numerical data and lack in understanding regarding their nature of influence. However, the experience of field experts may provide an effective database towards this estimation. In order to effectively utilize the knowledge of field experts in the assessment process, Analytical Hierarchy Process (AHP) was used for quantifying the contribution of influencing criteria and factors to the cost and benefit of each alternative.

2. PROPOSED METHODOLOGY

2.1 STUDY APPROACH

Assuming a successful integration of RCM & PHM analysis in the design phase, four alternatives may be applicable:

1. Run-to-failure (RTF)
2. Selecting RCM's Preventive Tasks (PM)
3. Incorporation of PHM (PHM)
4. Design-Out-Maintenance(DOM)

The objective is to select the most cost-effective alternative, which positively affects on aircraft operational availability. In fact, we are looking to find the alternative, whose cost-benefit ratio is the lowest among various alternatives, competing for a given amount of investment.

Due to a long list of contributory factors, inadequacy in required information and numerical data, and also lack in modeling the cost and benefit factors interaction and influence, exact quantification of the cost-benefit analysis of alternatives is not an easy exercise. However, the experiences of field experts provide an effective database towards this estimation. In order to effectively utilize the knowledge of field experts in the assessment process, Analytical Hierarchy Process (AHP) was used for quantifying the contribution of influencing criteria and factors to the cost and benefit of each alternative.

2.2 ANALYTICAL HIERARCHY PROCESS (AHP)

To make optimal decisions and allocate limited amount of resources to solve major problems in complex systems, we require implementing applicable methods to choose the best combination. AHP is one of the useful methods for decision making. The method was proposed by Thomas L. Saaty and since then it has been extensively used by decision makers to arrive at appropriate decision using personal experiences of experts in the field (1980). Furthermore, the AHP method is a flexible in approach and allows individuals or groups to shape ideas and define problems by making their own assumptions and deriving the desired solution from them [10].

Based on Saaty (1980) some of the advantages of AHP are:

1. Unity: It provides a single, easily understood, flexible model for a wide range of unstructured problems.
2. Complexity: The AHP integrates deductive and systems approaches in solving complex problems.
3. Hierarchic Structuring: It helps to sort elements of a system into different levels.
4. Synthesis: It leads to an overall estimate of the desirability of each alternative.
5. Consistency: It tracks the logical consistency of judgments used in determining priorities.
6. Tradeoffs: The AHP takes into consideration the relatives priorities of factors in a system and enables people to select the best alternative based on their goals.

2.3 PAIRWISE COMPARISON MATRIX

This approach is based on the fundamental principle that it is more difficult to evaluate n elements (where $n > 2$)

simultaneously than to compare two such elements at a time. In pair wise comparison experts compare the importance of two factors on a relatively subjective scale. In this way a judgment matrix of importance is build according to the relative importance given by the experts. Table I represents a pair wise comparison scale for value rating of judgements and for deriving pair wise ratio scales. Table I includes reciprocals, which are equally often adopted for relative measurements or comparisons of factors. A total of judgements are required for comparing n factors.

Table 1: Pair wise comparison scale

Value rating for judgement	Verbal judgement
1	Elements are equally preferred
3 or (1/3)	One is moderately preferred to the other
5 or (1/5)	One is strongly preferred to the other
7 or (1/7)	One is very strongly preferred to the other
9 or (1/9)	One is extremely preferred to the other
Note: (2, 4, 6, 8: intermediate judgemental values between adjacent scale values)	

2.4 ALGORITHM FOR THE PROPOSED MODEL

The following steps form the proposed AHP-based algorithm for maintenance strategy selection (See Fig. 2):

Step 1: Based on RCM and criticality analysis, one failure mode is selected. It implies that decision making process to specify the best maintenance strategy is made based on this specific failure mode.

Step 2: Build a hierarchical structure for both Benefit and Cost criteria. It means that by decomposing these criteria, an attempt is made to prioritize and simplify the problem and come down from the goals to specific and easily controlled factors.

Step 3: Calculate the weight of each sub criteria in the lower levels by implementing pairwise comparison matrix. After this calculation it is necessary to check the consistency of each matrix and in a case that consistency ratio exceeds 10%, the experts are asked to modify their judgments. Considering that the opinions of different experts are used for pairwise comparison it is essential to calculate the mean weight for each sub criteria.

Step 4: By implementing AHP method prioritize four maintenance strategy alternatives (RTF, RCM, PHM, and DOM) for each factor in the lowest level of the Benefit and Cost hierarchies. Similar to prior step mean weight for each factor should be calculated.

Step 5: Compute the synthesized value for each alternative. It implies that by multiplying the priority of each factor to the weight of each alternative for that specific factor and summing up the synthesized value for each maintenance strategy in both Benefit and Cost hierarchies is calculated.

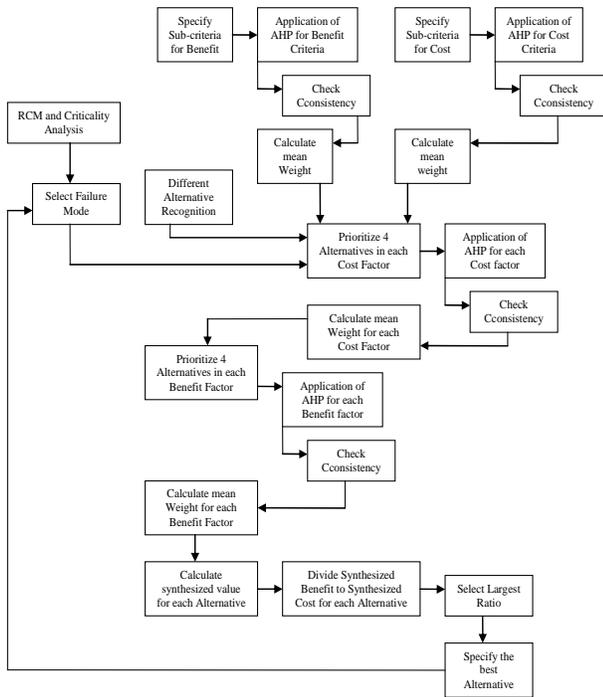


Figure 2. Algorithm for the PHM model

Step 6: By dividing the synthesized value of Benefit to the synthesized value of cost for each alternative, Benefit/Cost ratio should be calculated.

Step 7: Select the largest ratio as a Best maintenance strategy for this specific failure mode. It is necessary to go back to the first step and select another failure mode and repeat the analysis again.

2.5 COLLECTION OF JUDGEMENTS FROM DIFFERENT EXPERTS

To perform the pairwise comparison, a suitable team of experts should be invited. It should be noted that the level of experience and appropriate knowledge about the case, are vital when choosing the respondents. A multiple choice questionnaire consisting of questions regarding the relative importance of one decision criteria, (e.g. benefit) to the others (e.g. cost), as shown in a sample questionnaire in Appendix A can be used.

2.6 MEASURING INCONSISTENCY IN JUDGEMENTS

As human judgements are the bases of the pairwise comparison, some degree of inconsistency may be introduced in judgment due to:

- Lack of adequate information;

- Improper conceptualisation;
- Mental fatigue.

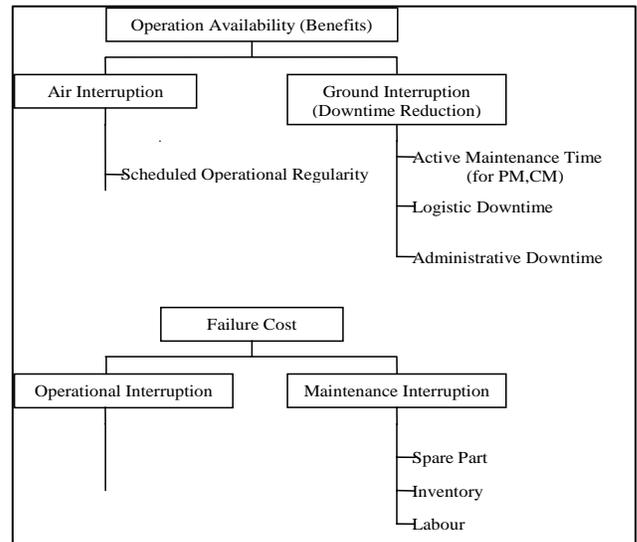


Figure 3. Cost and Benefit Hierarchical Criteria

Saaty (1980), proposed a Consistency Index (CI) as:

$$CI = \frac{\lambda_{\max} - n}{n - 1}$$

Where, where, λ_{\max} is the largest Eigen value and n is the number of comparisons. The closer this CI is to zero, the better the overall consistency in the judgements.

A perfectly consistent judgement will yield a CI of zero (0), the Consistency Ratio (CR) will also be zero. Usually, a value of CR between 0 and 0.10 (i.e. 10 percent of what would be the outcome from random judgements) is acceptable (See Table. 2). If the obtained value of CI is not within an acceptable range, the experts may be asked to modify their judgements in the hope of getting a modified consistent matrix.

Table 2. Final CR values of the judgement matrices for delays less than 15 min

Expert	CR value
No. 1	0.01
No. 2	0.0037
No. 3	0.0175
Aggregate	0.0002

2.7 AGGREGATING JUDGEMENTS OF DIFFERENT EXPERTS

As pointed out by Aczel et al, (1983), the same pairwise comparison for each expert can be aggregated into a group comparison by taking the geometric mean of all comparisons. The geometric mean is the only averaging process that maintains the reciprocal relationship ($a_{ij} = \frac{1}{a_{ji}}$) in the aggregate matrix.

The general formula for calculating a geometric mean for a group response is:

$$\text{Weighted mean value of } a_{ij} = \left(\prod_{k=1}^n w_k \bullet a_{ij} \right)^{1/\sum_{k=1}^n w_k}$$

Where a_{ij} is each expert's paired comparison value, n is the number of expert, and w_k is the weight of the k^{th} expert.

In this study we have assumed that all the experts have equal expertise in their judgements and therefore $w_k = 1$ for all k . The individual and overall judgement matrixes are given in Appendix B.

3. ILLUSTRATION OF PROPOSED METHODOLOGY:

In order to illustrate the proposed methodology, we have used a hypothetical Ventilation System (VS) of a single aisle, twin-engine aircraft, which can be used to cool different avionics equipment. The VS is equipped with an electrically operated air inlet valve which will be installed in the fuselage to provide an outdoor air supply gateway for electronic bay on the ground.

One of the functional failures which might occur with VS could be defined as "Ventilation Air Inlet Valve fails to close at take-off power setting".

Taking off with the Ventilation Air Inlet valve open (instead of closed), damages the avionics ventilation ducts, and may have potential effects on degradation of avionics ventilation performance. Therefore, the valve is designed to be fully open on ground and must be fully closed in flight. As standard design practice, if the failure has any operational consequences, it should be evident to the crew.

In case, the valve is not function properly at take-off power setting (prior to take-off) the system is designed to provide warning message on the cockpit display, to alert the cockpit crew. As this failure has no catastrophic or safety effect on the aircraft and its occupants, the system safety analysis advice that the aircraft can flight with inoperative ventilation system, in the condition that maintenance crew close the valve manually on the ground (Prior to take off) and related electrical connection should be isolated.

However, in order to manage the consequence of failure, the designers have the following choices:

1. **Run-to-failure (RTF):** Providing warning message on the cockpit display unit, the valve can be closed and isolated manually on the ground prior to take off by maintenance crew. This is an immediate action, which is required to fly with an inoperative Ventilation Air Inlet Valve within a certain limited time, without any operational restrictions. Therefore, the aircraft has to be returned to the ramp/gate so that the maintenance crew can perform these actions before further dispatch, which will results in "Ground delay at departure" at the cost of \$70 /min,
2. **Preventive Tasks (RCM):** In addition to 1, to define a restoration task to reduce the probability of occurrence of failure, every 3000 FH (C checks), at a total cost of \$2000 per component.
3. **Incorporation of PHM Technology (PHM):** To include sensors, to detect any possible potential failure such as slow???? operation, or delayed operation, to implement Condition-Based or Opportunistic Maintenance,
4. **Design-Out-Maintenance strategy (DOM):** to increase the reliability level of Ventilation valve (Higher MTBF).

In this paper for analysis and choosing the most cost effective failure management strategy among RTF, PM, PHM, DOM, we selected two criteria of Cost and Benefit. As it was mentioned before the first step is to build hierarchical structure for these criteria as they were shown in Fig. 3.

Thereafter, we calculated the priority of all sub criteria e.g. Air interruption Vs. Ground interruption, in operational availability criteria, (See Fig. 3) by implementing pair wise comparison matrix, as described in step 3. To perform the pairwise comparison, a suitable team of experts should be invited to give their opinion on the multiple choice response sheets. The questionnaire should consist of questions regarding the relative importance of different criteria or factors to each other. As an example, one pairwise comparison for Operational Availability Criteria is shown in Table 3.

Table 3: Comparing benefits (operation availability) of the maintenance major benefit criteria

Operation Availability	Air Interruption	Ground Interruption	Priority
Air Interruption	1	3	0.75
Ground Interruption	1/3	1	0.25

The CR of the judgement matrixes of all the experts was calculated. Depending on the value of the CR some experts were asked to modify their judgements. To prevent unnecessary repetition, it is important to consider

consistency check was done for all of pairwise comparisons in the following text.

Following of step 3, the weights of all sub criteria factors should be calculated as shown in Tables 4. The given weights are called Local priority and mean that how much benefit can be obtained by preventing the failure. In order to calculate the Global Priority, Local priority should be multiplied to the weight of their sub criteria.

Table 4: Pairwise comparing the maintenance ground interruption (reduction) benefit

Ground interruption	Active Maint. Time	Logistic Delay Time	Administrative Delay Time	Priority (Local)
Active Main. Time	1	1/3	1/7	0.1105
Logistic Delay Time	3	1	5	0.5796
Administrative Delay time	7	1/5	1	0.3099

As step 4, the experts were asked to mark their opinion about the relative comparison weight of alternatives (i.e. RTF, PM, PHM and DOM) for each factor e.g. spare parts. Consequently, the priority of all of maintenance strategy alternatives was calculated as shown in Tables.5. This implies that which of these four alternatives has more priority in each factor in the lowest level of the hierarchy of specific criteria.

Thereafter in the step 5 we computed the synthesized value for each alternative in both criteria. This calculation was done by multiplying the priority of each factor to the weight

Table 5: Comparing maintenance strategy alternatives under operation availability (Regularity)

Operation Regularity	RTF	PM	PHM	DOM	Priority
RTF	1	3	5	9	0.5764
PM	1/3	1	3	5	0.2556
PHM	1/5	1/3	1	3	0.1172
DOM	1/9	1/5	1/3	1	0.0507

of the alternative for that specific factor and summing up.

As shown in Table.6, by dividing the combined value of each alternative in Benefit criteria to the synthesized value of same alternative in Cost Criteria and selecting the larger ratio we recognized the most appropriate choice among 4 alternatives based on 2 criteria of Benefit and Cost for Specific failure.

Tables 6: The Benefit/Cost ratios

Benefits	Priority	RTF	RCM	PHM	DOM
Active Main. Time	0.028	0.312	0.283	0.201	0.204
Logistic Delay Time	0.145	0.469	0.327	0.145	0.059
Administrative Delay time	0.077	0.0417	0.133	0.2676	0.5577
Operation Regularity	0.75	0.576	0.256	0.117	0.051
Synthesis		0.511952	0.25758	0.135008	0.09546
Costs					
Operation Interruption	0.75	0.379	0.284	0.191	0.146
Spare parts	0.021	0.164	0.156	0.215	0.465
Inventory	0.0483	0.465	0.2751	0.134	0.1259
Labors	0.181	0.24	0.304	0.265	0.191
Synthesis		0.353594	0.284587	0.202202	0.159917
Benefit/Cost		1.447854	0.9051	0.667689	0.596934

4. CONCLUSIONS

In this paper we present an approach for selecting the most appropriate maintenance strategy for specific failure mode using operational availability (Benefit) and failure cost as two criteria for decision making. To illustrate this algorithm, we take an example of a failure in ventilation system of an aircraft. Relative benefit and cost of implementing different maintenance strategy for each factors (e.g. active maintenance time) of sub-criteria (down time reduction) in lowest level of the hierarchies were obtained by pair wise comparison method (see Figure 3). After computing synthesized value of benefit and cost for each alternative and dividing the synthesized value of benefit to cost, the best maintenance strategy was recognized by selecting the largest ratio.

Furthermore, Table 6 can be used for marginal cost benefit analysis. It implies that where the company should allocate additional resources for the greatest marginal return [12]. .

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Appendix A:

RTF	Extremely preferred	Very Strongly preferred	Strongly preferred	Moderately preferred	Equally preferred	Moderately preferred	Strongly preferred	Very Strongly preferred	Extremely preferred	RCM
	<input type="checkbox"/>									
RTF	Extremely preferred	Very Strongly preferred	Strongly preferred	Moderately preferred	Equally preferred	Moderately preferred	Strongly preferred	Very Strongly preferred	Extremely preferred	PHM
	<input type="checkbox"/>									
RTF	Extremely preferred	Very Strongly preferred	Strongly preferred	Moderately preferred	Equally preferred	Moderately preferred	Strongly preferred	Very Strongly preferred	Extremely preferred	DOM
	<input type="checkbox"/>									
PHM	Extremely preferred	Very Strongly preferred	Strongly preferred	Moderately preferred	Equally preferred	Moderately preferred	Strongly preferred	Very Strongly preferred	Extremely preferred	RCM
	<input type="checkbox"/>									
PHM	Extremely preferred	Very Strongly preferred	Strongly preferred	Moderately preferred	Equally preferred	Moderately preferred	Strongly preferred	Very Strongly preferred	Extremely preferred	DOM
	<input type="checkbox"/>									
RCM	Extremely preferred	Very Strongly preferred	Strongly preferred	Moderately preferred	Equally preferred	Moderately preferred	Strongly preferred	Very Strongly preferred	Extremely preferred	DOM
	<input type="checkbox"/>									