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‘Worst case’ methodology for the initial assessment of societal risk from proposed major accident installations

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Abstract

This paper considers the application of one of the weighted risk indicators used by the Major Hazards Assessment Unit (MHAU) of the Health and Safety Executive (HSE) in formulating advice to local planning authorities on the siting of new major accident hazard installations. In such cases the primary consideration is to ensure that the proposed installation would not be incompatible with existing developments in the vicinity, as identified by the categorisation of the existing developments and the estimation of individual risk values at those developments. In addition a simple methodology, described here, based on MHAU’s ‘‘Risk Integral’’ and a single ‘‘worst case’’ even analysis, is used to enable the societal risk aspects of the hazardous installation to be considered at an early stage of the proposal, and to determine the degree of analysis that will be necessary to enable HSE to give appropriate advice. Crown Copyright © 2000 Published by Elsevier Science B.V. All rights reserved.

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1. Introduction

The use of quantified risk assessment (QRA) methodology is well established for most types of chemical major accident hazard installations. MHAU estimates the residual risk to persons offsite that remains after the risks at the installation or group of installations concerned have been made as low as is reasonably practicable. The usual product of the methodology is a set of individual risk contours for the local area, that is,

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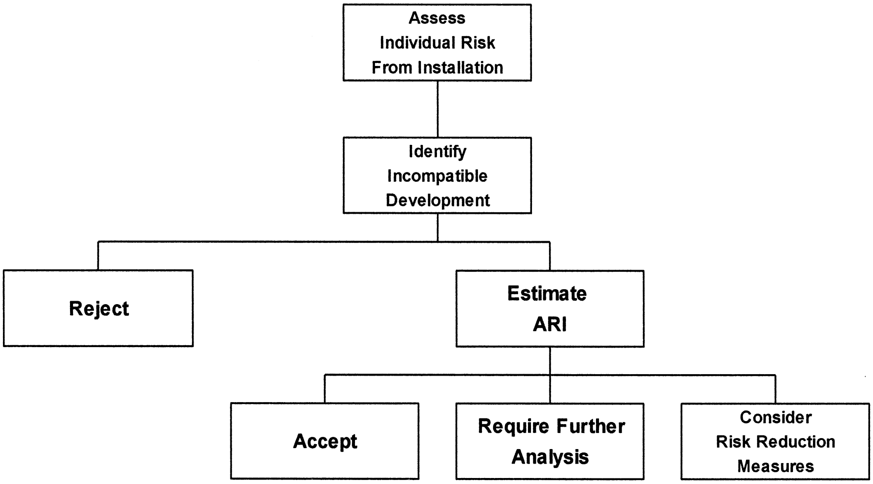

Fig. 1. Strategy for new installations.

lines joining locations of equal risk to a hypothetical house resident who spends all of their time in or in the vicinity of their dwelling. These contours form the basis of Health and Safety Executive's (HSE) advice to planning authorities on future land uses [1].

When HSE is consulted about a proposal for a new hazardous installation, or a significant addition or modification to an existing installation, MHAU first considers whether the proposal is compatible with the existing land uses in the vicinity on the basis of an individual risk assessment. If this is the case, the wider societal risk aspects of the proposal are then considered using a simple methodology called the Approximate Risk Integral (ARI), described here. Only if the societal risk aspects are also acceptable would the HSE not wish to advise against the proposal. Otherwise, further analysis would be appropriate, possibly with consideration of additional risk reduction measures. The approach is summarised in Fig. 1.

Cumulative risks from multiple hazardous installations to a defined community (''local societal risk'') or the entire nation (''national societal risk'') may also be worthy of consideration but are beyond the scope of these methods.

2. Individual risk criteria

The product of an individual risk assessment is a set of contours on a map, representing defined levels of individual risk (currently 10, 1, and 0.3 chances per million (cpm) per year of the hypothetical house resident being exposed to a dangerous dose or worse of the harmful agent). These are used to determine 'inner', 'middle', and 'outer' zones respectively for the purposes of formulating land use planning advice. In some cases, where the risk is from a clearly defined and dominating hazard such as a BLEVE fireball at a small bulk LPG installation, the three zones may be established on the basis of consequence levels alone.

The whole of the area within the three zones is known as the ‘consultation distance’. This is notified to the Local Planning Authority (LPA) which is statutorily required to consult HSE before granting planning permission for most proposed developments of land in that area.

Land use planning policy is based on an objective of keeping incompatible developments apart. However, total separation is normally not feasible and a judgement must be made when proposals for new developments are received. HSE classifies developments into four broad categories; ‘industrial’, ‘shopping or leisure’, ‘housing’ and ‘institutional or sensitive’. Within the inner zone only moderate ‘industrial’ type development and limited numbers of other small developments are not advised against, while within the outer zone, only ‘institutional or sensitive’ developments and very large examples of ‘shopping or leisure’ developments are advised against. Across the middle zone and where developments straddle zone boundaries, each development proposal is considered on its merits. The main factors that are considered are the numbers of persons (particularly members of the public and sensitive communities) that are likely to be present, the intensity of the development, and the level of individual risk, taking into account the likely pattern of use of the development. These types of consideration come within the general description of ‘‘societal or group risk’’, and when estimated for a particular development proposal are called the ‘‘case societal risk’’.

3. The risk integral (RI)

‘‘Societal risk’’ from a chemical major hazard installation is sometimes expressed as the relationship between the number of fatalities N and the frequency f at which precisely N fatalities are predicted to occur. The relationship between f and N (and the corresponding relationship involving F, the cumulative frequency of events causing N or more fatalities) are usually presented graphically on log-log axes. An example plot of f against N and the corresponding plot of F against N are shown in Fig. 2. The example chosen is $f(N) = 100/N^2$, extending up to $N_{\max} = 1000$. In general a relationship of the form $f(N) = A/N^2$ is a good approximation for a liquefied toxic gas installation where the predominant events are highly directional and the numbers affected are strongly influenced by the wide range of possible weather conditions. The corresponding plot of F is seen to have a slope close to -1 over much of its length. Several published F–N plots of chemical establishments follow this example [8].

In principle, the acceptability of a new development could be determined by comparing the plot of f (or F) against N with some agreed criterion line, requiring the plot to be below the criterion line at all points. However, it is known that such comparison can lead to inconsistencies. This can be avoided by replacing the plot of f (or F) against N by a single parameter which integrates the plot in some defined manner, and then requiring the integral parameter to be below a criterion value.

One integral parameter which can be calculated from the f–N plot is the Expectation Value (EV) of f, sometimes called the Expected Number of Fatalities per Year. It is evaluated as:

$$\mathrm{EV} = \sum f(N)N, \text{ summed over all values of } N. \tag{1}$$

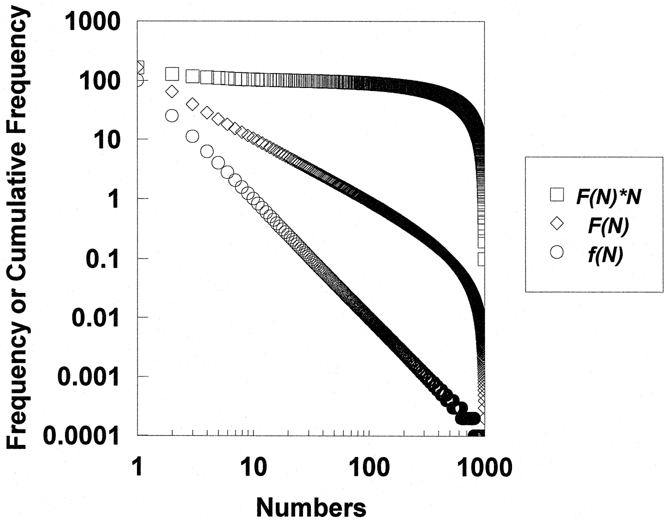

Fig. 2. Frequency and cumulative frequency curves.

It has been shown [3] that the EV is also equal to $\Sigma F(N)$ summed over all values of N, and this proof is reproduced here in Appendix A. So the EV can be interpreted alternatively as the area beneath the plot of F against N.

However, the EV makes no allowance for ‘‘scale aversion’’, so its use would not be compatible with HSE’s current approach to land use planning which ‘‘allows for society’s increasing aversion to large-scale disasters’’ [1].

In considering what allowance is appropriate, we accept that the inclusion of a high degree of aversion into the criteria (or otherwise into the methodology) may not be justified except in specific cases. The specific case that we identify as being appropriate for a level of aversion that is at the high end of the range suggested by others relates to the situation where the persons concerned all or mainly belong to a single ‘‘community’’. This is generally the situation in land use planning cases considered by MHAU (such as housing or community facilities in a particular location). However, MHAU considers that a lower level of aversion, such as suggested in Ref. [7], if any, would be appropriate when considering a proposal to create a facility such as a major transport route in the vicinity of a chemical major hazard installation, where the persons affected by an accidental release would be likely to come from diverse locations.

An alternative view of aversion is that more weight is given to the estimated consequences than the estimated frequencies. In fact, many countries in Europe disregard numerical estimates of frequencies almost completely, as did the UK’s Advisory Committee on Major Hazards in its First Report [4], ‘‘ . . . hazards should be minimised’’. In its Third Report [5] the ACMH states that ‘‘if the possible harm from an incident is high, the risk that the incident might actually happen should be made very low indeed’’.

As already noted, the Expectation Value makes no allowance for scale aversion. MHAU therefore uses a different integral parameter as the basis of its land use planning advice, similar in form to the EV but giving more weight to the consequences of accidents than their frequencies. The integral parameter chosen is called by MHAU the Risk Integral (RI) and is defined as:

$$\mathrm{RI} = \sum F(N)N, \text{ summed over all values of } N. \tag{2}$$

It has been shown [2] that the RI can also be written as $\sum f(N)(N+N^2)/2$, summed over all values of N, and this proof is reproduced here in Appendix B. When the RI is written in this form, the degree of scale aversion within it can be readily compared with the degrees of scale aversion that have been proposed by others. Integral parameters known to MHAU have ranged from $\sum f(N)N^{1.2}$ to $\sum f(N)N^2$. The RI lies within, and towards the upper end of, this range [3].

4. Proposal for a new or modified installation — the approximate RI

As already described above, when considering a proposal for a new or modified chemical installation, MHAU first checks to see that there are no clearly incompatible developments in the vicinity, on the basis of the individual risk based criteria. If there are none, the case societal risk is assessed using the RI.

If the F–N relationship for the proposed installation and the population existing in its vicinity is known, then the RI can be calculated directly from it and compared against a suitable criterion value. However, this is not the usual approach. Performing a full QRA to produce a comprehensive F–N plot is generally not practicable, particularly at an early stage of a proposal when details of the installation may not be known and when the time available for HSE to formulate its views is short. To enable a rapid initial assessment of the case societal risk to be made, a screening tool has been developed called the ARI. The ARI can be used to determine whether the case societal risk aspects of a proposal are immediately acceptable, or whether HSE should advise the LPA that early approval is not appropriate.

Following from its definition, the RI can be interpreted as the area beneath the plot of $F(N)N$ against N. This plot is also shown on Fig. 2, where it can be seen to delineate an area which is approximately rectangular with height $F(1)$ and width $N_{\max}$. So one approximation to the RI is the product of $F(1)$ and $N_{\max}$. This is the definition of the ARI, as previously reported in Ref. [2]. Thus:

$$\mathrm{ARI} = F(1)\,N_{\max}. \tag{3}$$

The ARI follows from the observation that for typical chemicals installations the slope of the F–N plot is close to -1. A reasonable approximation where the maximum hazard potential of the event is clearly defined and determines the maximum number of persons that may be affected (typically omni-directional events, such as fireballs, vapour cloud explosions and vertical jet flames) is to truncate the F–N plot at this maximum point (Fig. 3). In this case the formula for ARI is exact.

In attempting to evaluate the ARI using Eq. (3), it has been found that the practical problems associated with estimating $F(1)$ are excessive, given the requirement for a simple screening tool. It is much easier to estimate the maximum number $N_{\max}$ affected by a ‘‘worst case’’ event along with the likely frequency of that type of event $F(N_{\max})$.

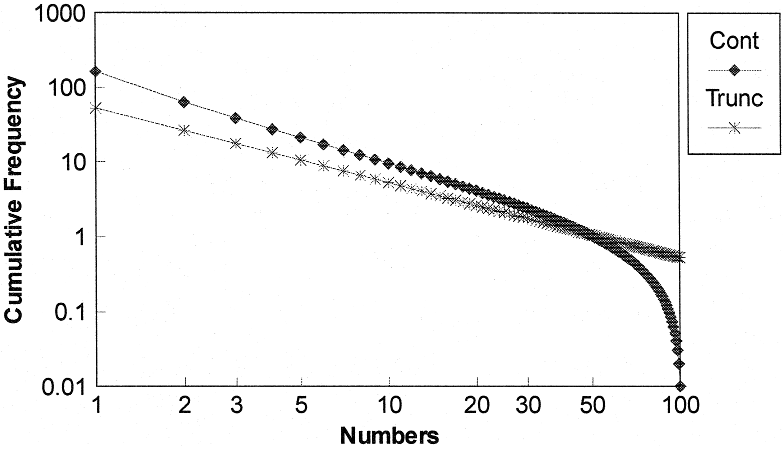

Fig. 3. Continuous and truncated cumulative frequency curves.

If the slope of the F–N plot were exactly -1, then $F(1)$ would be equal to $F(N_{\mathrm{max}})N_{\mathrm{max}}$. Using this to eliminate $F(1)$ from Eq. (3) leads to an alternative formula for the ARI:

$$\mathrm{ARI} = F(N_{\mathrm{max}})N_{\mathrm{max}}^2. \tag{4}$$

The selection of the ''worst case'' event and the estimation of the corresponding frequency has to be considered carefully for the type of installation concerned. Where

Determine "worst case" event

- **Draw LD50 contour**
- **Orientate on map to worst position**

Estimate frequency

Obtain population data

- **Maps, GIS, site visit**

Estimate number of fatalities

Use appropriate formula

Fig. 4. ARI procedure. If the ARI criterion value is exceeded then the case societal risk aspects of the development are significant and a more detailed assessment of the risks would be appropriate, with consideration of additional risk reduction measures.

the event is omni-directional, such as a fireball or vapour cloud explosion, the event is taken as representative of its 'type' and the frequency is estimated for all events of that type.

The defining case for acceptability is a proposal for an installation with a ''worst case'' type of event such as a fireball or vapour cloud explosion causing 10 fatalities at a frequency of 10^{-4} (100 cpm) per year. This value is comparable with the original conclusion of the First Report of the ACMH [4] which recommended that the chance of a serious accident (involving the death of 10 people) at any one major non-nuclear plant should be less than 10^{-4} (100 cpm) per year. This leads to a criterion value of ARI of 10,000 (that is, 100×10^2).

Where the dominating events are subject to orientation and ambient variability (typically unidirectional such as a toxic gas cloud or a flash fire) the ''worst case'' has to be a single defined event, and the frequency is that estimated for the individual event. Appendix C shows that in this case the previous equations $\mathrm{RI} = \sum f(N)(N + N^2)/2$ and $f = A/N^2$ lead to the formula: $\mathrm{RI} = cf(N_{\max})N_{\max}^3$, where c is a function of $N_{\max}$ but may be set to 0.5 as a reasonable approximation. This makes the appropriate formula:

$$\mathrm{ARI} = 0.5\ f(N_{\max})\ N_{\max}^3. \tag{5}$$

5. Method and examples of application

The event frequency for an omni-directional event such as a BLEVE or vapour cloud explosion is the generic event frequency for that type of event, as used in common QRA methodologies such as RISKAT [6].

The event frequency for a unidirectional event such as a toxic gas cloud is determined as: failure frequency, as used in RISKAT [6], × conditional plume probability; × population distribution factor; × weather probability; × directional probability.

The *conditional plume probability* is the relative likelihood of being inside the plume irrespective of direction, and is approximated by the angular width of the plume at the distance corresponding to the maximum width:

$$\frac{2\arctan\left(\frac{\text{max plume halfwidth}}{\text{distance to max plume width}}\right)}{360\text{degrees}}$$

The values are obtained by using the appropriate dispersion model with the cumulative concentration and time value set to that required to give an LD50 including attenuation for indoor population when appropriate (e.g., residential population at night). The number of survivors within the contour is assumed to equal the number of fatalities outside the contour, which will be cautions in most cases.

The *population distribution factor* reflects whether a small deviation in the direction of the plume would produce a significant change in the numbers affected. This may occur where the population of interest is localised and in the far field of the hazard range. Practice has shown that a value ranging from 0.2 to 1 is appropriate for this factor. As the final result is not particularly sensitive to the value chosen, this factor can be judged by visual inspection.

The *weather probability* is the overall likelihood of the type of windspeed and stability combination selected, obtained from statistical weather data for the local area.

The *directional probability* is the relative likelihood of the type of weather selected in the direction of interest. It is also obtained from local weather data and depends on the windrose. The sum of directional probabilities from the all sectors of the same windrose is equal to the number of sectors. The value for the closest sector is generally sufficient for this purpose, but values from the two closest sectors may be proportioned for greater accuracy where there is a major variation between the two sectors.

A summary of the procedure is shown in Figs. 4–7.

6. Example 1: Chlorine

The ‘‘worst case’’ for a bulk liquefied toxic gas installation is significant failure of one of the vessels. For a 25-tonne vessel of chlorine in an open air location, the LD50 contour for stable weather, indoor population, is estimated to be 1900 m long with a maximum width of 1000 m.

The event frequency is determined by: failure frequency × conditional plume probability × population distribution factor × weather probability × directional probability. The failure frequency is 5 cpm per vessel-year (2 cpm for catastrophic vessel failure plus 3 cpm for a large hole in the liquid space with an equivalent hazard range). The conditional plume probability is 2arctan(500/950)/360, that is, 0.15. The population distribution factor is 0.2 for a localised population. Stable night time weather probability

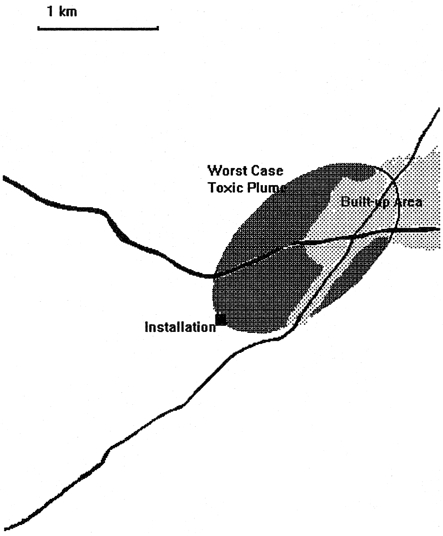

Fig. 5. Chlorine example.

is about 0.14. Directional probability is about 1 depending on the windrose. The specific event frequency is the product of the above, i.e., about 0.02 cpm per year. The appropriate formula for ARI is Eq. (5), $\mathrm{ARI} = 0.5 f(N_{\max}) N_{\max}^3$. So for ARI not to exceed 10,000, $N_{\max}$ must not exceed 100.

In a recent case, it was proposed to replace a chlorine drum storage facility with a single bulk 25-tonne installation in the open air. The proposal was accepted without further analysis of societal risk as no more than 40 houses (or equivalent) were located within the worst case iso-pleth.

7. Example 2: LPG

The ‘‘worst case’’ for a small bulk LPG installation is a BLEVE of the delivery road tanker. For a typical road tanker the omni-directional hazard range (to a thermal dose of 1800 $\mathrm{kW}^{4/3}\mathrm{s}$) is about 100 m.

In a recent case, a Garden Centre was proposed which would receive LPG from such a tanker into small (1 and 2 tonnes) bulk storage tanks. Cylinders of LPG were also to be stored on the site, in quantities sufficient to require consent. The BLEVE frequency for delivery operations was estimated to be 2.9 cpm per year, taking account of the expected frequency of deliveries. The number of persons within the hazard range was estimated to be up to 150, when the Garden Centre was open to members of the public. The appropriate formula for ARI in this case, Eq. (4), is $\mathrm{ARI} = F(N_{\max}) N_{\max}^2$, giving a value of 65,250, well in excess of the criterion value of 10,000. It was therefore not possible to agree the proposal at that stage.

The ARI for the storage vessels alone was found to be 6400, below the criterion value. It was, therefore, concluded that road tanker deliveries should only occur when the site was closed to members of the public, and this was made a condition of consent.

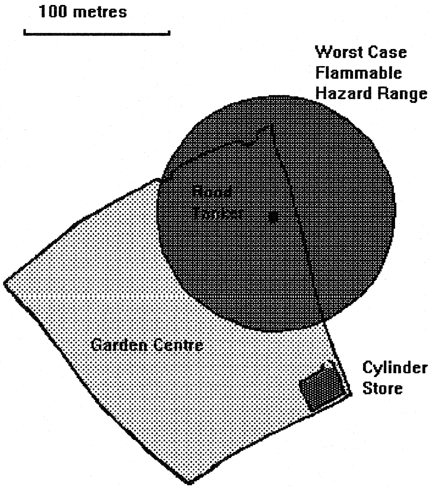

Fig. 6. LPG example.

8. Example 3: ammonium nitrate

The ‘‘worst case’’ for a warehouse containing 300 tonne stacks of bagged ammonium nitrate fertiliser is ‘burn-through’ of a stack in high windspeed (D15) conditions. For a building measuring 130 m × 32 m × 9 m high the LD50 contour for toxic decomposition products is estimated to be 2125 m long with a maximum width of 280 m.

The event frequency is determined by: Fire frequency × conditional plume probability × population distribution factor × weather probability × directional probability. The fire frequency depends on the location and conditions at the warehouse. In a recent case, for a warehouse in a rural location with mixed storage, the frequency of a fire sufficient to result in the ‘‘burn through’’ of a stack of fertiliser was estimated to be 1.2 cpm/year. The conditional plume probability is 0.037. The population distribution factor is 1 for a widely distributed population. 15 m/s or more wind speed probability is about 0.02. Directional probability is about 1 depending on the windrose. The specific event frequency is the product of the above, about 9×10^{-4} cpm/year. The appropriate formula for ARI is $\text{ARI} = 0.5 f(N_{\text{max}}) N_{\text{max}}^3$. So for ARI not to exceed 10,000, N_{max} must not exceed about 280.

For the case in question, N_{max} was estimated using available population data to be about 800. It was therefore not possible to agree the proposal at that stage; in fact, certain risk reduction measures were agreed.

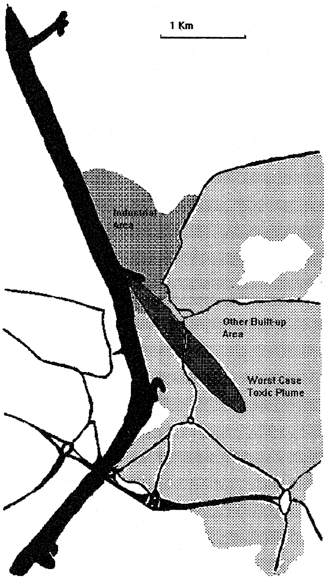

Fig. 7. Ammonium nitrate example.

Appendix A

To show that the EV is equal to $\Sigma F(N)$, summed over all values of N. By definition,

$$\begin{aligned} F(1) &= f(1)+f(2)+f(3)+\dots+f(N_{\max}) \\ F(2) &= f(2)+f(3)+\dots+f(N_{\max}) \\ F(3) &= f(3)+\dots+f(N_{\max}) \\ &\text{and so on until} \\ F(N_{\max}) &= f(N_{\max}). \end{aligned}$$

Adding by columns gives $\Sigma F(N) = f(1)1 + f(2)2 + f(3)3 + \dots + f(N_{\max})N_{\max} = \Sigma f(N)N$, which is the definition of the EV.

Appendix B

To show that $\mathrm{RI} = \Sigma f(N)(N+N^2)/2$, summed over all values of N. Substituting for $F(N)$ in the definition of the $\mathrm{RI} = \Sigma F(N)N$, gives:

$$\begin{aligned} \mathrm{RI} = &\left[f(1)+f(2)+f(3)+\dots+f(N_{\max})\right]1 \\ &+\left[f(2)+f(3)+\dots+f(N_{\max})\right]2 \\ &+\left[f(3)+\dots+f(N_{\max})\right]3 \\ &\text{and so on until} \\ &+\left[f(N_{\max})\right]N_{\max}. \end{aligned}$$

Adding now by columns gives

$$\begin{aligned} \mathrm{RI} = &f(1)1 \\ &+f(2)(1+2) \\ &+f(3)(1+2+3)+ \\ &\text{ and so on until} \\ &+f(N_{\max})(1+2+3+\dots N_{\max}) \\ = &\Sigma f(N)(N)(N+1)/2, \quad \text{as required.} \end{aligned}$$

Appendix C

To show that the plot $f(N) = (A/N^2)$ truncated at $N_{\max}$ has a RI approximately equal to $0.5 f(N_{\max})N_{\max}^3$.

It has been shown above that the RI is equal to $\Sigma f(N)[(N+N^2)/2]$. Substituting the definition of $f(N)$, this is the same as

$$\mathrm{RI} = \Sigma(A/N^2)\left[(N+N^2)/2\right],$$

which simplifies firstly to

$$\mathrm{RI} = \Sigma(A/2)\left[(1/N) + 1\right],$$

and finally to

$$\mathrm{RI} = (A/2)\left\{\Sigma(1/N) + N_{\max}\right\}.$$

It is convenient now to eliminate A using $A = f(N_{\max})N_{\max}^2$, which follows from the equation of the plot. This leads to the expression

$$\mathrm{RI} = cf(N_{\max})N_{\max}^3,$$

where

$$c = 0.5\left[\Sigma(1/N)/N_{\max} + 1\right].$$

The value of c for any value of $N_{\max}$ could be estimated using Euler's approximation:

$$\Sigma(1/N) = 0.5774\ldots + \log_e(N_{\max}).$$

However, evaluation for a range of values, below, shows that for practical purposes c can be set equal to 0.5.

$N_{\max}$	10	30	100	300	> 300
c	0.65	0.57	0.53	0.5	0.5

It is concluded that the RI is approximately equal to $0.5f(N_{\max})N_{\max}^3$, as was to be shown.

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