

Safety Risk Aggregation: The Bigger Picture

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ABSTRACT

This paper discusses what Risk Aggregation means in the context of Safety Management. It identifies six different types of “Risk Aggregation”, each with a different purpose. The paper considers who should be interested in Safety Risk Aggregation and identifies a range of measures of Aggregated Risk and techniques available. It also discusses some possible problems with Safety Risk Aggregation.

ACKNOWLEDGEMENT

Much of the content of this paper was developed while the author was providing support to MoD’s Safety Improvement Programme. MoD has kindly given permission for this material to be shared with the wider community of Safety professionals.

INTRODUCTION

Before the credit crunch most of the banking whiz kids thought they understood the risks associated with their clever financial instruments. But despite complicated risk models, they didn’t really grasp the interaction and dependency of seemingly separate risks. Perhaps their senior managers were convinced by the precision used when risk estimates were presented to them. For whatever reason, they didn’t ask the right questions and didn’t appreciate the bigger risk picture.

For risks of any type, it is important for decision makers to see more than just a mass of detailed information: they should understand the context of the separate risks, how they might interact and their possible cumulative effects.

WHAT IS “RISK AGGREGATION” ?

Risk Management Vocabulary (2008) [1] includes the following definition:

risk aggregation: process to identify and illustrate the interaction of several, differently correlated individual risks of an organization in order to obtain the overall risk

The purpose of Safety Risk Aggregation is to provide a more complete picture of the Risks posed by a system, or Risks faced by an individual or group of people or an organisation, than is given by considering possible Accidents one at a time.

If managers or Risk Acceptance Authorities consider Risks of Accidents only one at a time (hereafter called “Single Risks”¹), then they will not have an adequate appreciation of the context or implications of that information. Risk decisions should be taken with a good understanding of the total risk of an activity and/or total risk to a person or group of people or an organisation.

“Risk Aggregation” is a concept that can be relevant at various levels in Safety Management. For example, this paper identifies the following six situations where some type of Risk Aggregation may be appropriate:

- **Type 1:** Aggregating Risks for a “Single Risk” where multiple outcomes are possible (e.g. fire – consequence can range from no harm to multiple fatalities, with each outcome having a different likelihood),
- **Type 2:** Aggregating Risks to an individual or group of people from a range of possible Accidents or Activities or Systems;
- **Type 3:** Aggregating Risks for all the possible Accidents that a System might cause;
- **Type 4:** Aggregating Risks for all the Systems / Facilities / Operations within an organisation;
- **Type 5:** Aggregating Risks for multiple Systems functioning together (e.g. “System of Systems”);
- **Type 6:** Aggregating Risks for multiple Systems that may not be independent (e.g. due to “Domino Effects” or “Common Causes”).

Terms Related to Risk Aggregation

There are several terms in use which have a similar meaning to “Risk Aggregation” or “Aggregate Risk”. These include:

- **“Risk Accumulation”** and **“Cumulative Risk”**. “Accumulation” is a term used in a very similar way to “Aggregation” but it should be noted that “Cumulative Risk” can also be used in human health or environmental assessments to refer to the combined threats from exposure via all relevant routes to multiple stressors including biological, chemical, physical, and psychosocial entities.
- **“Total System Risk”** The author understands that although the term “Total System Risk” had been included in the December 2005 working draft of US MIL-STD-882E [4], it is currently intended to continue using 882D [5]. Instead, the topic is covered in Draft US Industry Standard [6] which has the following definition “Total system risk (R). An expression of overall system risk, comprising the combined separate properties of all partial risks.”

¹ The term “Single Risks” is used in this paper in preference to “Individual Risks” to avoid confusion with the level of risk of death an individual is exposed to as the result of an activity or operation. “Single Hazards” is used by some people, but is not considered appropriate, because several Hazards may be involved in the Accident Sequence leading to the outcome of interest. The UK Treasury Orange Book on general Risk Management [2] uses “Specific Risks” for a similar concept, and Ekholm [3] uses “Partial Risks” but none of these terms is defined.

- **“Risk Profile”** has several different definitions in different documents.
 - In [1] as “description of a set of risks”;
 - In HM Treasury Orange Book [2] as “the documented and prioritised overall assessment of the range of specific risks faced by the organisation”;
 - In LUL QRA Update, 2001 [7] as “a graphical representation of the risk attributed to each Top Event. It allows the dominant Top Events (i.e. major hazards) to be easily determined.”
- **“Integrated Risk Picture”** EUROCONTROL have developed a series of models covering the gate-to-gate Air Traffic Management (ATM) cycle for civil aviation (see [8]). The models currently use Fault Trees, Event Trees and Influence Diagrams. The “Integrated Risk Picture” is the output of these models and it represents the overall contribution of ATM to aviation risk and the relative importance of different accident categories, and the causal factors underlying the ATM contribution to risk.
- **“Combination of Risks”** Ref. [9] notes that the “Defining Risk Criteria phase” includes (inter alia) “whether and how combinations of risks will be taken into account.” However, this draft Standard provides no further information on how this might be done.
- **“Potential Equivalent Fatality”** The UK Railways Yellow Book [10] describes this convention for aggregating harm to people by regarding major and minor injuries as being equivalent to a certain fraction of a fatality. Other sectors also use similar approaches and similar relative values.
- **“Hazard Footprint”** is defined in MoD’s JSP 430 [11] as “A statement summarising hazards identified within a safety case, the full mitigation of which is outside the control of a Duty Holder and likely to affect third parties. This concept helps to communicate the effects of hazards or accident sequences and their implications for third parties. The format of this communication will cover both consequences (under the precautionary principle) and the estimated risks (under the proportionality principle).” JSP 430 states “The concept of hazard footprints has been developed to facilitate the consideration of risks for a mobile system or platform and between equipment/systems and platforms, which may interact with their surroundings, under different contexts and operational scenarios. These interactions may include risks to naval bases or commercial ports in the UK or Overseas; Sites of Special Scientific Interest (SSSI); risks which impact on or threaten operations at sea or friendly foreign vessels (especially during military operations, which should be subject to Operational Analysis). The Platform Duty Holder should provide safety case reports with the necessary information and advice on their ship’s ‘hazard footprint’ to the shore-based Duty Holder or second/third-party ship Duty Holders.”

- “**Organisational Risk Profile**”. Although the term is not defined in the AS/NZS Risk Management Standard and Handbook [12] & [13], the handbook does state: “at a strategic level, broad categories of risk may be identified and analysed to provide an organizational risk profile that shows important issues for which management systems and risk treatments need to be established.”

WHY AGGREGATE SAFETY RISKS ?

The reasons why it may be useful to consider aggregated measures of safety risk include the following:

- To avoid inaccurate Risk Estimates made through over-simplification. For example, taking Worst Cases for both the likelihood and severity when estimating the Risk of an Accident type that may have a range of outcomes. This can lead to inconsistency in the Risk Assessment and inappropriate allocation of risk reduction resources. [**Type 1** Aggregation]
- To compare Risk estimates with Requirements or Targets expressed in terms of overall Risk. For example the Individual Risk of fatality per year (IR) criteria of 1×10^{-3} , 1×10^{-4} or 1×10^{-6} from HSE’s document R2P2 [14] relate to the total exposure to Risks from all work-related sources and not to “Single Risks” one at a time. [**Type 2** Aggregation]
- To compare Risk estimates with Requirements or Targets expressed in terms of overall System Risk (e.g. Platform Loss). **OR** To provide a context for the consideration of Risk estimates for “Single Risks” so that their wider significance can be appreciated. [**Type 3** Aggregation]
- To consider the total Exposure to Loss which an organisation faces across its portfolio of Systems/Facilities/Operations. [**Type 4** Aggregation]
- To understand the Safety consequences of multiple Systems functioning together, where the interactions affect the Hazard and Accident types, their Likelihoods and Consequences. [**Type 5** Aggregation]
- To understand the Safety vulnerability of multiple Systems that may be simultaneously affected by dependent events or “domino effects”. [**Type 6** Aggregation]

ALARP Arguments & Risk Aggregation

The UK Health & Safety at Work etc Act (HSWA) 1974 [15] requires that any safety risk must be reduced So Far As Is Reasonably Practicable (SFAIRP). The UK HSE considers that this will be achieved if the risks are reduced to a level that is As Low As is Reasonably Practicable (ALARP).

HSE have published the following diagram in R2P2 [14]:

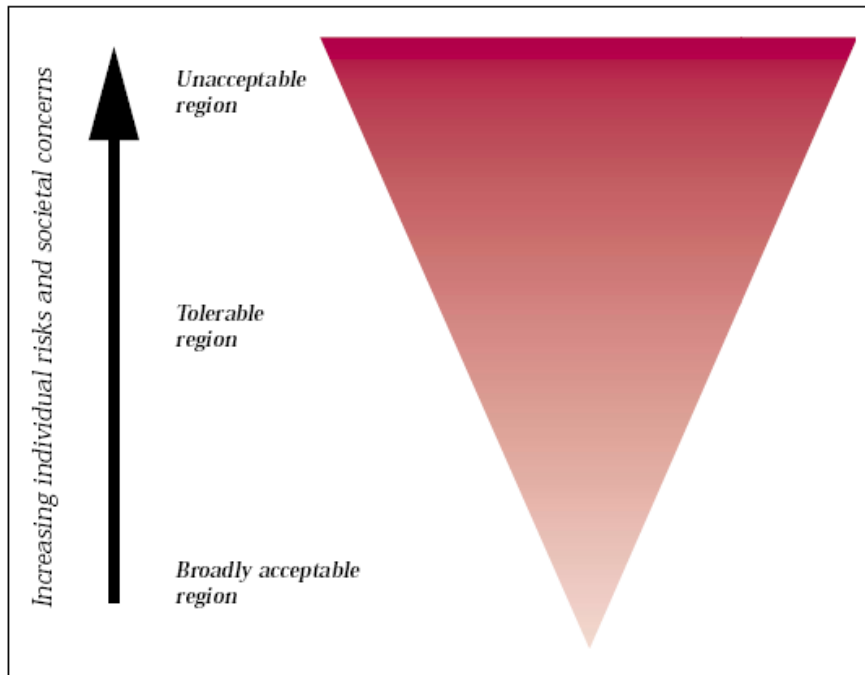


FIGURE 3 – HSE Framework for the Tolerability of Risk

Ref. [14]. Includes the following:

HSE when regulating will consider that normally risk reduction action can be taken using good practice as a baseline – the working assumption being that the appropriate balance between costs and risks was struck when the good practice was formally adopted and the good practice then adopted is not out of date. However, there will be cases where some form of computation between costs and risks will form part of the decision-making process. Typical examples include major investments in safety measures where good practice is not established.

One of HSE’s principles stated in R2P2 [14] is that:

there should be a transparent bias on the side of health and safety. For duty holders, the test of ‘gross disproportion’ implies that, at least, there is a need to err on the side of safety in the computation of health and safety costs and benefits.

Where Cost-Benefit Analysis is used to justify that Risks are ALARP, there is a need to apply a “Disproportion Factor” (DF) which reflects this “bias on the side of health and safety”. In consideration of what DF should be considered appropriate, HSE have said:

Although there is no authoritative case law which considers the question, we believe it is right that the greater the risk: the higher the proportion may

be before being considered 'gross'. But the disproportion must always be gross.

"HSE has not formulated an algorithm which can be used to determine the proportion factor for a given level of risk. The extent of the bias must be argued in the light of all the circumstances. It may be possible to come to a view in particular circumstances by examining what factor has been applied in comparable circumstances elsewhere to that kind of hazard or in that particular industry.

Taking greater account of the benefits as the risk increases also compensates to some extent for imprecision in the comparison of costs and the benefits. It again errs on the side of safety, since the consequences of the imprecision have greater impact, in terms of the degree of unanticipated death and injury, as the level of risk rises.

Widespread practice is for the value of the Disproportion Factor (DF) to increase for Risks further away from the Broadly Acceptable region. Generally DF values between 1 and 10 are used, as illustrated in Figure 2 below.

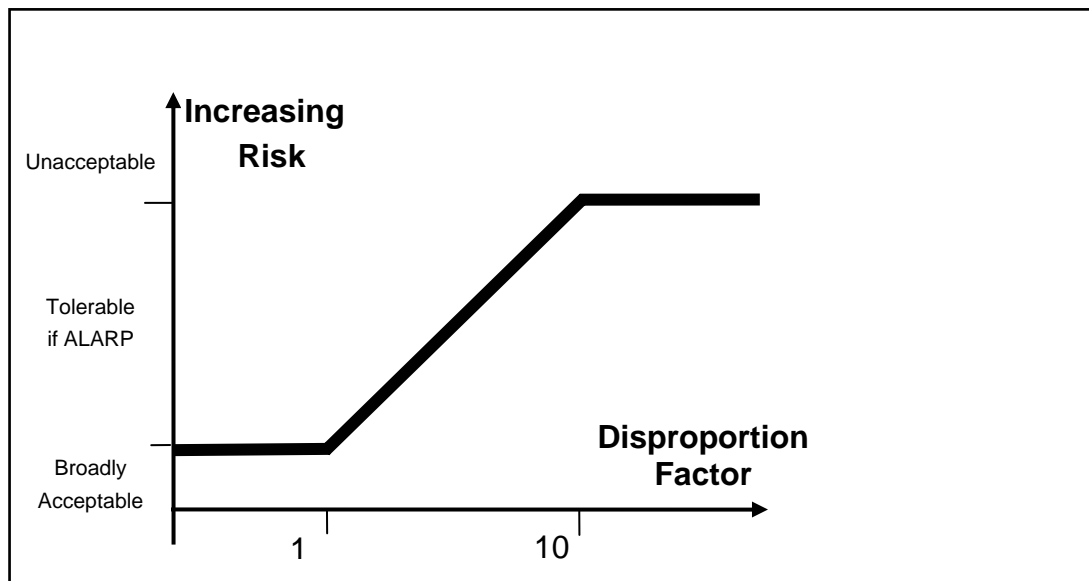


FIGURE 2 – Example of how DF for CBA ALARP Arguments Increases with Risk

It should be noted that Gross Disproportion only applies legally to the human aspects of the possible loss (the fatalities and injuries). It does not apply to other elements such as financial loss, asset damage or reputation degradation.

If 'single risks' are compared with risk tolerability criteria defined for overall risk (e.g. total individual risk per working year), then they will seem to be much more acceptable than they should be. If there are several 'single risks', then each may separately seem to be 'broadly acceptable' whereas the individual

is exposed to an overall risk that should be judged only 'tolerable', or even 'unacceptable'.

Furthermore, if ALARP arguments based on Cost Benefit Analysis (CBA) are made for 'single risks' without appreciating the aggregated risk, too low a Disproportion Factor (DF) will be used and incorrect decisions may be reached to reject risk reduction measures as being 'grossly disproportionate'. Where ALARP arguments based on CBA are made, they should be based on the aggregated risk, compared against the appropriate criteria for overall risk.

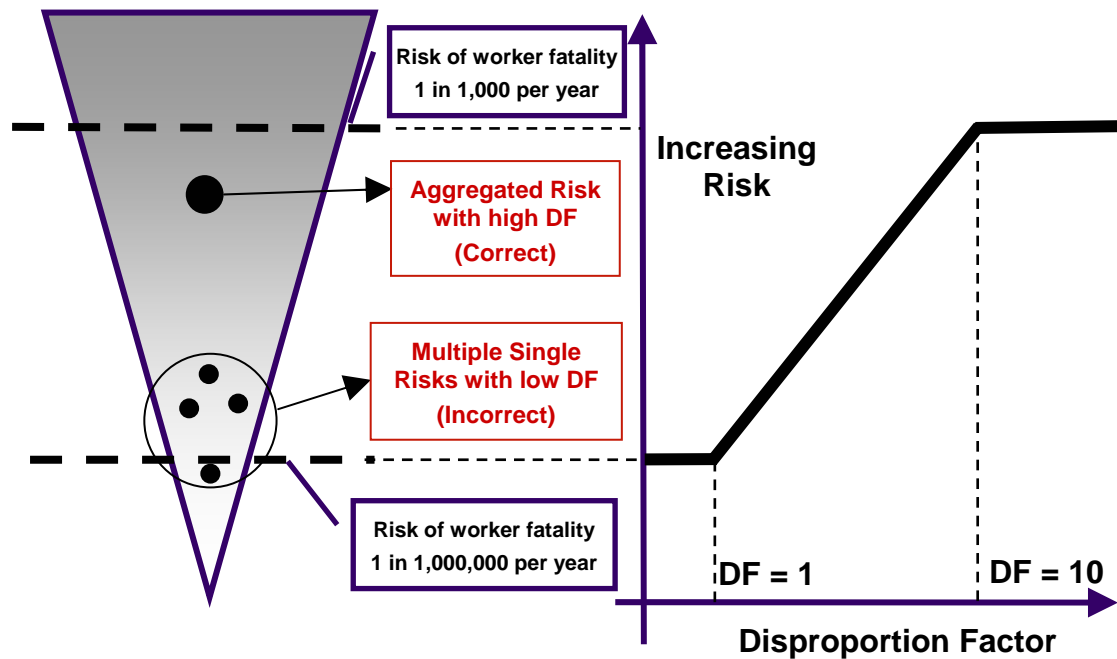


FIGURE 3 – Comparing Single Risks with Overall Criteria Gives Misleading Tolerability and Incorrect Disproportion Factor

It is noted that comparing the aggregated risk (if known) against overall risk criteria will provide a DF that should be used for CBA on any safety improvements that are being considered. It is the absolute position of the overall risk that determines the DF, rather than that of a 'single risk'. It is the incremental improvement in the aggregated risk that is of interest, rather than the change in the 'single risk' issue. These incremental improvements may be the same, but they could be different if one safety improvement affects more than one 'single risk'.

“Risk Referral” & “Single Risks”

In some sectors, it is common for the Safety Risk of identified possible Accidents to be estimated and then compared separately against a specified threshold of tolerance. If every possible Accident for a System or an Activity falls below the threshold, then the risk for system is judged to be tolerable. Sometimes multiple thresholds may be defined, with the position of each Risk estimate, relative to the thresholds, determining the management level that is authorised to give approval.

The total Risk presented by the System of interest is a parameter that should be understood by Risk Managers and Risk Acceptance Authorities, but it is seldom calculated and presented explicitly. Instead, there may be an implicit assumption that if all of the separate Risks are tolerable, then the total Risk must be tolerable. This assumption may be founded on different views, including the following:

- The Risk thresholds were calculated taking account of the actual or likely number of separate Risks;
- There are a small enough number of separate Risks that aggregating them is unlikely to move the “worst case” Risk estimate sufficiently to place it in a higher Risk category;
- The highest Risk Category of any of the separate Risks represents the System Risk Category.

There is no “correct” definition of what constitutes a “Single Risk”. Different analysts may each define different “Safety Issues” as “Single Risks” (e.g. “Aircraft Loss” and “Controlled Flight Into Terrain” (CFIT) and “CFIT due to Human Error”). At the level of a single System, this is acceptable, providing that Safety issues are being recognised and managed. However, for a Senior Manager, this lack of consistency makes it impossible to have a consistent comparative view of Risks across multiple Systems.

Where Senior Managers need to compare exposure to possible loss across multiple Systems/Facilities/Operations, then they require metrics which can be directly compared. This would give Managers improved appreciation of the context or implications of “Single Risks” and might be presented in terms such as:

- Exposure to Loss (calculated in terms of predicted equivalent fatalities per person-year exposed);
- Exposure to Loss (calculated in terms of number of predicted events in each Severity Category, per person-year exposed);
- Exposure to Loss (calculated in terms of predicted equivalent fatalities per system year or per fleet/inventory year);
- Exposure to Loss (calculated in terms of number of predicted events in each Severity Category, per system year or per fleet/inventory year).

HOW TO AGGREGATE SAFETY RISKS

There are several alternative ways of calculating and presenting the results of Risk Aggregation, each with its own terminology. Table 2 presents example methods for Risk Aggregation, including:

- System Risk Class;
- Risk Profiles / F-N Curves;
- Exposure to Loss:
 - for an Accident that may have several different outcomes;
 - for a Severity Category;

- for a System;
- Total System Risk;
- Total Individual Risk.

Safety Risk Aggregation and Matrices

It should be noted that “Risk Aggregation” is not specifically related to Risk Matrices: there is a need to have an appreciation of overall risk whatever techniques are used to estimate, evaluate, accept and manage Safety Risks.

HSE Research report 2001/063 on Marine Risk Assessment [16] has a section reviewing various techniques and amongst the identified weaknesses of the risk matrix approach it states:

A risk matrix looks at hazards “one at a time” rather than in accumulation, whereas risk decisions should really be based on the total risk of an activity. Potentially many smaller risks can accumulate into an undesirably high total risk, but each smaller one on its own might not warrant risk reduction. As a consequence, risk matrix has the potential to underestimate total risk by ignoring accumulation.

The Draft BS EN Standard on Risk Management [9] reviews methods of Risk Assessment and includes the following limitation for risk matrices:

Risks cannot be aggregated (i.e. one cannot define that a particular number of low risks or a low risk identified a particular number of times is equivalent to a medium risk).

Draft US Industry Standard [6] states that:

Mishap risk assessment matrices are used to assess risks and also to determine who will accept risks. They may also serve as a useful tool to combine the individual risks into a total system risk for the system.

Ref. [6] also provides examples of the matrix approach applied to Total System Risk (TSR) and how TSR criteria can be plotted as “iso-risk” lines using the same severity and probability scales that define matrices (see below). These “iso-risk” lines define decision-making areas associated with an appropriate level of acceptance authority.

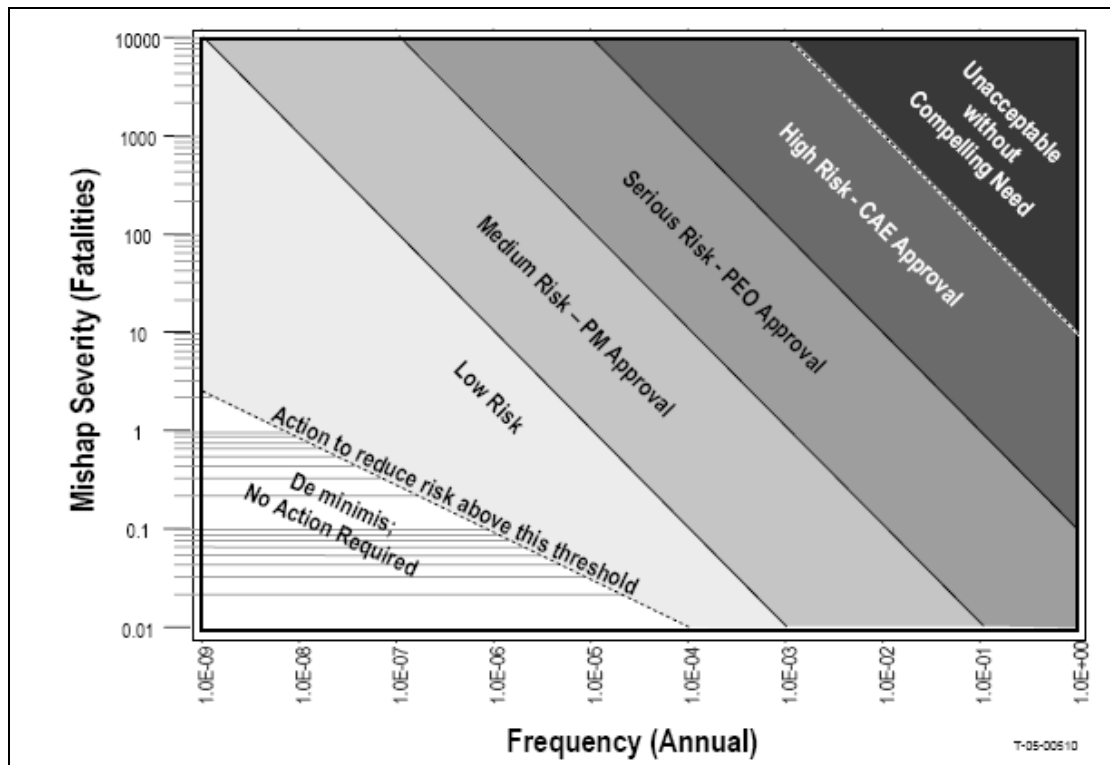


FIGURE 4 – Example “Total System Risk” Assessment Criteria (Ref. [6])

Ref. [6] also identifies the following four possible measures of Total System Risk. Importantly, it notes that “these measures assume summed hazards are totally independent”.

- **Expected loss rate.** This measure computes the severity component as the average loss per system exposure interval that would be realized if numerous copies of the system were operated for numerous life cycles. The probability to be plotted is a value of 1.0 since this method estimates the level of loss that, on average, will happen every time the system is operated for the specified exposure interval.
- **Maximum loss.** This measure assigns the severity component to be plotted as the level of loss corresponding to the most severe single hazard. The probability of maximum loss is computed by dividing the expected loss rate by the maximum loss level.
- **Most probable loss.** To plot this measure, sum the probabilities of hazards at each level of severity. The severity level with the highest probability is the most probable loss. Plot this severity level with a probability computed by dividing the expected loss rate by the most probable loss level.
- **Conditional loss rate.** The probability value is the sum of the probabilities for all hazards. The severity value is the conditional expected loss and is computed by dividing the expected loss rate by the value of the summed probabilities. The result displays the probability that a mishap will occur, and the expected amount of the loss, given that a mishap does occur.

Notwithstanding the quotations from Refs. [16] and [9] above, some sectors do use Risk Matrices to examine the overall Risk posed by a system or an activity. The main ways in which this is done are:

- **Scatter Plot on the Matrix**, simultaneously showing all the “Single Risks”. This is usually examined “by eye” rather than in a quantitative way (see Measure 2b in Table 2);
- **Line Profile on the Matrix** or on a separate Likelihood/Severity diagram. Typically, the likelihood of Single Risks in each Severity column are summed to form representative points in each column, through which a line is drawn (see Measure 2c in Table 2);
- **Total System Risk** (or expected rate of equivalent fatalities), calculated as (b) above, but the different Severity column values are then combined by assuming that major and minor injuries are equivalent to a certain proportion of a fatality (typically 0.1 and 0.01) (see Measure 4 in Table 2).

Table 2 presents the advantages and disadvantages of each of these ways of considering overall Risk.

Risk Profile for an Organisation

Various organisations use some graphical representation of “Risk Profile” to illustrate the range of Risk issues that they face. The information may be based on historical data and/or forward-looking assessments, and in some cases draws on complex models. This allows significant issues to be recognised, communicated and prioritised for action.

For example in the UK Railways sector, the Safety Risk Model (SRM) is owned by the Rail Safety and Standards Board (RSSB). The SRM is a structured representation of the causes and consequences of potential accidents arising from railway operations and maintenance on the railway. It comprises a total of 120 individual computer based models, each representing a type of hazardous event. A hazardous event is defined as an event or an incident that has the potential to result in injuries or fatalities. The SRM is regularly updated in the light of new data and modelling work.

The results of the SRM are published within the 'Profile of Safety Risk on the UK Mainline Railway' (e.g. RSSB's Risk Profile Bulletin [17]). The Risk Profile Bulletin (RPB) provides risk information to assist members of the Railway Group to manage safety effectively, and to inform the Railway Group and the wider railway industry of RSSB's current view of the dominant contributors to risk on the mainline railway.

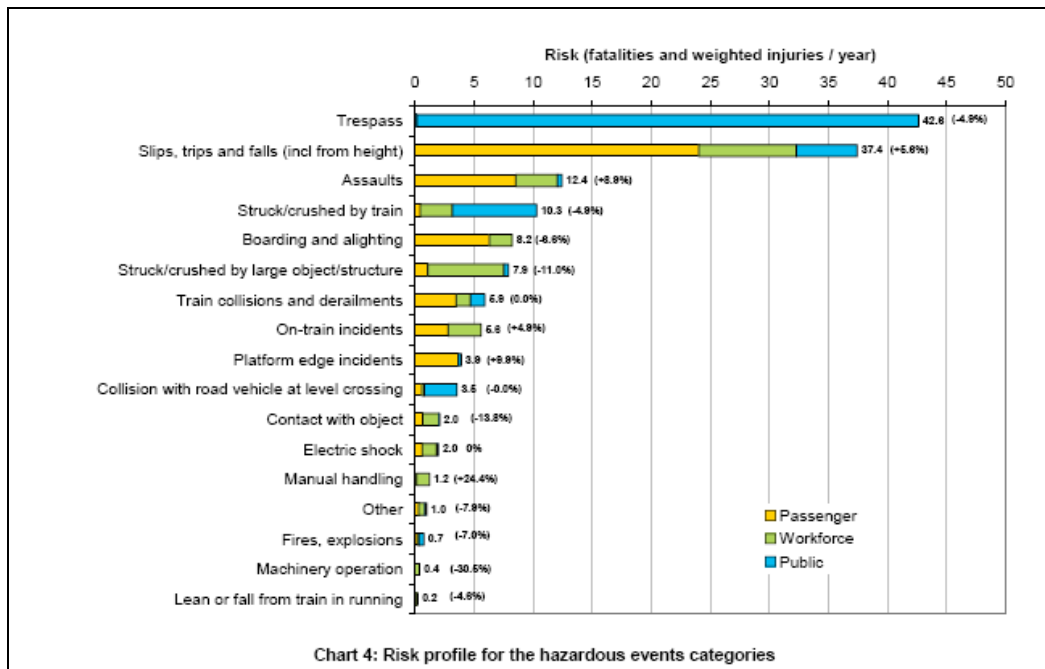


FIGURE 5 – Example Risk Profile Chart from UK Railways Sector

London Underground Ltd (LUL)'s major accident Quantified Risk Assessment (QRA) models help it to understand its risk profile and identify key contributors to that risk. The outputs of these models are used to identify areas for improvement.

The LUL Risk Profiles are presented (e.g. as in LUL QRA Update, 2001 [7]) as bar charts of the contribution of the various standard "Top Events" used in the QRA models. Predicted accident consequences are presented in the Risk Profile in Fatalities and Weighted Injuries (FWI) and so the High Severity/Low Likelihood Risks (e.g. Flooding) can be compared against Medium Severity/Medium Likelihood Risks (e.g. Derailment). F-N Curves are used to illustrate the expected range of accident consequences faced by LUL.

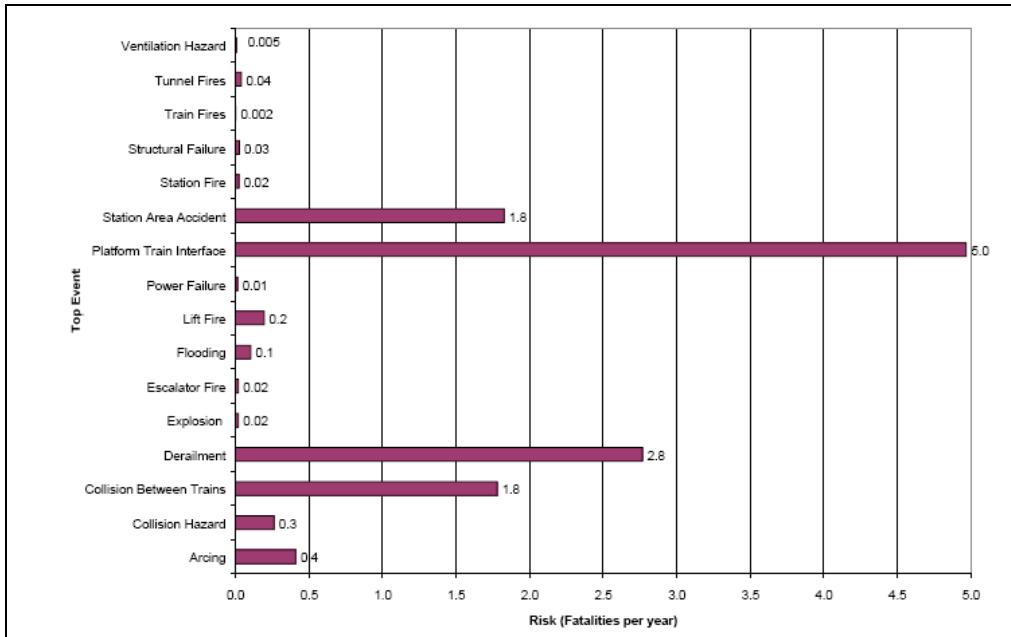


FIGURE 6 – Example Risk Profile Chart from LUL (2001)

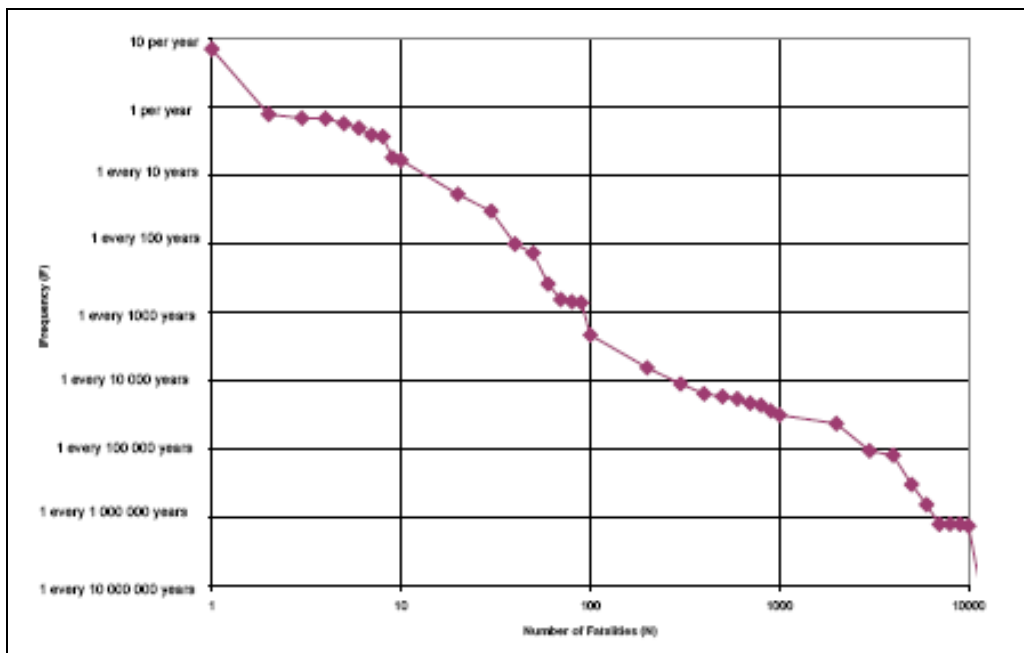


FIGURE 7 – Example F-N Curve from LUL (2001)

Other sectors use different representations of “Risk Profile”. For example, Figure 8 is taken from the European Air Traffic Management sector:

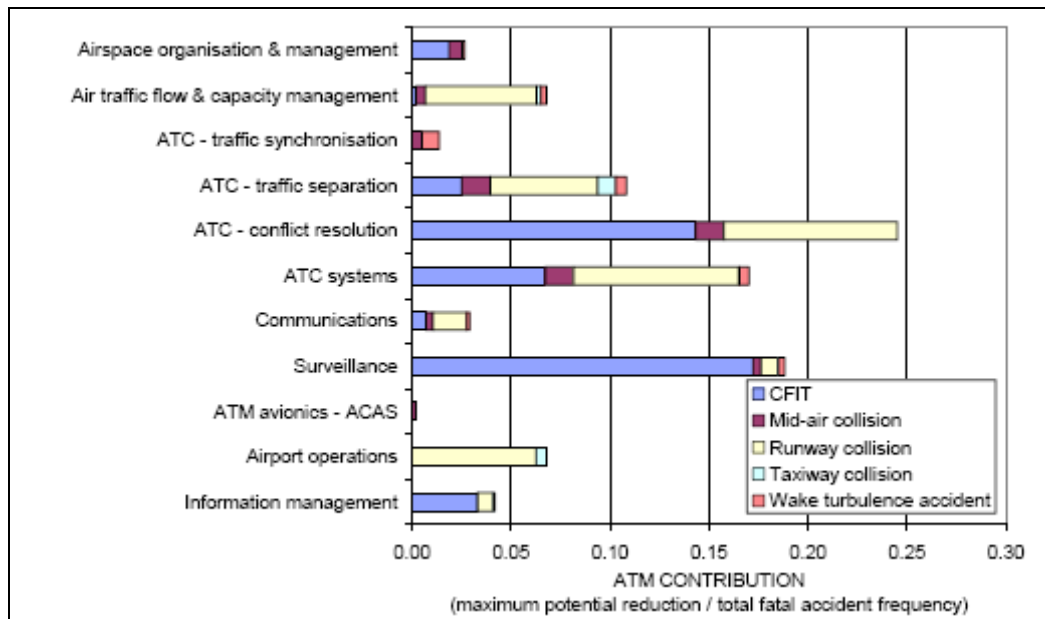


FIGURE 8 – Example “Integrated Risk Picture” from European ATM Sector

The Risk Profile can be used not only to communicate the range of Risk issues faced by an organisation, but also how these may change (a “living risk picture”). For example “What-If ?” model runs may provide modified Risk Profiles, or expert advice may be communicated through a changed profile, representing the expected Risks for a new operation (e.g. production continuing while part of the plant is off-line and hot cutting operations are underway).

It should be noted that Risk Profiles for in-service systems are different in nature to those for Projects at earlier stages of the lifecycle. The former represent the “best estimate” of the Risk profile today (given all the recorded assumptions); the latter represent the “current estimate” of the Risk profile once the system comes into service.

POSSIBLE PROBLEMS WITH AGGREGATION

Aggregation & Information Loss

There are some concerns that “Risk Aggregation” might lead to loss of useful information about Risk. There appear to be two aspects of concern:

- If Senior Managers are presented only with a single piece of information on Risk, then they will not have information on the detail;
- Average measures of the “Exposure to Possible Loss” for Low Likelihood/High Consequence events may look the same as those for High Likelihood/Low Consequence events.

Aggregated measures of Risk should never take the place of detailed information about “Single Risks”. Instead, the appropriate aggregated

measures of Risk should be used by Senior Managers to understand the “big picture” and the context of lower level information.

Some commentators propose that single measures of “Total System Risk” should be used, such as the “expected number of equivalent fatalities per system year.” This obscures important information about the spread of possible Consequences and also fails to represent uncertainty in the estimates. By their nature, frequently occurring harmful events should be well understood in terms of their causes and frequency. Likelihood estimates for very rare events are naturally subject to more uncertainty and the consequences may also be poorly understood. The Senior Managers should be aware of the potential for High Consequence events and associated uncertainty. It is therefore concluded that Aggregated Risk exposure is better expressed as a Profile with “uncertainty” rather than a single number.

Independence & Aggregation

Care must be taken when attempting to combine “Single Risks” that may not be independent. The results of simple summation of likelihood would not be mathematically correct, and might be very misleading, if the causes of those “Single Risks” were connected. This might be due to a range of factors such as the following:

- Shared components or utilities (e.g. GPS feed, emergency response resources);
- Shared human components (e.g. error-prone operator or maintainer);
- Human overload responding to one event makes another Human error more likely;
- Underlying factors (e.g. ageing assets, cutbacks in manpower or training).

Risk Assessments are sometimes based on a large number of “Single Risks”, often because the assessment is done for each separate Hazard. Several Hazards may lead to or cause the same Accident type and they therefore share many of the important factors in the accident sequence (e.g. preventative controls, recovery controls and escalation controls).

Current Good Practice is to recognise this “Many-to-One” or “Many-to-Many” linkage between Hazards and Accidents and to assess Risks at the level of possible Accidents. Modelling techniques such as Bow-tie Analysis, when done well, can take account of dependent failures (e.g. shared components) and shared controls. It is very much harder to quantify the effects of underlying factors, even where these are recognised.

EUROCONTROL’s Integrated Risk Picture ([8] and [18]) takes account of some underlying factors through an influence model covering all accident categories. This represents common causes of apparently separate failures. The output of the influence model is a set of modification factors, which are applied to the frequencies and probabilities of the base events of the Fault Tree models.

Where the underlying assessment is based on a large number of “Single Risks” (e.g. one-to-one Hazard-Accident basis), it is recommended that

Aggregated Risk should be treated with great caution. This is because they are likely to be misleading because they do not address dependency between the “Single Risks”.

It is concluded that Risk Aggregation using any approach is unlikely to represent dependency issues across multiple systems due to underlying factors such as ageing assets, cutbacks in manpower or training. Features such as these must continue to be considered in a qualitative way by Senior Management.

CONCLUSIONS

Good Risk decisions can only be taken with an understanding of the total risk of an activity and/or the total risk exposure to individuals, groups or organisations. Attempts to judge risk significance for each “single Risk” in isolation, can lead to incorrect decisions about tolerability and whether to adopt further risk control measures. Well-presented information about overall Risk, allows significant issues to be recognised, communicated and prioritised for action.

Where Senior Managers need to compare exposure to possible loss across multiple Systems/Facilities/Operations, then they require metrics which can be directly compared. For proper comparison, metrics must consider exposure (e.g. number of people and proportion of the year exposed) as well as expected losses.

It is vital that aggregating Risks should not mask important information about the range of possible outcomes and the uncertainty of risk estimates. For this reason, measures of overall risk should always be used to show the context of estimates about “single Risks”, but not to replace them.

Senior Managers should be aware of the potential for High Consequence events and associated uncertainty. It is therefore concluded that Aggregated Risk exposure is better expressed as a Profile with “uncertainty” rather than a single number.

It is also important to consider the issue of dependency between “single Risks” when aggregating Risk, otherwise the results could be mathematically incorrect, highly misleading and lead to poor decisions.

Senior managers making risk decisions should demand information about bigger picture (“the wood”), in order to appreciate the importance of detailed risk estimates for the many possible separate sources of harm (“the trees” and even “branches” and “twigs”).

Table 1 – Risk Aggregation Types, Purpose and Example Techniques

Risk Aggregation Type	Purpose(s)	Example Techniques
<p>Type 1: Aggregating Risks for a “Single Risk” where multiple outcomes are possible (e.g. fire – consequence can range from no harm to multiple fatalities, with each outcome having a different likelihood)</p>	<p>To avoid inaccurate Risk Estimates made through over-simplification. For example taking Worst cases for both the likelihood and severity when estimating the Risk of an Accident type that may have a range of outcomes. This can lead to inconsistency in the Risk Assessment and inappropriate allocation of risk reduction resources.</p>	<ol style="list-style-type: none"> 1. Event Tree Analysis (ETA) of Accidents with range of Likelihoods & Consequences consolidated by conversion to equivalent fatalities (e.g. Minor Injury = 0.01, Major Injury =0.1). See Refs. [19], [20] & [10] 2. As above, but using Bow-Tie Analysis rather than ETA. 3. As above but using SQEP Stakeholder group to estimate Likelihoods & Consequences for low Impact “Single Risks” (e.g. maximum of one fatality). <p>NB. Any of the techniques above may have the results presented as a single value for “Expected equivalent fatalities” (e.g. Total System Risk method 4 in Table 2), or as separate values in each Consequence category.</p>
<p>Type 2: Aggregating Risks to an individual or group of people from a range of possible Accidents or Activities or Systems</p>	<p>To compare Risk estimates with Requirements or Targets expressed in terms of overall Risk. For example the Individual Risk of fatality per year (IR) criteria of 1×10^{-3}, 1×10^{-4} or 1×10^{-6} from HSE’s document R2P2 (Ref. [4]) relate to the total exposure to Risks from all work-related sources and not to “Single Risks” one at a time.</p>	<ol style="list-style-type: none"> 1. Calculated by summing Risk of fatality for a person or “most-at-risk hypothetical person” from different sources. Presented as a bar chart against Individual Risk criteria or as a Pie-chart. Usually only Risk of Fatalities and not injuries, but considering Major Accident Hazard sources as well as Occupational (job-related) Hazards. See Refs. [10] & [16]. <p>NB. If comparing estimated Individual Risk with Requirements for whole year, then assessment must cover all activities and sources of Risk in the year. If the Requirement is based on an apportionment of an annual figure, then the assumptions must be recorded and justified.</p>

Risk Aggregation Type	Purpose(s)	Example Techniques
<p>Type 3: Aggregating Risks for all the possible Accidents that a System might cause</p>	<p>A. To compare Risk estimates with Requirements or Targets expressed in terms of overall System Risk (e.g. Platform Loss).</p> <p>B. To provide a context for the consideration of Risk estimates for “Single Risks” so that their wider significance can be appreciated.</p>	<ol style="list-style-type: none"> 1. (For purpose A) System Accident Model (e.g. Aircraft Loss Model using large Fault Tree Analysis) to show causes of and dependencies between different sources of Risk. 2. (For purpose B) Simple overview of number and spread of “Single Risks” for a System, for example simultaneously plotted on a Risk Matrix. Additional information may be represented through error bars to show uncertainty of likelihood and/or severity estimates. Range of possible outcomes for each “Single Risk” may be represented by an area rather than a point. 3. (For purpose B) Combination of “Single Risks” for a System, for example rules of thumb for combining all recorded Risks in each Severity column of a Matrix. See Ref. [11] but beware of dependencies between Risks and the need to consider appropriate apportioned Risk Target (if relevant). 4. (For purpose B) Techniques and presentation metrics may include: <ul style="list-style-type: none"> • System Risk Class (not preferred by SAS because of inability to generate measure which is absolute and can be cross-compared); • Total System Risk (not preferred by SAS because it obscures key information on Range of Consequences); • Exposure to Loss: <ul style="list-style-type: none"> ○ Predicted equivalent fatalities per person-year exposed; ○ Number of predicted events in each Severity Category, per person-year exposed (Risk Profile) ○ Predicted equivalent fatalities per system year or per fleet/inventory year); ○ Predicted events in each Severity Category, per system year or per fleet/inventory year (Risk profile).
<p>Type 4: Aggregating Risks for all the Systems / Facilities/Operations within an organisation</p>	<p>To consider the total Exposure to Loss which an organisation faces across its portfolio of Systems/Facilities/Operations</p>	<ol style="list-style-type: none"> 1. Techniques and presentation metrics may include Risk Profile for the Organisation or Corporate F-N Curve. See Refs. [7], [17].

Risk Aggregation Type	Purpose(s)	Example Techniques
<p>Type 5: Aggregating Risks for multiple Systems functioning together (e.g. “System of Systems”)</p>	<p>To understand the Safety consequences of multiple Systems functioning together, where the interactions affect the Hazard and Accident types, their Likelihoods and Consequences</p>	<ol style="list-style-type: none"> 1. System Analysis by the Authority responsible for the “System of Systems” and drawing on information provided by Authorities for each of its sub-systems. Sub-system authorities should provide information on Hazards at their sub-system boundary and “Hazard Footprint” in terms of “Consequence Footprint” and “Dependence Footprint”. See Refs. [21], [11].
<p>Type 6 Aggregating Risks for multiple Systems that may not be independent (e.g. due to “Domino Effects” or “Common Causes”).</p>	<p>To understand the Safety vulnerability of multiple Systems that may be simultaneously affected by dependent events or “domino effects.”</p>	<ol style="list-style-type: none"> 1. Consideration of Domain effects through Zonal Analysis. See Ref. [21]. 2. Consideration of Dependent Failures (incl. Common Cause and Common Mode) and representation in FTA or other Analysis. See Ref. [21]. 3. Consideration of “Domino Effects” through “Hazard Footprints”. See Refs. [21] & [11]. Likely to require complex modelling.

Table 2 – Risk Aggregation Measures and Techniques

Measure of Overall or Aggregated Risk	Reference Sources and Technique Description	Advantages	Disadvantages
1. System Risk Class	<p>Def Stan 00-56 Issue 2 [22] Defined as “<i>The highest risk class of the identified accidents associated with a system</i>”</p>	Simple measure (one value from A, B, C or D).	Takes no account of aggregation of Risks from many “Single Risks”. May therefore be very misleading where Hazard Logs contain more than a small number of “Single Risks”. Risk Class measures are not absolute, so cannot be compared across different systems.
2a. F-N Curves	<p>HSE R2P2 [14] BS EN 31010 [9] JSP430 [11] Used when there may be societal concerns arising for systems or facilities with a risk of multiple fatalities occurring in one single event. F-N curves plot the frequency (F) at which such events might kill N or more people, against N. Usually represented on log-log scales, with sloping boundary lines showing the criteria for limits of tolerable and broadly acceptable risks. The technique provides a useful means of comparing the impact profiles of man-made accidents with the equivalent profiles for natural disasters with which society has to live.</p>	Well recognised and widely used technique for Major Accident Hazards. Criteria publish by HSE for limits of Tolerable and Broadly acceptable Risk. Readily understood graphical representation of range of possible outcomes. Directly comparable across multiple systems or facilities.	Does not (on its own) show whether some person or group of people are exposed to Unacceptable levels of Risk. Criteria are directly applicable only to risks from major industrial installations and may not be valid for very different types of risk such as flooding from a burst dam or crushing from crowds in sports stadia. Likely to require detailed assessment and modelling of possible major accidents, for which data may be sparse, and understanding of distribution of people who may be affected.
2b. Risk Profile (scatter plot on Severity-Likelihood diagram)	<p>US Paper on Summing Risk [19] Typically, Risk Estimate results for all identified “Single Risks” are plotted simultaneously on a Risk Matrix or on a Severity-Likelihood diagram.</p>	Readily understood by those familiar with Risk Matrices. Distinguishes between High Severity and Low Severity outcomes.	Users of Scatter Plot required to intuitively comprehend significance of multiple points on a single diagram. Assumes that each “Single Risk” is an independent event.

Measure of Overall or Aggregated Risk	Reference Sources and Technique Description	Advantages	Disadvantages
2c. Risk Profile (line plot on Severity-Likelihood diagram)	US Paper on Summing Risk [19] Typically, Risk Matrix results are summed in each Severity Category and a single Likelihood point calculated as equivalent of the aggregate. A line is plotted through the points in each Severity Category. The plot may alternatively be shown against Cumulative Frequency (similar to F-N Curves).	Readily understood by those familiar with Risk Matrices. Similar presentation to F-N Curves. Distinguishes between High Severity and Low Severity outcomes.	Summing semi-quantitative values from a Risk Matrix to give a quantitative value. Typically mid-cell values have to assumed. Assumes that each "Single Risk" is an independent event.
2d. Risk Profile (bar-chart of Risk Types)	London Underground QRA [7] LUL Definition - <i>"a Risk Profile is a graphical representation of the risk attributed to each Top Event. It allows the dominant Top Events (i.e. major hazards) to be easily determined."</i> Plots the "expected equivalent fatalities per year" against "Top Event" (e.g. Escalator Fire, Collision, Flooding) Usually shown together with F-N Curve that represents the Consequence range of outcomes (as a single summed plot). Calculated from large FTA models with 16 Top Events and ETA consequence models. (Bow-tie)	Highlights highest contributors to expected sources of fatality. Senior Managers (and others) can see most significant issues). Can combine multiple and single fatality events with major and minor injury events. The model provides a base line measurement of current safety standards against which any proposed change to equipment, procedure, organisation or any other aspect of operation can be judged in terms of its effect on safety.	"Risk" units appear to be "number of (equivalent) fatalities per year", without account of number of people at Risk. Profile alone does not distinguish between High Severity and Low Severity causes. Should therefore always be considered together with F-N Curve.
3a. Exposure to Loss for an Accident that may have several different outcomes	See (4) below for "Total System Risk"		
3b. Exposure to Loss for a Severity Category	US Paper on Summing Risk [19] Typically Risk Matrix results are summed in each Severity Category and a single Likelihood point calculated as equivalent of the aggregate.	Can be applied retrospectively where Risk Matrices already exist. Can be aggregated across multiple Projects (where the same Severity Categories are used) to provide a measure of "Exposure to Loss" at successively higher levels of an organisation.	Summing semi-quantitative values from a Risk Matrix to give a quantitative value. Typically mid-cell values have to assumed. Assumes that each "Single Risk" is an independent event.

Measure of Overall or Aggregated Risk	Reference Sources and Technique Description	Advantages	Disadvantages
3c. Exposure to Loss for a System	Draft US Industry Standard [6] US Paper on Summing Risk [19] As (3b) above, but results for all Severity Categories combined into a single value. Methods of summing Risks include: <ul style="list-style-type: none"> ○ Expected Loss Rate ○ Maximum Loss ○ Most Probable Loss ○ Conditional Loss Rate 	As (3b) above.	As (3b) above. System "Exposure to Loss" value alone does not distinguish between High Severity and Low Severity causes.
4. Total System Risk	Swedish Papers [3] & [20] Draft US Industry Standard [6] For "Single Risk" events with a range of possible outcomes, this method assigns an estimated Likelihood and Severity to each. Using "equivalent fatalities" for serious and minor injuries, an expected number of fatalities is calculated. TSR can be presented in terms of "expected number of equivalent fatalities" (e.g. per system year, per fleet lifetime). For Systems with many "Single Risks", this method is the same as 3c above.	Applicable to "Single Risks" with a range of possible outcomes as well as to whole Systems. Allows "Single Risk" Risk values to be realistic by avoiding over-simplification. For example taking Worst cases for both the likelihood and severity when estimating the Risk of an Accident type with a range of outcomes. Single Value for System Risk can allow comparison across multiple projects. Can combine single fatality events with major and minor injury events. TSR can be used in Cost-Benefit Calculations of possible Risk Reduction measures. Swedes have developed a simple spreadsheet which automates the calculation of "Total System Risk" for "Single Risk" events and aggregates it for whole systems.	Total System Risk value alone does not distinguish between High Severity and Low Severity causes. Comparison across multiple Projects can be very misleading unless care is taken to address exposure time.
5. Total Individual Risk	HSE Paper [16] UK Railways [10] Presented as a bar chart against Individual Risk criteria or as a Pie-chart. Usually only Risk of Fatalities and not injuries, but considering Major Accident Hazard sources as well as Occupational (job-related) Hazards.	Provides quantitative estimate of Individual Risk (e.g. for "most-at-risk hypothetical person"). This value can be compared with published IR Criteria.	Does not address injuries. For Service Personnel it may be very difficult to identify and assess all sources of Risk during a working year if IR Requirements are stated in this way. De3mands Quantitative Risk Assessment where this may not otherwise be necessary.

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