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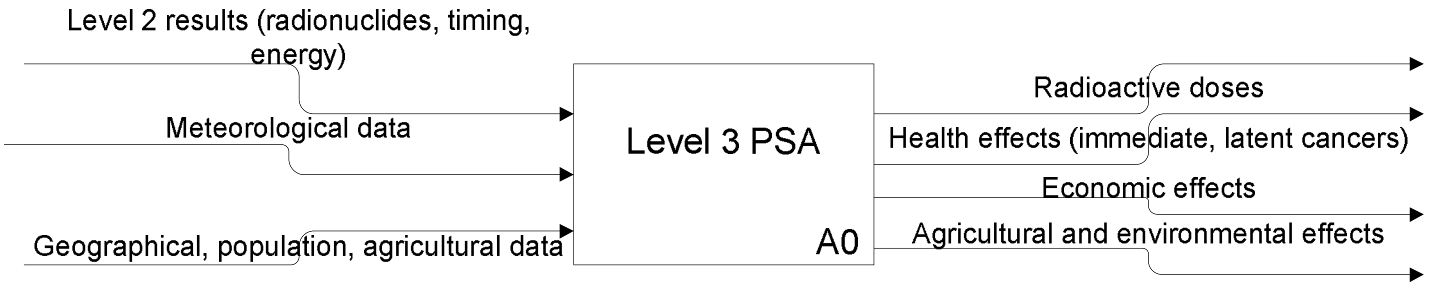

Level 3 PSA from a software architecture point of view

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Summary

This report concerns the data interface between level 2 and level 3 PSA, and how the computations on level 3 should be conducted on a software architecture level. A data interface between level 2 and level 3 PSA is proposed, with special regard to the level 2 code SPSA. The interface is object-oriented, and aimed at giving all the information needed in computing the dispersion of the radioactive substances in a accidental release from a nuclear power plant. On level 3, the data needs, calculations and outputs are summarized. There are several alternatives on how to use software to do level 3 calculations and result presentation. The main alternatives are using existing level 3 codes, utilization of special-purpose software tools (e.g. atmospheric dispersion simulation, uncertainty analysis and data visualization), and construction of a new software. A roadmap for achieving software for level 3 computations is outlined. It is concluded that the main alternatives are to use an existing software, or to utilize generally available tools for each level 3 task and integrate them programmatically by implementing data management, user interface and other services.

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Preface

This report was written as a part of the effort to develop level 3 probabilistic safety analysis (PSA) in the PRADA project, which is a part of The Finnish Research Programme on Nuclear Power Plant Safety 2011 - 2014 (SAFIR-2014). The intent of the report is to aid the development of and application of level 3 software. VTT already has FinPSA for level 1 computations and SPSA for level 2. Software for level 3 will complement these, and together they will provide a complete set of tools for the PSA of nuclear power plants.

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Ilkka Karanta

Contents

1. Introduction

Level 3 probabilistic safety analysis (PSA) concerns the dispersion and effects of a radioactive release resulting from an accident at a nuclear power plant. The classical studies in level 3 analysis are WASH-1400 [21], the deutsche Risikostudie [2], and NUREG-1150 [23]. The analysis, in terms of its inputs and outputs, can be characterized as in figure 1.

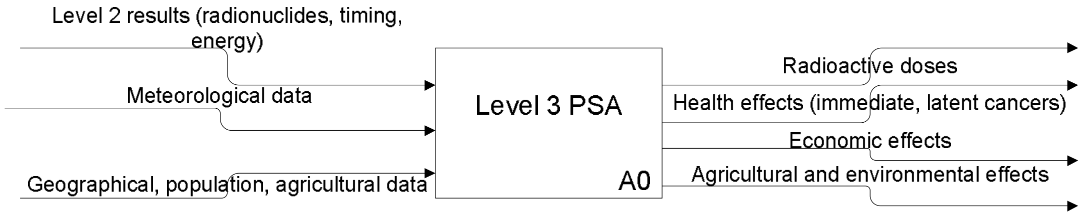

Figure. 1. The inputs and outputs of level 3 PSA

The main input to level 3 is the source terms from level 2 PSA: the amount of different radionuclides, the timing of the leakage and its energy. Currently there are no standardized interfaces between levels 2 and 3; rather, the interface is defined between each pair of level 2 and 3 codes (computer programs).

VTT is currently developing two computer programs related to the probabilistic safety analysis of nuclear power plants. FinPSA is a level 1 code, essentially a fault tree program with capabilities for model creation, analysis, traceability, reporting and information exchange[4]. SPSA [12][13] (Stuk PSA) is a level 2 code, essentially an event tree management and computation program.VTT is in the process of taking charge of FinPSA and SPSA development. As a part of this, the interface between SPSA and level 3 codes, and the role of SPSA on level 3 have to be considered. More generally, the software architecture of level 3 computations needs to be considered. The long-term goal is that VTT would have a complete software suite for level 1-3 computations.

2. Goal

This report aims at exploring alternatives in conducting a level 3 probabilistic safety analysis, and the role that SPSA could take in this. The scope is an architectural one: how to integrate existing methods and software to a meaningful, usable and useful whole. The presentation takes two perspectives:

- an idealized view that considers how the principles of atmospheric physics, meteorology, epidemiology and other sciences could be used to determine the dispersion and its effects, if all relevant information and infinite computational capacity were available. Also the idealized end products of the analysis are considered.
- a practical view that considers how the idealized analysis and results could be approximated taking into account existing data, programs, guidelines and so on. In particular, the data interface to be provided by SPSA is considered.

3. Level 3 PSA in context

In this section, we consider level 3 from a theoretical viewpoint. Thus, the data needs, computations and outputs are viewed from an idealized viewpoint, disregarding the practicalities. A practical treatment is delayed to later sections.

3.1 Interface with level 2

The main output from level 2 to level 3 is the information on the radioactive release. In order to compute the dispersion of the radioactive materials, the following information must be either provided by level 2, or inferred on level 3:

- amount of each radioactive isotope. Preferably this includes mass flow rate or release rate.
- chemical composition. This is not considered to be a significant matter regarding radioactive metals, but plays a large role in determining the effects of radioactive iodine (organic vs. non-organic).
- particle size distribution. In principle this may vary with the chemical compounds present in the particle (and thus bigger particles could have different compounds than the smaller ones).
- energy of the release. The temperature of the aerosol is the main concern, but also convection velocity might be taken into account.
- height of the release from the ground level. If the geometric shape and dimensions of the aperture in the containment were known, the shape of the plume could be computed from this. Also vertical and horizontal direction of the leakage might have an effect. In practice, to relieve computational burden, the aperture can be approximated by a single-point release source, the height from ground level of which is given.

3.2 Other data needs

Level 3 analyses need a varying collection of other data, depending on the purpose of the particular analysis.

Meteorological data is needed for plume dispersion modelling. Relevant data consist of the following:

- air temperature
- wind speed and direction (or more generally, airflow patterns)
- amount of atmospheric turbulence (usually characterised by stability class)
- precipitation (rainfall)
- mixing layer altitude

Many commonly used probabilistic consequence analysis (PCA) codes require these to be available on an hourly level for a year and for a single location (preferably close to the release location) [5], but more complete datasets would have these for several years and for locations covering the whole area of interest.

Local geographic conditions are also important. These include

- ground elevation (topographical) data
- bodies of water
- vegetation (especially tree coverage) data
- locations of houses
- road network (if evacuation is included in the analysis)

If population effects are analysed, demographic data such as the number and location of people are also needed. Evacuation modelling also needs information about the logistical infrastructure such as road network data and transport capacity (the number and location of cars, boats, helicopters and other vehicles used in evacuation), evacuation plans, communications network information, information on the types of buildings (e.g. blocks of flats, big workplaces) etc. Of paramount importance is the timing of the decision to evacuate; this, in turn, depends not only on the adopted policies (evacuation plan), but also on the timing of information from the plant. Following an initiating event, there may be several levels of alertness, first perhaps a provision state (varautumistila), and then a plant emergency state (laitoshätätila). Also of importance is the time when the local fire brigade is informed.

If economic effects are to be included in the analysis, various kinds of information are needed: the value of agricultural land in the affected area, the value of real estate in the area, the estimated value of industrial and other facilities in the area that would have to be evacuated (and the cost of evacuating them), the estimated value of production breaks in them, information from analysis of population effects, an estimate of the annual monetary value of tourism in the area etc. The computation of these, in turn, may require data on the location, extent and value per hectare of the agricultural land in the area, the location and estimated value of the real estate and facilities in the area, etc. A comprehensive analysis of the costs of a nuclear accident would require also data or judgement on on-site costs, costs related to power production, and image costs [15].

3.3 Level 3 analyses

On level 3, the basis of all further analysis is the analysis of the dispersion of the radioactive elements. This may occur through air (plume dispersion) or through water (aquatic dispersion). Once dispersion – or where radioactive substances end up – has been determined, the effects of the leakage can be analysed. These include effects on public health (cancer and possible radiation sickness), agricultural land (can the fields be used for food production, and if not, how long are they contaminated), economy (a derivative of health, agricultural and other effects).

There are two main approaches to analysing plume dispersion: gradient-transport theory and statistical theory. Both have the same needs concerning level 2 analysis results, and therefore will not be treated separately here. Various atmospheric dispersion models have been developed for the purpose [20].

It seems that aquatic dispersion has received considerably less attention within the nuclear safety community. A common reference is the NRC regulatory guide 1.113 [22] from the year 1977.

Population effects concern the number of people in the impact area, the intake of radiation doses they get, and the effects of the doses on their health. A crucial issue in this analysis is how many people have been evacuated before the radioactive plume reaches them. To analyse this, regional evacuation models [6] can be used; if needed, these can be combined with building evacuation models [8].

Effects on agriculture concern the amount of contaminated agricultural area, the amounts of radioactive material on it, and how long the area has to be out of agricultural use.

Economic effects – direct and indirect costs – of a radioactive release are to a large extent derivative to evacuation and health, agricultural and environmental effects. The monetary value of all business that is affected by the release should be calculated, together with the costs of health consequences, housing of the evacuees, value of lost agricultural production etc. A comprehensive estimate of the costs of a nuclear accident would require also analysis of on-site costs, costs related to power production, and image costs [15].

Uncertainty analyses are an essential part of any level 3 analysis. At simplest, this involves taking weather variation into account by simulating plume dispersion under various weather conditions. Further uncertainty analysis considers the uncertainty related to level 2 results, evacuation schemes and other factors. The main results of uncertainty analysis are the uncertainty distributions of level 3 results (e.g. the number of cancers), and uncertainty importance measures of various inputs (e.g. the energy of the source term).

3.3.1 Computational aspects

The analyses described in above have to be carried out for all meteorological conditions (with emphasis on the typical ones). Furthermore, uncertainty analyses usually have to be carried out for all sources of uncertainty considered important. All of this causes an enormous amount of computation that would have to be carried out.

3.3.2 Level 3 results, their uses, presentation and meaning

Currently, level 3 analyses are not required by STUK. However, STUK is updating regulatory guides [19], and it is expected that instead of fixed activity limits, the guides will contain a statement about not needing to evacuate in the early phase. This approach may require level 3 studies to some depth.

There are hence no strict requirements in Finland for what data the analyses should produce and how it should be represented. Therefore, the following is an inquiry into what should and could be presented to the end user of the analyses, and how this presentation could be done.

The main results of level 3 analyses are severity estimates of various consequences, together with their uncertainty distributions. It might be that the user is interested in comparing the results of level 2 with those of level 3, and therefore cross-tabulation might be needed.

It is useful to represent level 3 results in a visual form. For example, plume diffusion is best understood if presented on a map. Also contaminated areas can be represented by a contour plot drawn over a map.

4. Some existing codes for level 3 PSA

Various codes for PCA exist such as ARANO (Finland), CONDOR (UK), COSYMA (CEC), LENA (Sweden), MACCS (USA), OSCAAR (Japan), CRACIT and NUCRAC (USA), UFOMOD (Germany) and ALICE (France). A comparison of the six first-mentioned is given in [10]. A common problem with these codes is that they are old: for example, ARANO [18] is from the 1970’s, although it has been maintained to account for more modern developments in the field.

For atmospheric dispersion calculations, several codes have been developed ([11] lists 84 distinct codes); of them, e.g. AERMOD has been widely used.

For aquatic dispersion calculations, it seems that there are few if any dedicated codes. However, programs developed for computational fluid flow, hydrology and oceanography may be adapted for this purpose.

Some codes are available for uncertainty analysis. A noteworthy program in this field is OpenTURNS [12]. It has a wide user base, and it is being actively developed.

There is an abundance of graphics and visualization software available: the data mining site KDNuggets lists 56 commercial and 19 free visualization programs available (see also [1]). A notable free computer graphics program is Gnuplot [7]. A much used program for geographic data visualization (e.g. contour plots on a map) is ArcGIS [1]. Also the visualization capabilities of general-purpose statistics or data mining programs such as R [17] may be utilized.

For agricultural consequence calculation, GIS programs like ArcGIS offer some useful facilities. For example, in ArcGIS it is easy to calculate the area of agricultural land that has received a certain amount of radioactive material, given the size, shape and location of the fallout; naturally, map data that contains the agricultural plots is needed.

It is uncertain whether readily available specialized programs exist for dose calculations; however, the methods described in e.g. [16] can be implemented for example in Excel.

As for economic consequences calculation, it seems likely that an Excel workbook would be sufficient; obtaining the formulae and economic data involved are most probably the difficult part, but the computations involved are likely to be simple.

5. The interface between level 2 and level 3 PSA

We proceed to define a data interface between levels 2 and 3 precisely enough that it can be implemented. A well-defined interface between levels 2 and 3 has many benefits. First, it tells program designers on level 2 what is expected from their software. Second, it tells program designers on level 3 what they can expect as input. Third, it lessens the amount of work in creating interfaces: for n level 2 codes and m level 3 codes, nm interfaces would have to be created if all programs would have their own output, but only n+m interfaces when there is only one data interface format used by all.

We take a time-based approach, where the release is approximated by piecewise constant portions. This allows for a variety of levels of precision, where on the coarsest level the whole release is approximated by a single leakage, and on the most accurate level the release is approximated by a long series of individual leakages.

The release consists of gases, aerosols, particles (in the gas) and liquids (usually liquids are not modelled, so this category might be seldom used). In the interface, it is assumed that the radioactive compounds are classified not only by their isotope, but also by the molecule they are part of, and the state (gas, aerosol, particle, liquid) of the substance they are in.

This representation of the release (or source terms) is visualized in figure 2. The ReleaseSequence object represents the whole release. It may consist of several source terms that occur at different times (possibly with intermediate times between them). In this way, several plumes from a single accident, or a single heterogeneous plume (with for example different radioactive substances and different energy at different phases of the plume), can be handled.

The accidentStartTime attribute of the ReleaseSequence object is assumed to be given in a date and time format (the date need not have any significance). This is the time when the initiating event happened. alarmSetoffTime is the amount of time (in seconds) from the initiating event to when alarm was given to the external world; it is not clear how this should be defined, as discussed in section 3.2. The signals that trigger an evacuation need to be thought through more thoroughly. At this moment, alarmSetoffTime should be seen as a placeholder for the time/alarm data (to be defined later) needed in evacuation calculations. releaseStartTime is the time (in seconds from accidentStartTime) when the release starts (i.e. radioactive substances start leaking from the containment). The time available for appropriate countermeasures is often defined as releaseStartTime- alarmSetoffTime. Note that, in the strict sense, releaseStartTime is redundant information, because the release consists of several phases in this model; the start time of the earliest of these phases is then the start time of the release.

A SourceTerm is defined here as a phase of the release giving rise to an individual radioactive plume (or a relatively homogeneous part of a plume). It has constant composition, convection rate and energy. It consists of various radioactive compounds.

An individual RadioactiveCompound is a chemical compound containing a radioactive isotope. Most such compounds are either atomic (as in the case of noble gases), metallic or oxides; in these cases, the chemical composition is of minor importance. An important class of compounds is organic molecules containing radioactive iodine, because these can be absorbed by the human body, ending through blood circulation to different parts of the human body. The amount of each RadioactiveCompound varies from phase to phase.

The phases are assumed to follow each other sequentially in time, and thus one can state that SourceTerm[i].startTime + SourceTerm[i].duration ≤ SourceTerm[i+1].startTime.

ParticleSizeDistribution describes the particle size distribution of the source term (if it contains aerosols or particulates). The intent is to express a parametric distribution (together with its parameters), or a nonparametric distribution as a frequency table. The object in the figure is an abstract one. For each distribution used, there should be an instance of it with the parameters of the distribution as attributes, and computation of the distribution's value at a given point as a method.

ContextInformation gives information given on level 1 or 2 that modifies the computations at level 3. For example, if the initiating event on level 1 has been the formation of frazil ice, it is not meaningful to conduct level 3 simulations and analyses using the temperature distribution of the whole year; rather, a fixed value for the outdoor temperature (given by an element of the attribute fixedQuantities), or a predefined distribution (given by an element of the attribute givenQuantities) ought to be used. A suitable form of representing these two lists is as association lists, where the first element identifies the variable(s) involved and the second lists the appropriate value(s).

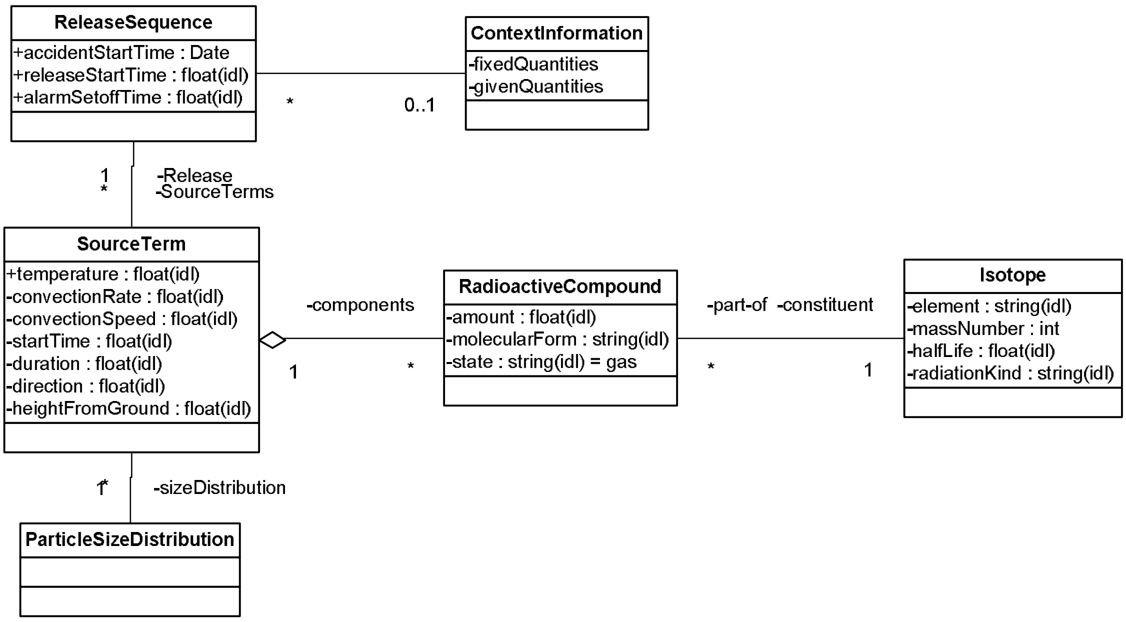

Figure 2. The data interface between levels 2 and 3. Isotope and ParticleSizeDistribution objects are permanent information, and need not be given in the interface

In practice, the interface can be implemented for example as a relational database or an XML file.

6. System-level alternatives of conducting level 3 analyses

There are several ways of implementing PSA level 3 computations, given that the results from level 2 are available. In this section, we will consider two: using a dedicated level 3 code, and using available special-purpose program tools. The third main alternative, developing a PSA level 3 program, is tedious and costly albeit providing most flexibility.

The simplest alternative is utilize an existing level 3 analysis code. Then, the only new thing needed is an interface between SPSA and the level 3 code as shown in figure 3.

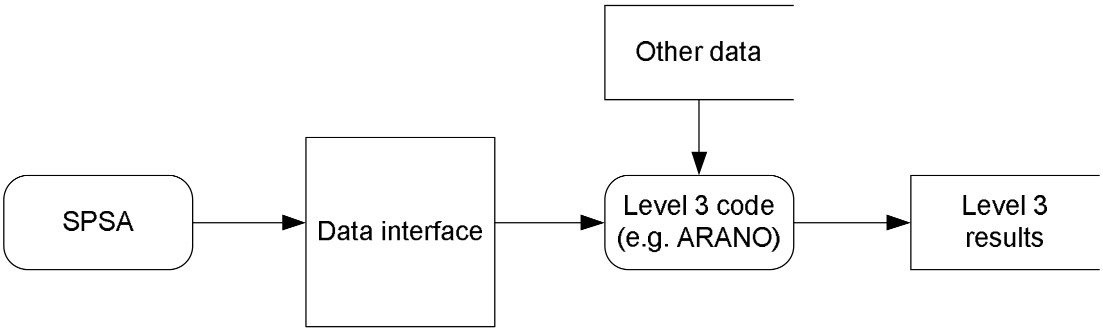

Figure 3. Level 2 and 3 analyses with a PCA code for levels 2 and 3

This approach has the advantages of simplicity and ease of implementation. However, the approach is inflexible, because advantages in e.g. atmospheric dispersion modelling cannot be utilized. Complementing level 3 analysis by analyses that doesn't exist in the code used is cumbersome. Existing level 3 codes are old, and some of them have not been updated to account for modern developments in e.g. meteorology.

An alternative is to utilize existing special purpose programs (handling e.g. atmospheric dispersion) to orchestrate a level 3 analysis. A possible architecture for implementing this approach is presented in figure 4. The figure could easily be complemented with economic or agricultural effects calculation.

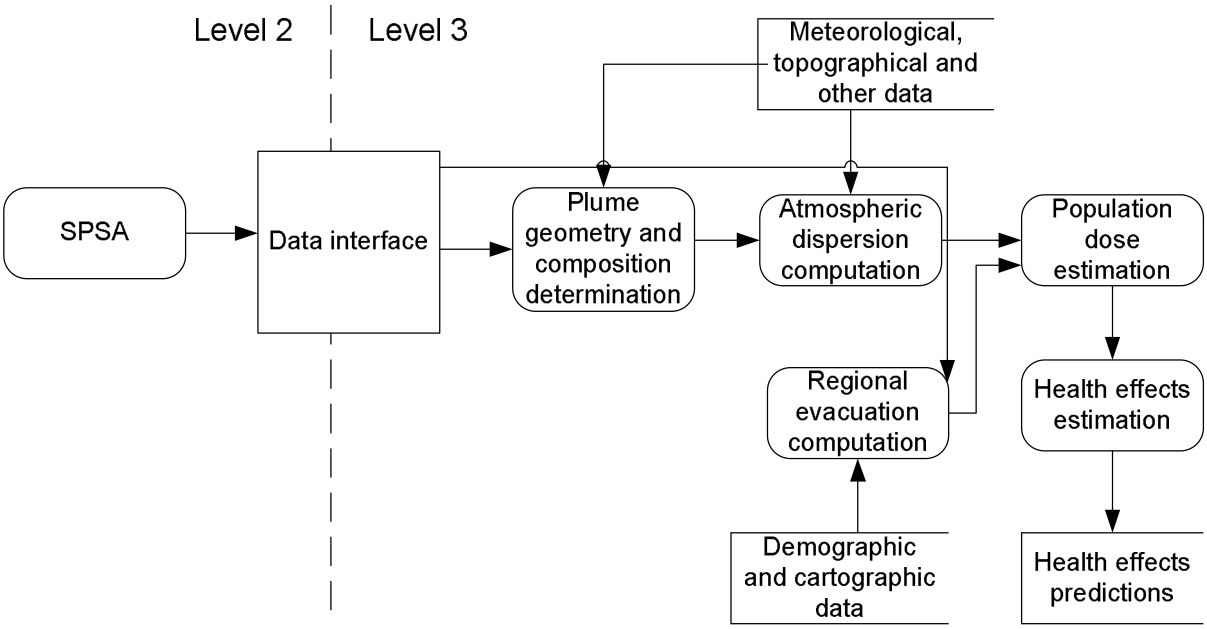

Figure 4. Level 2 and 3 analyses with various special purpose codes for level 3

This approach provides flexibility as a suitable code can be selected or implemented for each level 3 analysis. However, this flexibility comes with a cost: interfaces between each program have to be implemented. Furthermore, the user(s) have to cope with using several different programs, possibly with widely different usage logics.

There is yet another architectural alternative: constructing an overall programmatic layer that provides user interface, data management, visualization and other such services, and utilizes dedicated programs that do the analysis and computation. An example structure is provided in figure 5.

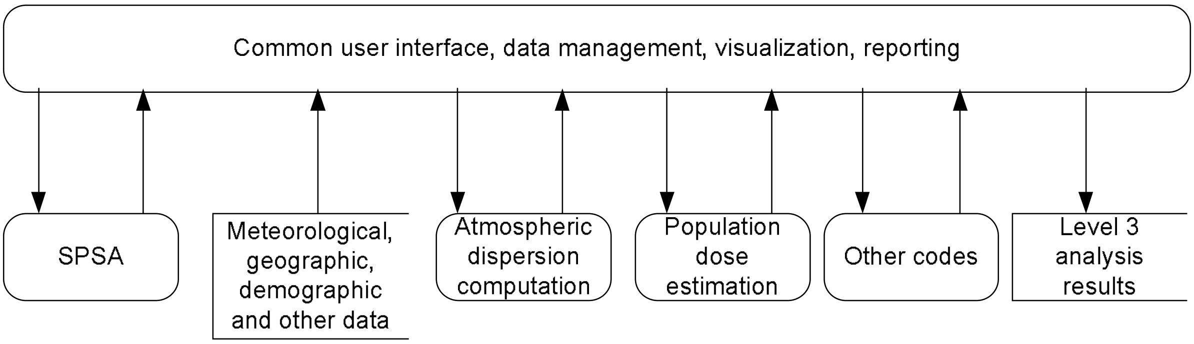

Figure 5. Level 2 and 3 analyses a control program coordinating various computations

7. A roadmap for developing software-based level 3 analyses

Synthesizing a set of software tools for level 3 that is easy to use, flexible, reliable, and reduces workload is a nontrivial task. At VTT, a good long-term goal would be to incorporate this as a part of the development of level 1 and 2 programs FinPSA and SPSA. However, a useful set of tools can be achieved with less effort. This section describes a way to construct such a set of tools.

The first task is to outline the needs and requirements of level 3 analyses and the presentation of results.

Based on the needs, the next task is to review existing codes more deeply: are they freely available (and if not, at what price), is their source code available, what information they expect and in what form, how simple they are to use, what kinds of analyses they support, what methods they use for analysis, how flexible they are and so on. Based on this, the level 2-3 interface outlined in this report can then be defined more precisely.

After this initial screening, one or more of these codes considered suitable may be taken for a deeper inspection. The goal of this is to find a suitable code or set of codes with which to conduct level 3 analyses.

Once a suitable set of tools has been decided upon, they need to be interfaced with SPSA and one another. In practice, a suitable format for representing level 2 results in SPSA has to be decided upon (a good starting point would be the proposed data interface of section 5), and a conversion program from this format to the one accepted by the level 3 code or atmospheric dispersion program is to be constructed. This program need not be more complicated than a script that converts data from one format to another. Particular emphasis should be put on satisfying level 3-specific needs and requirements, such as legislation, guidelines etc. It is probable that these need to be addressed on the program level.

The set of chosen codes will then be integrated into a more coherent whole. A set of distinct programs, many of them perhaps difficult to use, doesn’t provide a good platform on which an analyst could perform level 3 calculations. A solution to this conundrum is to create a set of tools that provide a unified user interface, hide the idiosyncracies of the use of individual programs from the user, and still provide a flexible platform for level 3 analyses. This can be accomplished by using computer programs to provide the user interface, convert data from one format to another, call the different programs with suitable parameters, and show the results to the user. These kinds of programs have sometimes been called software glue in the software literature. Script languages, such as Python, Ruby, Perl and others have sometimes been pointed out as especially suited for creating software glue. Of these, Python seems especially interesting because it has been proposed as the next generation scripting language for SPSA.

Once a suitable software infrastructure has been created with the steps outlined above, it may be continuously improved by taking account of lessons learnt in usage.

8. Conclusions

This report outlines the analyses performed on level 3 PSA, discusses the data needs for the analyses, proposes a data interface between levels 2 and 3, and sketches some alternatives for conducting level 3 computations on a software architecture level.

The object interface between SPSA (or more generally, level 2 code) and level 3, outlined in this paper, is as of yet a sketch. There are several details that need refining or perhaps even reworking. A case in point is the handling of contextual information (the ContextInformation object). The kinds of contextual information from levels 1 and 2 that affect computations on level 3 need to be carefully analysed and listed, and their representation thought through. Only then will there be sufficient information to determine the exact representation of contextual information in the level 2-3 interface.

The computations on level 3 can be carried out in numerous ways. In this report, using an existing level 3 code, and utilizing general-purpose programs for level 3 tasks such as atmospheric dispersion simulation, uncertainty analyses and result visualization, were identified as the main alternatives in the short run. If the latter approach is selected, data flow from one application to another, user interface, data presentation and other services are to be arranged; this can be accomplished by using scripting languages such as Python.

A roadmap for achieving level 3 analysis capabilities on the software level is proposed. The long-term aim is to achieve seamless analysis on levels 2 and 3.

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