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Framework for Aviation Safety Cost Optimization through Risk Mitigation Tolerance Analysis

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Abstract— The aviation industry depicts itself to be one of the topmost safety-conscious industries where thorough emphasis is focused on safety management systems as a toolbox for hazard identification and risk mitigation. The promulgation of regulatory safety measures for in-air and on-ground operations has collated additional time and operational costs for all types of aviation establishments. The risk probability and severity aspects of safety models have been vastly studied in previous research mainly through qualitative analysis and risk matrix formulation. In conventional studies, the "risk tolerance" has been mainly incorporated with the probability and the severity of the risks where less or no emphasis is laid on the cost-benefit analysis. Hence, this study focuses on the implications of the "cost variable" on risk mitigation tolerance analysis in a collaborative approach of qualitative and quantitative analysis. The study converges the theoretical relationship of the "safety tolerance levels", towards the "overall safety cost" which aims to bridge a significant gap in the contemporary aviation safety literature. In bridging the unpredictability of the post-failure cost, the optimization of the cost of safety assurance enables expanded forecast ability by mathematically calibrating the strategic positioning of the safety threshold. The scale of the airline and the regulatory mandates have been considered in developing the conceptual ideology. Moreover, the study will span through to the development of a data-driven mathematical model for the cost to tolerance variation. Hence, the theoretical framework of this study proposes a more generalized approach that can be customized for the safety cost-benefit analysis and resources allocation policies of diversified airline operations spanning from low-cost carriers to high-end niche markets with utmost safety concerns.

***Keywords**: Safety Management Systems (SMS), Safety Risk Management (SRM), aircraft maintenance cost benefit, risk mitigation, risk tolerance.*

I. INTRODUCTION

As aviation is considered as a safety-critical industry the overall measures are developed as such supports and manipulates every operation to be supportive of reaching an acceptable range of safety. (Smith, 2005) Delivering a safer product consists of not only operational safety but the primary safety aspects such as design and maintenance safety measures. Due to the requirement of critical safety consideration, the International Civil Aviation Organization (ICAO) has developed the global standard safety risk probability value table as per the following Table 1.

Table 1. Safety risk probability table
Source: SMM (ICAO)

Likelihood	Meaning	Value
Frequent	Likely to occur many times (has occurred frequently)	5
Occasional	Likely to occur sometimes (has occurred infrequently)	4
Remote	Unlikely to occur, but possible (has occurred rarely)	3
Improbable	Very unlikely to occur (not known to have occurred)	2
Extremely improbable	Almost inconceivable that the event will occur	1

The maintenance aspect of aviation operations has developed various means of safety management options and policies throughout the years of air travel. (Fumero, 2018) The development of tolerance levels and risk matrix are two key aspects of semi-quantitative approaches of aircraft maintenance safetyassessment.

The conventional approach in developing the risk matrix revolves around the comparative analysis of severity vs likelihood. Due to its biased nature under differential expectations and varied understanding of the data sources, a quantitative measure has been developed through time. (Song and Lee, 2015) The validation has been enumerated through qualitative measures, by comparison, quantitative measures by value assigning, and hybrid methods by risk calculation and matrix development.

In most conventional systems, the cost factor depending on the tolerance level has been overlooked through the intervention of insurance or post-accident recovery measures. (Xie, 2017) Under the said conditions the operators have given minimal consideration towards optimizing the selection of tolerance levels. (Čavka and Čokorilo, 2012).

J. Conditional liability sharing/transference

One of the most common mislead methods integrated into the aviation industry in terms of safety cost management is the reliance on insured entity.

This method deemed to be an indemnifying scheme in the sense of risk transference rather than risk mitigation. A third party transference may build a one-off occurrence assurance but will not guarantee a continuous safety process.

The cost benefit of safety assurance will not be met in liability sharing and transference. Thus, the process improvement can be emphasised as an optimal method in improving the safety tolerance to be in a continuous basis.

Table 2. Example safety risk severity table
Source: SMM (ICAO)

Severity	Meaning	Value
Catastrophic	• Aircraft / equipment destroyed • Multiple deaths	A
Hazardous	A large reduction in safety margins, physical distress or a workload such that operational personnel cannot be relied upon to perform their tasks accurately or completely • Serious injury • Major equipment damage	B
Major	A significant reduction in safety margins, a reduction in the ability of operational personnel to cope with adverse operating conditions as a result of an increase in workload or as a result of conditions impairing their efficiency • Serious incident • Injury to persons	C
Minor	• Nuisance • Operating limitations • Use of emergency procedures • Minor incident	D
Negligible	• Few consequences	E

The Table 2 depicts the most general definitions of the severity of occurrences derived by the International Civil Aviation Organization.
The systematic explanation has been contemplated in accordance with the previous occurrences and anticipated incidences. In such case the direct tolerability require task wise as well as operation wise broader scope in decision making.

II. CONCEPTUAL DEBRIEF

The capping of tolerance ranges to differentiate the regions does not possess a global standard optimal position. (Čokorilo et al. 2010) Thus, the capping margin has been varying from operator to operator without a standard means of variance. This has driven the majority of operators to overlook the tolerance levels and highly depend solely on the risk analysis (Lališ et al. 2018). With respect to the cost factor, this measure has been overlooked. (Cavka, Petrović and Cokorilo, 2014)

Safety Risk		Severity				
Probability		Catastrophic A	Hazardous B	Major C	Minor D	Negligible E
Frequent	5	5A	5B	5C	5D	5E
Occasional	4	4A	4B	4C	4D	4E
Remote	3	3A	3B	3C	3D	3E
Improbable	2	2A	2B	2C	2D	2E
Extremely improbable	1	1A	1B	1C	1D	1E

Figure 2. Risk Matrix
Source: SMM (ICAO)

In this study, the variance of the optimal position for the tolerance range is objectified as the primary output of the study in aspects of mathematically calculable means.

III. THEORETICAL FRAMEWORK

A. Overview and Rational

When considering the regional disposition, the range varies under the three sectors of risk management namely, Unacceptable region, Tolerable region, and Acceptable region (Zhang et al., 2018). The optimal positioning of the safety threshold could be derived on par with the cost factor consideration whereas the cost of safety could be brought to a reasonable balance by addressing the production and protection dilemma.

The generalized tolerance is globally depicted as per the following Figure 2 is derived from the aforementioned matrix in Figure 1 and risk analysis methods.

Suggested Criteria	Assessment Risk Index	Suggested Criteria
Intolerable Region	5A, 5B, 5C, 4A, 4B, 3A	Unacceptable under the existing circumstances
Tolerable Region	5D, 5E, 4C, 4D, 4E, 3B, 3C, 3D, 2A, 2B, 2C	Acceptable based on risk mitigation. It may require management decision
Acceptable Region	3E, 2D, 2E, 1A, 1B, 1C, 1D, 1E	Acceptable

Figure 2. Generalized Safety Tolerance Levels

B. Objectives

i. To identify the conditional variations of risk tolerance levels.

ii. To mathematically model the variations subjected to a generalized form.

iii. To introduce the cost benefit factors in supporting any type of airline through the derived model

iv. To suggest the optimal safty engagement achievable by any airline withrespect to its financial position.

IV. CONCEPTUAL FRAMEWORK

A. Unacceptable region - (Beyond High upper tolerable limit)

The range can be considered to be the standard specific upper limit where the disposition is limited to increment of the range under practical conditions. With respect to the organization policies, this range could be increased under the capacity to control the cost aspect in a higher range.

B. Tolerable Region - ALARP Principle

In accordance with the tolerable region, the upper limit can only be reduced with respect to the limitation of the unacceptable range and the lower limit could vary with either a positive or negative gradient (Jaiswal et al., 2018). With respect to the organization's focus on production and protection, this region could be kept at a reasonably practicable range according to the ALARP principle.

As Low as Reasonably Practicable or well known as ALARP principle signifies the economically viable and socially desirable range of safety. (Yasseri, 2013) In risk based safety management the range in favour and range in imminent failure is averaged from ALARP principle.

In generalized form the overall risk is defined as the summation over all conceivable vulnerabilities towards their respective consequences. Whereas, the ALARP depicts the pressure on the practical condition with respect to cost and benefit to the operator in attaining safer operation. (Rus, 2021)

C. Acceptable region (Below Lower tolerable limit)

With the intervention of the direct and indirect cost factors, for the positioning of the acceptable range, the threshold may differ. The variance of the region may differ with respect to the capability of the organization to manage the secondary costs.

In retrospect, the experimental design could be developed in such a way as to model the variance of the upper tolerable threshold and lower tolerable threshold.

V. EXPERIMENTAL DESIGN

The following assumptions have been made in the derivation of a calculable model for the subject conditions.

i. The unacceptable region cannot be reduced from a set point due to the set hazardous margins by the manufacturer and unavoidable safety risks taken in general operations.
ii. The acceptable region cannot be zero as it is improbable to reach a hundred percent safe operational conditions.

The cost factor of the aircraft operation directly incorporates with the safety cost against the marginal profit towards the same. In set conditions higher profit margin will provide the organization to expand towards its safety expenses. The same conditions may vary among the threshold of risk mitigation without overlooking any and all factors.

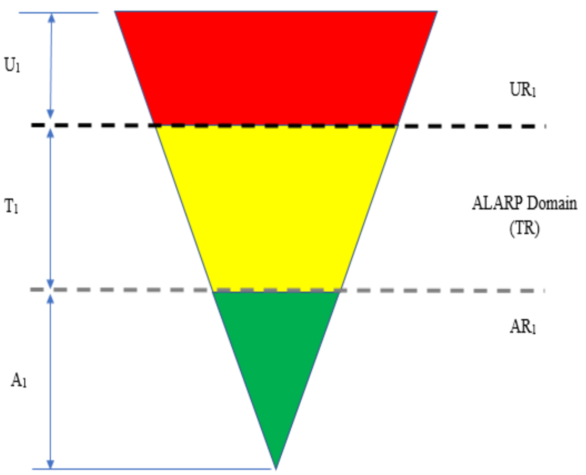
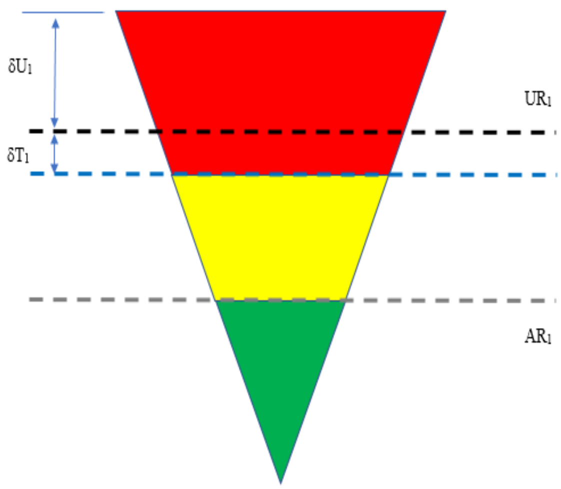
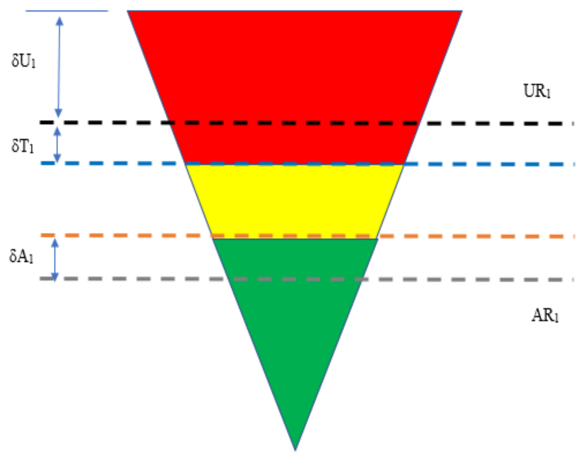
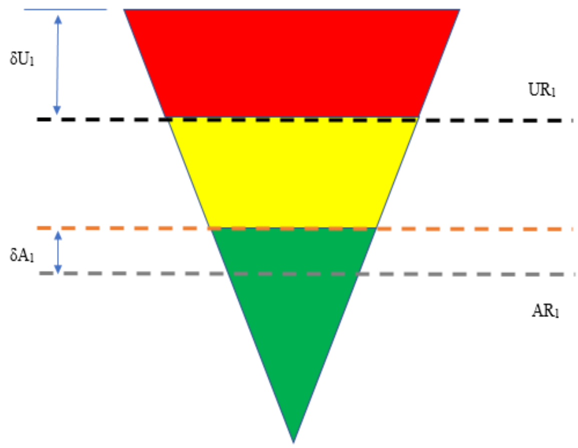
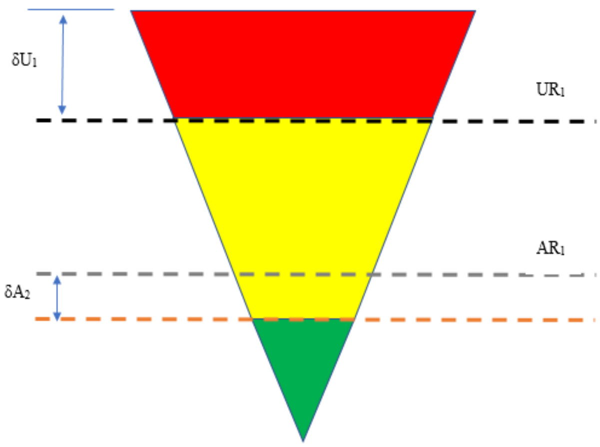
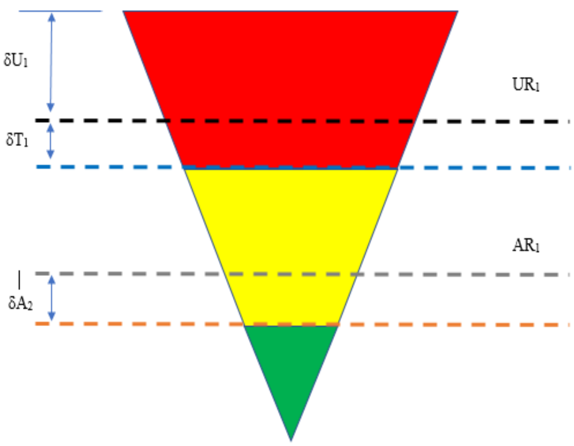
The tolerability segmentation according to the operational safety may differ with respect to the engagement of the airline towards its safety assurance engagement. This could be varying from socio-economic factors to financial stability of the enterprise.

In this study the focus has been towards the general contribution measurment by any scale of airlines to improve its safety. The contributing factor considered is the cost benefit towards tolerability region variation.

Prior to addressing the cost factor the tolerability variance is studied in this stage crossfitting the first two objectives as prior mentioned. Further, the qualitative cost condition is introduced to support the third objective of the study.

The variance of tolerability ranges can be signified under the following five conditions as per Table 3. While benchmarking the generalized model as per Figure 2, the differentiation between the conditions has been mathematically promoted by specifying the ALARP range in accordance with Table 3.

Table 3. Risk tolerance conditions

Generic Tolerance Levels	Condition 1
	
Condition 2	**Condition 3**
	
Condition 4	**Condition 5**
	

K. Nomenclature

UR_1 –Unacceptable Region tolerance level
TR (T_1) – Tolerance Range (ALARP Domain)
AR_1 – Acceptable Range tolerance level
U_1 – Unacceptable Range
A_1 – Acceptable Range

δU_1 – The change in Unacceptable Range
δT_1 – The change in Unacceptable Region tolerance level
δA_1 – The negative change in Acceptable level
δA_2 – The positive change in Acceptable level

L. Derivation

Considering the two base levels of ALARP Domain,

From UR1 base level δT_1 as (↓ +)

From AR1 base level δA_2 as (↓ +) and δA_1 as (↑-)

$$f(TR) = T_1, \delta T_1, \delta A_1, \delta A_2 \text{ .... } (1)$$

$$\delta T_1 \geq 0 \text{ .... } (2)$$

From generic ALARP principle,

$$AR_1 - UR_1 = TR \text{ .... } (3)$$

From eqn (1), eqn (2) and eqn (3)

For Condition 1,

$$TR = T_1 - \delta T_1 \text{ ....} (4)$$

The primary means of variance for the generic model can be the increase of the unacceptable range while promoting a constant acceptable range. This will impact directly on the cost of safety depicting the limited expenditure and high liability.

For Condition 2,

$$TR = T_1 - (\delta T_1 - \delta A_1) \text{ .... } (5)$$

The equilibrium state of the cost and tolerance can be depicted in this condition. The increase of unacceptable range and the safety cost that need to overcome the same may be balanced off. This can be done through the profitability incurred by increase of acceptable region in secondary means.

For Condition 3,

$$TR = T_1 + \delta A_1 \text{ ....} (6)$$

With respect to safety wise secondary profit making the condition provide the best approach an airline may reach. The increase in acceptable range while sustaining the unacceptable range of generic operation depicts pure profit.

For Condition 4,

$$TR = T_1 + \delta A_2 \text{ .... } (7)$$

The initial condition of loss making portrays substantially from the reduction of the acceptable range while the unacceptable range stays consistent. This interprets the inability to generate revenue to support safety cost.

For Condition 5,

$$TR = T_1 - (\delta T_1 - \delta A_2) \text{ .... } (8)$$

The poorest condition in terms of cost vs safety tolerance is contrasted by the increase of unacceptable region and the reduction of acceptable region. The unattainable safety cost with respect to revenue generation devices the scenario to be addressed under excessive means through cost benefit analysis.

Assuming,

$$|\delta A_2| = |-\delta A_1| = \delta A \text{ .... } (9)$$

The general equation without the cost factor can be written as,

$$TR = T_1 - (\delta T_1 - \delta A) \text{ .... } (10)$$

VI. DISCUSSION

The dominant factor of tolerance range variation with cost need to be derived with respect to each scenario and the type of operational properties. The derived general equation denotes the overall tolerance range of all scales of operators. This contemplates the optimal reference range to be the ALARP.

The forthcoming study will expand towards cost clustering towards safety expenses integrating with the generalized tolerance.

A. Cost Interaction

The cost interaction can be primarily derived among the tolerance regions with respect to the primary as well as secondary costs. Which could further clarify into safety assurance costs and post-incident costs.

i. Primary Costs

The costs pertaining to operation, quality, maintenance, labour, and Lease & Depreciation can be entailed as primary costs in aviation. In all these aspects the safety cost of each is intertwined with the overall amount.

ii. Secondary Costs

The secondary costs occur in inefficient utilization of primary costs. These cannot be depicted directly in books but will reflect in long term financial performance and brand competition of the organization.

Some of the major secondary costs can be named as customer satisfaction, quality of operation, consumer confidence, and environmental effect.

The introduction of better exploitation of safety costs incorporated with the primary costs converges into reduction of the negative effect on the secondary costs.

iii. Safety Assurance Costs

In terms of safety assurance, the expenses an airline is willing to spend may differ on number of conformities. Safety assurance under each cost frame of the primary items may differ with company policies. This will develop the said generic tolerance levels that company will incorporate towards its operations. Which in terms depicts the company engagement in risk mitigation.

iv. Post-incident Costs

The post-incident cost does not necessarily mean the recovery of incidents or accident in which it is not only the turnaround or compensation. But the cost of recovery from a market breakdown and consumer contradiction.

B. Integration to Tolerance Levels

The overall ideology on the safety cost and tolerance ranges contrasts the following;

i. Unacceptable range

The higher the organization invests on the critical safety conditions the more stable the unavoidable safety hazards become. Which will then be limited to the safety threshold where any and all flights has to bargain in operation.

ii. Tolerable Region

The optimal variability stands on the tolerable region with respect to safety cost. This region is prone to the intentional variation of the operator with respect to the revenue generated.

iii. Acceptable Range

The increase of acceptable range brings the best option for the organization as it evidently brings the capita to cover the safety cost as well as reducing the secondary cost by developing consumer confidence on the brand.

VII. CONCLUSION

The aviation safety tolerance is directly intrigued by the cost of safety the organization is willing to spend. Which in ethical means, safety has been delivered as a vague unit. The Implied Cost of Averting Fatality (ICAF) is the key consideration in aviation where a certain level of risk being persevere towards economic gain.

Due to the vague nature of safety the optimization of the tolerance levels is critical.

The price worth paying concept demarks the ALARP principle for the range of tolerance.

Thus, the change in the safety tolerance levels can be optimized through the inclusion of cost to general equation through quantitative modelling under real time data simulation benchmarking residual.
The importance of enhancing the ALARP over the acceptable range with respect to cost could be promoted in qualitative means. This may validate through cost benefit analysis in a further macro scale.

This framework can be concluded as cost of achieving optimal life safety through risk reduction.

VIII. FUTURE STUDY

The introduction of cost factors when promulgating safety can be rationalized by identifying the correlation of cost of safety assurance. Thus, future study can be carried out by quantitatively analysing the cost of achieving different levels of safety assurance.

Furthermore, insurable expense reduction can be calculated by risk liability management analysis. This could be curated by considering the surreal norm of post-accident assurance in aviation safety managment.

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