INTERNATIONAL STANDARD

ISO 16730

First edition
2008-07-15

Fire safety engineering — Assessment, verification and validation of calculation methods

Ingénierie de la sécurité incendie — Évaluation, vérification et validation des méthodes de calcul

Reference number
ISO 16730:2008(E)

PDF disclaimer

This PDF file may contain embedded typefaces. In accordance with Adobe's licensing policy, this file may be printed or viewed but shall not be edited unless the typefaces which are embedded are licensed to and installed on the computer performing the editing. In downloading this file, parties accept therein the responsibility of not infringing Adobe's licensing policy. The ISO Central Secretariat accepts no liability in this area.

Adobe is a trademark of Adobe Systems Incorporated.

Details of the software products used to create this PDF file can be found in the General Info relative to the file; the PDF-creation parameters were optimized for printing. Every care has been taken to ensure that the file is suitable for use by ISO member bodies. In the unlikely event that a problem relating to it is found, please inform the Central Secretariat at the address given below.

COPYRIGHT PROTECTED DOCUMENT

© ISO 2008

All rights reserved. Unless otherwise specified, no part of this publication may be reproduced or utilized in any form or by any means, electronic or mechanical, including photocopying and microfilm, without permission in writing from either ISO at the address below or ISO's member body in the country of the requester.

ISO copyright office
Case postale 56 • CH-1211 Geneva 20
Tel. + 41 22 749 01 11
Fax + 41 22 749 09 47
E-mail copyright@iso.org
Web www.iso.org

Published in Switzerland

--`,,```,,,,````-`-`,,`,,`,`,,`---

Copyright International Organization for Standardization
Provided by IHS under license with ISO
No reproduction or networking permitted without license from IHS
Not for Resale

Contents

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 16730 was prepared by Technical Committee ISO/TC 92, *Fire safety*, Subcommittee SC 4, *Fire safety engineering*.

Introduction

The objective of fire safety engineering is to assist in the achievement of an acceptable predicted level of fire safety. Part of this work involves the use of calculation methods to predict the course of events that can potentially occur in case of a fire or as a consequence of a fire. This work involves the use of calculation methods to evaluate the ability of fire protection measures to mitigate the adverse effects of a fire on people, property, the environment and other objects. The main principles that are necessary to establish the credibility of these calculation methods are assessment, verification and validation.

There is a need for a standard as a technical basis to provide the developers and users of calculation methods and third parties with procedures to check whether the calculation method's accuracy for particular applications is sufficient.

This International Standard addresses the assessment, verification and validation of calculation methods for fire-safety engineering in general.

It is necessary that potential users of calculation methods and those who are asked to accept the results be assured that the calculation methods provide sufficiently accurate predictions of the course and consequences of the fire for the specific application planned. To provide this assurance, it is necessary that the calculation methods being considered be verified for mathematical accuracy and validated for capability to reproduce the phenomena.

There is no fixed requirement of accuracy that is applicable to all calculation methods. The accuracy level depends on the purposes for which a calculation method is being used. It is not necessary that all calculation methods demonstrate high accuracy as long as the error, uncertainty and limits of applicability of the calculation methods are known.

This International Standard focuses on the predictive accuracy of calculation methods. However, other factors such as ease of use, relevance, completeness and status of development play an important role in the assessment of the use of the most appropriate method for a particular application. The assessment of the suitability of a calculation method for a special purpose within the field of fire safety engineering is supported by the use of quality-assurance methodology to ensure that the requirements are being fulfilled. Guidance for establishing metrics for measuring attributes of the relevant quality characteristics is outlined in short form in this International Standard.

This International Standard is intended for use by

a) developers of calculation methods (individuals or organizations that perform development activities, including requirements analysis, design and testing of components), to document the usefulness of a particular calculation method, perhaps for specific applications. Part of the calculation method development includes the identification of precision and limits of applicability, and independent testing,

b) developers of calculation methods (individuals or organizations who maintain computer models, supply computer models, and for those who evaluate computer model quality as part of quality assurance and quality control), to document the software development process and assure users that appropriate development techniques are followed to assure quality of the application tools,

c) users of calculation methods (individuals or organizations that use calculation methods to perform an analysis), to assure themselves that they are using an appropriate method for a particular application and that it provides adequate accuracy,

d) developers of performance codes and standards, to determine whether a calculation method is appropriate for a given application,

e) approving bodies/officials (individuals or organizations that review or approve the use of assessment methods and tools), to ensure that the calculation methods submitted show clearly that the calculation method is used within its applicability limits and has an acceptable level of accuracy,

f) educators, to demonstrate the application and acceptability of calculation methods being taught.

It is necessary that users of this International Standard be appropriately qualified and competent in the fields of fire safety engineering and risk assessment. It is important that users understand the parameters within which specific methodologies can be used.

INTERNATIONAL STANDARD **ISO 16730:2008(E)**

Fire safety engineering — Assessment, verification and validation of calculation methods

1 Scope

This International Standard provides a framework for assessment, verification and validation of all types of calculation methods used as tools for fire safety engineering. It does not address specific fire models, but is intended to be applicable to both analytical models and complex numerical models that are addressed as calculation methods in the context of this International Standard. It is not a step-by-step procedure, but does describe techniques for detecting errors and finding limitations in a calculation method.

This International Standard includes

- a process to ensure that the equations and calculation methods are implemented correctly (verification) and that the calculation method being considered is solving the appropriate problem (validation),
- requirements for documentation to demonstrate the adequacy of the scientific and technical basis of a calculation method,
- requirements for data against which a calculation method's predicted results shall be checked,
- guidance on use of this International Standard by developers and/or users of calculation methods, and by those assessing the results obtained by using calculation methods.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO/TR 13387-1, *Fire safety engineering — Part 1: Application of fire performance concepts to design objectives*

ISO 13943, *Fire safety — Vocabulary*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 13943 and ISO/TR 13387-1 and the following apply.

NOTE Some of the definitions have been updated to illustrate the current understanding of the meaning of the terms in the field of fire-safety engineering.

3.1
accuracy
degree of exactness actually possessed by an approximation, measurement, etc.

NOTE In the context of this International Standard, the numerical (or mathematical) accuracy is part of the verification process for calculation methods, where a computer fire model may be such a calculation method. The accuracy may be expressed by indicating the uncertainty of a calculation or solution(s) of a model.

3.2
assessment
process of determining the degree to which a calculation method is an accurate representation of the real world from the perspective of the intended uses of the calculation method and the degree to which a calculation method implementation accurately represents the developer's conceptual description of the calculation method and the solution to the calculation method

NOTE Key processes in the assessment of suitability of a calculation method are verification and validation.

3.3
calculation method
mathematical procedure used to predict fire-related phenomena

NOTE Calculation methods may address behaviour of people as well as objects or fire; may be probabilistic as well as deterministic in form; and may be algebraic formulae as well as complex computer models.

3.4
calibration
⟨of a model⟩ process of adjusting modelling parameters in a computational model for the purpose of improving agreement with experimental data

3.5
computer(ized) model
operational computer program that implements a conceptual model

3.6
conceptual model
description composed of all the information, mathematical modelling data and mathematical equations that describe the (physical) system or process of interest

3.7
default value
standard setting or state to be taken by the program if no alternate setting or state is initiated by the system or the user

3.8
deterministic model
calculation method that uses science-based mathematical expressions to produce the same result each time the method is exercised with the same set of input data values

3.9
engineering judgment
process exercised by a professional who is qualified by way of education, experience and recognized skills to complement, supplement, accept or reject elements of a quantitative analysis

3.10
error
recognizable deficiency in any phase or activity of calculation that is not due to lack of knowledge

3.11
fire model
representation of a system or process related to fire development, including fire dynamics and fire impacts

3.12
mathematical model
sets of equations that describe the behaviour of a physical system

3.13
measure
variable to which a value is assigned as the result of measurement

3.14
measurement
set of operations having the object of determining a value of a measure

3.15
metric
measure, quantitative or qualitative, of relative achievement of a desired quality characteristic

3.16
modelling
process of construction or modification of a model

3.17
numerical model
numerical representation of a physical (fire) model

3.18
physical model
model that attempts to reproduce fire phenomena in a simplified physical situation, e.g. scale models

3.19
probabilistic model
model that treats phenomena as a series of sequential events or states, with mathematical rules to govern the transition from one event to another, e.g. from ignition to established burning, and probabilities assigned to each transfer point

3.20
simulation
exercise or use of a calculation method

3.21
simulation model
model that treats the dynamic relationships that are assumed to exist in the real situation as a series of elementary operations on the appropriate variables

3.22
uncertainty
potential deficiency in any phase or activity of the modelling process that is due to lack of knowledge

3.23
validation
process of determining the degree to which a calculation method is an accurate representation of the real world from the perspective of the intended uses of the calculation method

3.24
verification
process of determining that a calculation method implementation accurately represents the developer's conceptual description of the calculation method and the solution to the calculation method

NOTE The fundamental strategy of verification of computational models is the identification and quantification of error in the computational model and its solution.

4 Documentation

4.1 General

The technical documentation should be sufficiently detailed that all calculation results can be reproduced within the stated accuracy and precision by an appropriately qualified, independent individual or group. Sufficient documentation of calculation methods, including computer software, is essential to assess the adequacy of the scientific and technical basis of the calculation methods and the accuracy of computational procedures. Also, adequate documentation can assist in preventing the unintentional misuse of calculation methods. Reports on any assessment of a specific calculation method should become part of the documentation. The validity of a calculation method includes comparing results to data from real-world testing, from a survey or from real-world approximations and shall be stated by applying quality-assurance methodology. These give a measure or a set of measures that shall be compared to previously defined criteria to demonstrate whether agreed quality requirements are met.

Documentation shall include

- technical documentation that explains the scientific basis of the calculation method; see 4.2;
- a user's manual, in the case of a computer program; see 4.3.

In 4.2 and 4.3 are described the necessary requirements for technical documentation and a user's manual. The list is quite lengthy, but is not intended to exclude other forms of information that can assist the user in assessing the applicability and usability of the calculation method.

4.2 Technical documentation

Technical documentation is needed to assess the scientific basis of the calculation method. The provision of technical documentation of a calculation method is a task done by the model developers. It is necessary that the technical documentation thoroughly describe the calculation method and its basis, demonstrate its ability to perform adequately, and provide users with the information they need to apply the calculation method correctly. In case of calculations that make use of algebraic equations derived from experimental results by regression or when analytical solutions are applied, the user shall rely on relevant documentation from standards or similar material, such as the scientific literature. When standards are developed that contain calculation methods for use in fire-safety engineering, the source(s) for the calculation methods being used, together with technical documentation as described below, shall be given where applicable.

a) The description of the calculation method shall include complete details on

    1) purpose:

        - define the problem solved or function performed;
        - describe the results of the calculation method;
        - include any feasibility studies and justification statements;

    2) theory:

        - describe the underlying conceptual model (governing phenomena), if applicable;
        - describe the theoretical basis of the phenomena and physical laws on which the calculation method is based, if applicable;

    3) implementation of theory, if applicable:

        - present the governing equations;
        - describe the mathematical techniques, procedures and computational algorithms employed and provide references to them;

    - identify all the assumptions embedded in the logic, taking into account limitations on the input parameters that are caused by the range of applicability of the calculation method;
    - discuss the precision of the results obtained by important algorithms and, in the case of computer models, any dependence on particular computer capabilities;
    - describe results of the sensitivity analyses;

  4) input:

    - describe the input required;
    - provide information on the source of the data required;
    - for computer models, list any auxiliary programs or external data files required;
    - provide information on the source, contents and use of data libraries for computer models.

b) It is necessary that the assessment (verification and validation) of the calculation method be completely described, with details on

  - the results of any efforts to evaluate the predictive capabilities of the calculation method in accordance with Clause 5, which should be presented in a quantitative manner;
  - references to reviews, analytical tests, comparison tests, experimental validation and code checking already performed. If, in the case of computer models, the validation of the calculation method is based on beta testing, the documentation should include a profile of those involved in the testing (e.g. were they involved to any degree in the development of the calculation method or were they naive users; were they given any extra instruction that is not available to the intended users of the final product, etc.);
  - the extent to which the calculation method meets this International Standard.

  The technical documentation shall be collected into one document such as a manual as far as computer models are concerned. Whenever explicit algebraic equations are used to solve a fire-safety engineering problem, relevant technical documentation may be cited from sources as indicated above.

  Having prepared this documentation, however, the verification and validation processes are not considered finished until a third party has gone through the process independently (“third party auditing”). This auditing process is supported by the definition and use of relevant quality-assurance methods to arrive at a measure or a set of (derived) measures that allows scaling the quality of a calculation method and determines whether a calculation method is sufficiently accurate to meet the requirements of the intended user [see for example concept on internal and external metrics and on quality in use from the series of *Software Quality Requirements and Evaluation (SquaRE)* documents from the work of ISO/IEC JTC1]. For further information, see the series of ISO/IEC 25000 documents. The purpose of a calculation method's evaluation, in general, is to compare the quality of a calculation method against quality requirements that express user needs, or even to select a calculation method by comparing different calculation methods.

c) The technical documentation shall include at least one (or more) worked example(s). Worked examples may be required both for explicit algebraic formulae and for mathematical models. The latter is addressed in 4.3 h). The purpose of a worked example is to demonstrate what the required input data are and their limitations, and the range of applicability of the result(s) of the calculation method being considered. Examples for required input data and their intended range or limitations within which the calculation has been validated are, for example, geometry, material properties, and boundary conditions.

Standards on calculation methods shall include worked example(s) in an informative annex. By specifying the required components of a worked example in an International Standard on calculation methods (e.g. ISO 16734 through 16737), guidance is given on how to apply the International Standard correctly, together with information in the International Standard itself on requirements on limitations and input parameters. Examples taken from real-world problems include the temperature of a steel member or a fire insult to a cable in a nuclear power plant. Since there are examples available in the open literature, the requirement of the inclusion of worked examples in an informative annex to an International Standard on calculation methods may also be met by reference to textbooks that include such examples.

4.3 User's manual

A user's manual is required only in the case of computer models. The user's manual for a computer model should enable users to understand the model application and methodology, reproduce the computer operating environment and the results of sample problems included in the manual, modify data inputs and run the program for specified ranges of parameters and extreme cases. The manual should be sufficiently concise to serve as a reference document for the preparation of input data and the interpretation of results. Installation, maintenance and programming documentation may be included in the user's manual or may be provided separately. There should be sufficient information to install the program on a computer. All forms of documentation should include the name and sufficient information to define the specific version of the calculation method and identify the organization responsible for maintaining the calculation method and for providing further assistance.

In the case of computer models, it is necessary that the user's manual provide all the information necessary for a user to apply a computer model correctly. It should include

a) program description:

- a self-contained description of the model;
- a description of the basic processing tasks performed and the calculation methods and procedures employed (a flowchart can be useful);
- a description of the types of skills required to execute typical runs;

b) installation and operating instructions:

- identify the minimum hardware configuration required;
- identify the computer(s) on which the program has been executed successfully;
- identify the programming languages and software operating systems and version in use;
- provide instructions for installing the program;
- provide the typical personnel time and setup time to perform a typical run;
- provide information necessary to estimate the computer execution time on applicable computer systems for typical applications;

c) program considerations:

- describe the functions of each major option available for solving various problems with guidance for choosing these options;
- identify the limits of applicability (e.g. the range of scenarios over which the underlying theory is known or believed to be valid or the range of input data over which the calculation method was tested);
- list the restrictions and/or limitations of the software, including appropriate data ranges and the program's behaviour when the ranges are exceeded;

d) input data description:

- name and describe each input variable, its dimensional units, the default value (if any) and the source (if not widely available);
- describe any special input techniques;

- identify limits on input based on the stability, accuracy and practicality of the data and the applicability of the model, as well as their resulting limitations to output;
- describe any default variables and the process for setting those variables to user-defined values;
- if handling of consecutive cases is possible, explain the conditions of data retention or re-initialization from case to case;

e) external data files:

- describe the contents and organization of any external data files;
- provide references to any auxiliary programs that create, modify or edit these files;

f) system control requirements:

- detail the procedure required to set up and run the program;
- list the operating system control commands;
- list the program's prompts, with the ranges of appropriate responses;
- if possible to do so, describe how to halt the program during execution, how to resume or exit, and the status of the files and data after the interruption;

g) output information:

- describe the program output and any graphics display and plot routines;
- provide instructions on judging whether the program has converged to a good solution, where appropriate;

h) sample problems/worked examples:

- provide sample data files with associated outputs to allow the user to verify the correct operation of the program; these sample problems should exercise a large portion of the available programmed options; see, for comparison, 4.2 c);

i) error handling:

- list error messages that can be generated by the program;
- provide a list of instructions for appropriate actions when error messages occur;
- describe the program's behaviour when restrictions are violated;
- describe recovery procedures.

5 Methodology

5.1 General

Verification and validation of a calculation method are the processes used to determine the degree to which a calculation method is an accurate representation of the real world from the perspective of the intended uses of the calculation method and the degree to which a calculation method implementation accurately represents the developer's conceptual description of the calculation method and the solution to the calculation method. This is called the “assessment” of the calculation method (see the definitions). Verification is the process of determining whether the equations are being solved correctly. Presuming that the correct equations are being utilized, the next step is validation, which is to ensure that the results match what is expected in the real world.

In Figure 1, the phases of modelling and simulation, and the role of verification and validation in these processes as applied to computer fire models, are presented in a very general manner.

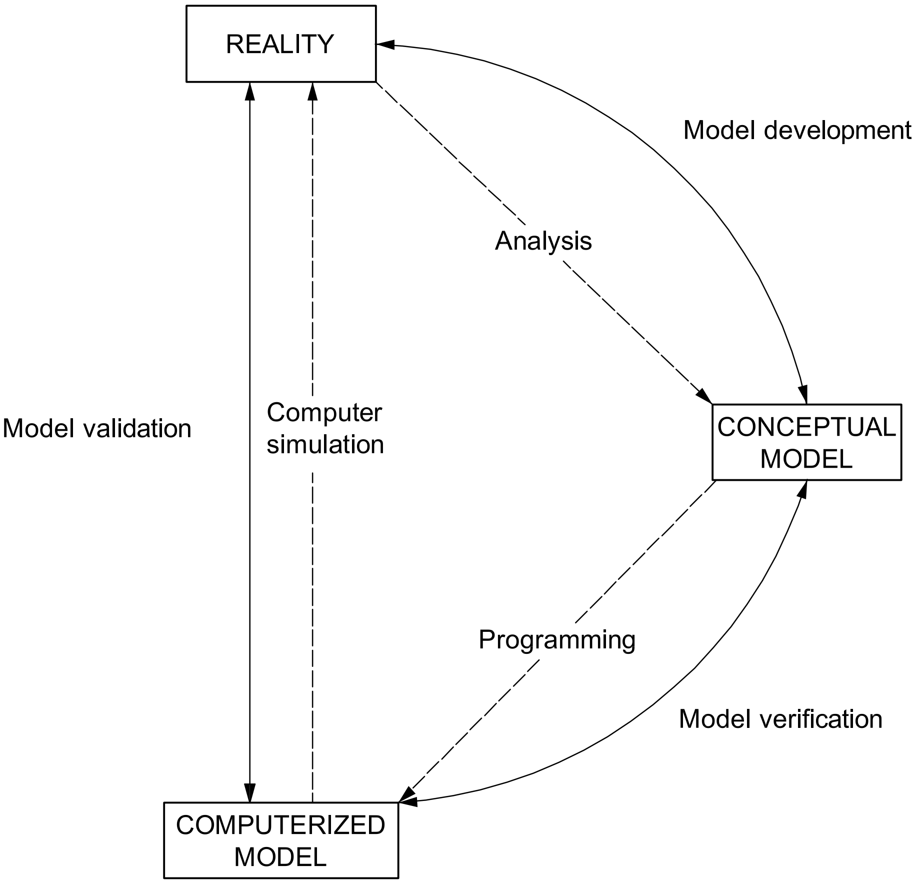


Figure 1 — Phases of development and assessment of computer(ized) models

The conceptual model is produced by analysing the real world (sometimes a physical system) and is composed of mathematical modelling data and equations that describe the physical system (Navier-Stokes equations, conservation of energy and mass, and additional physical models, such as turbulence models, human behaviour aspects, structural behaviour, risk, etc.). Verification deals with the relationship between conceptual model and computerized model, while validation deals with the relationship between computational model and reality.

Figure 2 develops Figure 1 and presents it in the form of a flowchart for general application, illustrating the potential use of algebraic equations where deemed appropriate.

The procedure starts with a required knowledge of tests and experiments or surveys to describe what is going on in the real world. From the perception of real-world behaviour, a conceptual model is developed as a detailed verbal description of the process(es) considered, which is further developed into a set of mathematical relationships. These are treated such that (a) solution(s) can be derived by breaking these down line by line from a highly sophisticated level to a less sophisticated level, applying approximations to such a degree that the problem can be solved with both sufficient accuracy and an acceptable solution effort (e.g. in time and computer performance).

The theoretical basis of the calculation method of a computer model should be reviewed by one or more experts fully conversant with the basic science of fire phenomena and computational techniques but not involved with the development of the model. This review should include an assessment of the completeness of the documentation, particularly with regard to the numerical approximations. The reviewer should be able to judge whether there is sufficient scientific evidence in the open scientific literature to justify the approaches being used. Data used for constants and default values in the code should also be assessed for accuracy and applicability in the context of the calculation method and intended use. The latter is especially true if data used for numerical constants can have specific values for specific scenarios. Practical upper and lower limits to variables used as input data should be defined clearly to restrict application to a proven range of applicability.

Between the steps of breaking elements down into a system that can be handled, it is necessary that the processes of verification and validation be carried out in order to permanently check the solution system for possible sources of error; see Annex A. A box is included in Figure 2 for algebraic equations, which are also considered in this International Standard, but which, due to the complexity of mathematical formulations of fire-related phenomena, are not necessary for the assessment of (empirical) calculation methods.

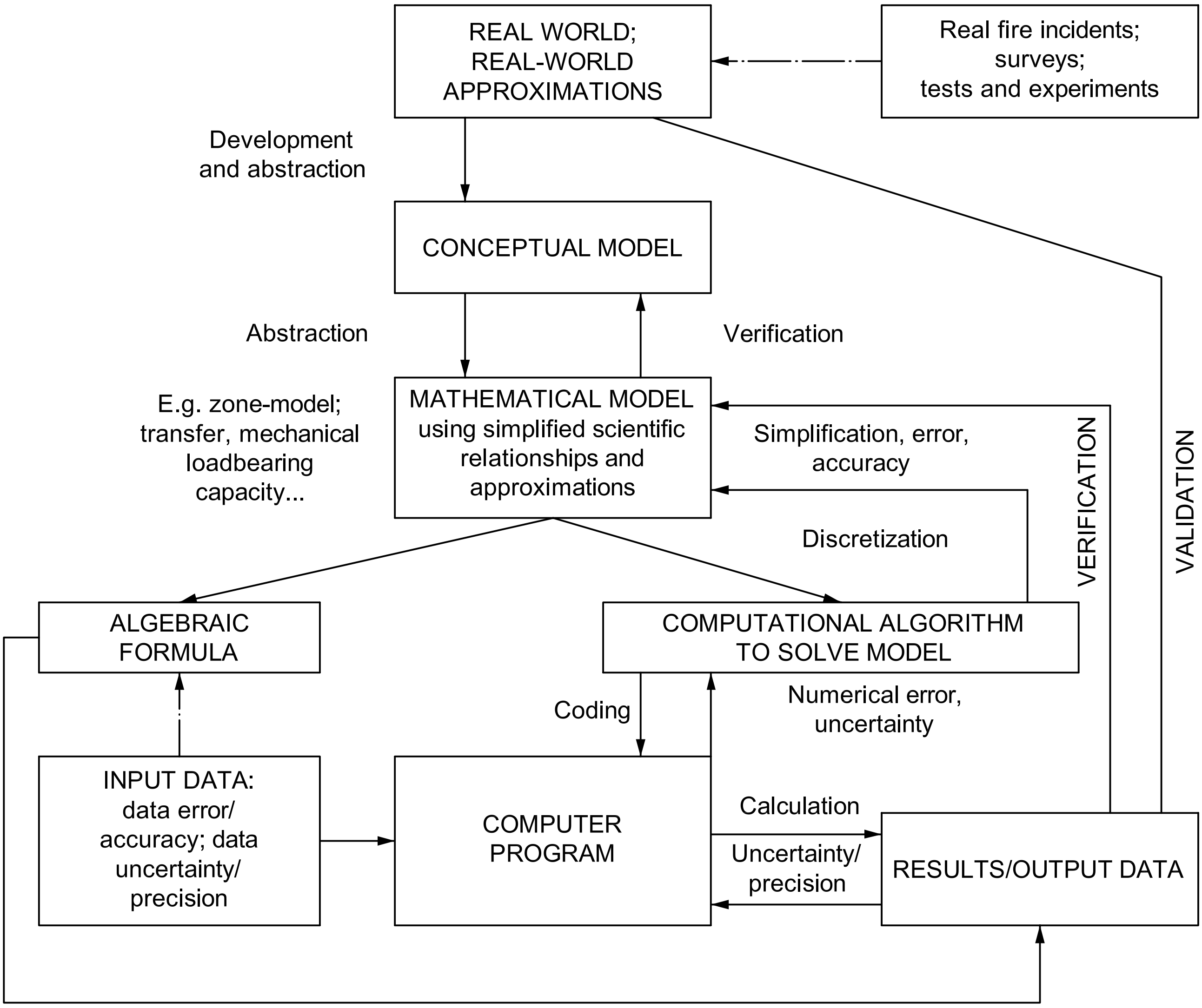


Figure 2 — Flowchart representation of model assessment, including validation and verification

The methodology is not at all restricted to fire spread and similar problems, but can also be applied to the assessment, validation and verification of calculation methods for behaviour and movement of people, to structural behaviour and to risk assessment (where risk equals the probability of occurrence times the consequence; see ISO 16732).

5.2 Verification

5.2.1 General

Verification is the process of determining that the implementation of a calculation method accurately represents the developer's conceptual description of the calculation method and of the solution to the calculation method. This does not imply that the governing equations are appropriate, only that the equations are being implemented and solved correctly and that the implementation accurately represents the developer's conceptual description of the calculation method and of the solution to the calculation method.

The aim of the verification process, then, is to check the code correctness and to assess the control of the numerical error, which can be divided into three categories:

a) round-off error, which occurs because computers represent real numbers using a finite number of digits;

b) truncation error, which occurs when a continuous process is replaced by a finite one; this can happen, for example, when an infinite series is truncated after a finite number of terms or when an iteration is terminated after a convergence criterion has been satisfied;

c) discretization error, which occurs when a continuous process such as a derivative is approximated by a discrete analog such as a divided difference.

An assessment of a computational method should include an analysis and discussions of the methods used and the inherent limitations in the particular choices that were made.

5.2.2 Code checking

The program code can be checked on a structural basis, either manually or by using code-checking programs to detect irregularities and inconsistencies within the computer code. Ensuring that the techniques and methodologies used to check the code, together with any deficiencies found, are clearly identified and recorded, increases the level of confidence in the program's ability to process the data reliably, but it cannot give any indication of the likely adequacy or accuracy of the program in use. It is not necessarily the case that an error renders a program unusable, but documentation of these “bugs” prevents the use of the affected functions.

5.2.3 Temporal and spatial discretization

Mathematical models are usually expressed in the form of differential or integral equations. The models are in general complex, and analytical solutions are often difficult to find. Numerical techniques are necessary for finding approximate solutions. In a numerical method, the continuous mathematical model is discretized, that is, approximated by a discrete, numerical model. Discretization is done both in time and in space (grid).

A continuous mathematical model can be discretized in many different ways resulting in as many different discrete models. To achieve a good approximation of the solution of the continuous models, the discrete model is required to mimic the properties and the behaviour of the continuous model. This means that the discrete solution should converge to the solution (when it exists) of the continuous problem, when the discretization parameters (time step, space mesh, etc.) decrease. This is achieved when the requirements for consistency and stability are met. Consistency means that the discrete model closely approximates the continuous model in the sense of some measure, i.e. a norm. Stability means that the error terms do not increase as the program proceeds.

The formal order of error in both spatial and temporal discretization should be explained and discussed. It might not be possible to be exhaustive, but it is necessary that an analysis be done as part of the process of verifying the transformation of the equations into discrete numerical form.

Many problems related to fire involve the interaction of different physical processes, such as the chemical or thermal processes and the mechanical response. Time and space scales associated with the processes can be substantially different, which causes numerical difficulties. Consequently, in solving differential equations, it is necessary to exercise some care when choosing the time and space steps, to ensure the stability (specially with respect to the time step for transient computations) and a sufficient convergence of the computation. Some numerical techniques can be used in order to dynamically monitor discretization parameters to meet stability and accuracy requirements (for example, as far as the spatial discretization is concerned, *a posteriori* error estimation coupled to dynamic meshing refinement). Making use of such methods is recommended, specially for the time-stability issue for nonlinear problems, as encountered in zone models. In this case, the code documentation should extensively explain how this has been accomplished and numerical experiments addressing the validity of the used algorithm should be presented. This does not prevent the user from performing, for a particular computation, a study of time and space convergence. How this task is accomplished systematically in the case of the choice of the discretization parameters is left to the user.

5.2.4 Iterative convergence and consistency tests

It is important to check that the implementation of the conceptual model as a computer program is done correctly. For this purpose, the following procedures should be executed, when applicable.

- Check the residual error criteria.

- Check for the stability of output variables.

- Apply global checks on the conservation of appropriate quantities.

- To the extent possible, do a comparison against analytic solutions.

- Do a comparison against more accurate solutions obtained by more complete models that are known to have been verified and validated.

- Check the effects of artificial boundary conditions for open-flow problems.

5.2.5 Review of the numerical treatment of models

A critical part of the assessment of a model is to verify that the equations and methods, as stated in the documentation describing the approach, have been implemented as intended. This includes an assessment of the documentation, an implementation of the equations in the computer code and an analysis of the discretization and numerical methods used.

5.3 Validation

5.3.1 The process of validation

The primary step is to compare predictions of the model or analytical technique with appropriate data. As outlined in the introduction, it is necessary to be clear that, whereas the model is the expression of a theoretical concept, experimental data are a representation of the real world. In this context, it is important to ensure that appropriate models and input data represent the experiment with which one is doing the comparison. Both representations have limitations and it is necessary that inherent errors and appropriate statements of the uncertainties in both be included in the comparison. Correctness in the sense of validation is that the model yields appropriate answers for input data representing the scenarios under consideration.

General analytic solutions do not exist for fire problems, even for the simplest cases. That is, there are no closed-form solutions to this type of problem. However, it is possible to do two kinds of checking. The first type is that by which individual algorithms are validated against experimental work. The second consists of simple experiments, e.g. conduction and radiation, for which the results are asymptotic. For example, for a simple, single-compartment test case with no fire, temperatures should equilibrate asymptotically to a single value. A model should be able to replicate this behaviour. Finally, it is possible to compute solutions to situations for which there are analytic answers, though these might not occur naturally.

Correlations are valid predictive tools and it is necessary that they be validated in the same sense as detailed computer models, using similar statistical methods.

The process of validation includes a statement of the range of validity of the input data.

The data, in general, are expected to ensure

- the completeness of environmental data, like temperature gradients in buildings or temperature differences between the building interior and the outside, wind effects,
- the use of correct property data; for example, if constants are used, it is necessary that a sensitivity analysis show their influence on the outputs. If constants are used instead of, for example, temperature-dependent variables, it is necessary that the outcome of this approximation (see above) be evaluated for the range of applicability of the model or calculation method.

For data taken from the literature, the sources shall be referenced. Examples for literature are handbooks, standards, journals, research reports. Where the data are not from peer-reviewed literature, they shall be checked against evidence.

The same principles apply, irrespective of the degree of sophistication of the representation of real-world phenomena, whether calculation methods or models, or both, are used to predict the course of a fire in a building or evacuation processes. Human behavioural aspects can also influence the results and should be evaluated based on the same principles. See, for example, Reference [3] for data for deterministic fire models.

5.3.2 Comparison of the complete calculation method against appropriate results

5.3.2.1 Comparison of a single-value prediction with data

While the results from algebraic equations are mostly single-value predictions, the same applies for these as for single-value predictions from computer models. Single-value predictions shall be checked against experimental or survey data, whenever these are available for the considered problem and if these were produced with an equivalent set of initial and boundary conditions. For more details, see 5.3.3. The description given there also applies to this subclause.

5.3.2.2 Comparison of a time-value prediction with data

Annex B describes a method for quantifying the similarities and differences of two curves, such as the time history of the upper-layer temperature for a model prediction and an experiment. It works by treating the curves as infinite dimensional vectors and then uses vector analysis to describe the differences. This analysis provides a quantitative method of verifying fire models and quantifying the uncertainty in experimental data.

While there are a variety of numbers that can be generated to describe the differences between two curves or a set of curves, two values are highlighted as giving appropriate information for determining the differences. The first, relative difference, gives a value for how different the two curves are. It is a positive, real-valued function that returns a 0 for identical curves; for curves that are different, it returns a value that increases with increasing difference. The second, the cosine, gives a measure of how the shapes of the two curves compare. It returns a value from 1 to −1 with 1 signifying that the curves have the same shape and −1, that the curves are mirror images; a value of 0 signifies that the curves have nothing in common.

Annex B describes the method and appropriate equations and shows examples of how to do the comparison.

5.3.2.3 Review of the theoretical and experimental basis of probabilistic models

The equations employed in a probabilistic model, typically as part of a risk assessment, are normally those that define risk in terms of a probabilistic function on a space defined by scenarios and those used to derive needed probabilities from other more readily available probabilities. The review of the correctness of the equations should answer the following questions.

- Does the model use only well defined probability variables and parameters?

  Probabilistic modelling and risk assessment typically use experiential databases or engineering judgment to produce probability variables and parameters. Evidence of accuracy of single-value variable or parameter estimates is obtained by comparing the estimates to alternative estimates computed in the same manner from independent data. For example, judgment values obtained from one group of experts can be compared to judgment values obtained from a second group of experts. In such a case, special attention should be paid to the characteristics of experts that are considered most likely to influence the judgments. Also, experientially based probabilities (for example ignition probabilities) can be verified by comparison to like probabilities based on experience from a different place or a different period of time.

  Output variables of a risk assessment are typically based on probabilities and consequences, where the latter are derived from a deterministic model. The deterministic-model predictions can be validated in the manner described elsewhere in this International Standard. The combined calculation of risk, either for the whole calculation or for a subsystem or other portion, can be validated by comparison with actual loss experience. Where the probability values are experientially based, the loss experience used for validation should be taken from the same places and times as were used to set the probability values.

- Do the probability variables, parameters and calculations follow the laws of probabilities (e.g. probabilities must fall between 0 and 1)?

- Are all equations that employ conditional probabilities complete?

  EXAMPLE For the equation $P(A) = [P(A \text{ given } B) \times P(B)] + [P(A \text{ given not } B) \times P(\text{not } B)]$.

  If the second part of the expression is omitted, it is necessary to make an explicit case that either $P(\text{not } B)$ or, more often, $P(A \text{ given not } B)$ is zero or approximately zero.

- Is risk defined by an explicit expression linking the measure of risk to probabilities and consequences of scenarios? If not, is there an underlying expression?

- Does the expression defining risk in terms of scenarios capture all possible scenarios? If not, does the calculation comprehensively address the impact of the omitted scenarios on the calculation?

- Are the uncertainties associated with the probabilistic variables and parameters explicitly addressed in the calculation? Are both random uncertainties and sources of systematic bias considered and addressed?

- If any equations are simplified from the complete forms, have they been compared for accuracy with their complete counterparts?

5.3.3 Comparison of subsystem models or of submodels against appropriate results

The comparison of the predictions of a subsystem model (e.g. smoke filling/venting) or of a submodel (e.g. plume model) with data gathered experimentally is the primary way users feel confident in its predictive capability. When a phenomenon is not well or fully understood, empirical validation provides a way of testing that its representation in the model (program) is adequate for the intended use of the program. Predictions should be made without reference to the experimental data used for the comparison. Of course, this restriction does not include required input data that may have been obtained by bench scale tests. Uncertainties in the measurements should be accounted for in a systematic and logical manner. No attempt to adjust a fit between the measurements and the predictions should be made.

Comparison of predictions with data requires

- thorough understanding of the sources of uncertainty in the data,
- quantification of these sources of uncertainty,
- sensitivity analysis to assess the effect of the uncertainty on the predictions,

- data/program comparison techniques to account for such uncertainty.

Most published work on the comparison of model predictions with experimental data is qualitative, i.e. reported as “satisfactory”, “good”, or “reasonable”. Some guidance on quantification is found in References [4] and [5].

All these comparisons may be against a) analytical solutions (c.f. verification), b) benchmark cases (well-defined, accurate results known), c) a set of experimental results, d) other computer codes, e) surveys.

5.4 Sensitivity analysis

A sensitivity analysis of a calculation method is a study of how changes in specific parameters affect the results generated by the calculation method. Predictions can be sensitive to uncertainties in input data, to the level of rigour employed in modelling the relevant physics and chemistry and to the use of inadequate numerical treatments. A well-designed and executed sensitivity analysis serves to

a) identify the dominant variables in the calculation methods,

b) define the acceptable range of values for each input variable,

c) demonstrate the sensitivity of output variables to variations in input data,

d) inform and caution any potential users about the degree and level of care necessary in selecting input and running the model,

e) provide insights as to which parameters should be monitored in large-scale experiments.

Conducting a sensitivity analysis of a complex fire model is an arduous task. Many models require extensive input data and generate predictions for numerous output variables over a period of simulated time. The technique chosen for use is dependent on the objectives of the study, the required results, the resources available and the complexity of the model being analysed.

Two basic approaches exist for obtaining sensitivity information.

- Local methods: These produce sensitivity measures for a particular set of input parameters and it is necessary that they be repeated for a range of input parameters to obtain information on the overall model performance. Finite difference methods can be applied without modifying a model's equation set, but require careful selection of input parameters to obtain good estimates. Direct methods supplement the equation set solved by a model with sensitivity equations derived from the equation set solved by the model in Reference [6]. The sensitivity equations are then solved in conjunction with the model's system of equations to obtain the sensitivities. It is necessary to incorporate direct methods into the design of a fire model that are not often available for already existing fire models.
- Global methods: These produce sensitivity measures that are averaged over the entire range of input parameters. Global methods require knowledge of the probability density functions of the input parameters, which, in the case of fire models, is generally unknown.

Local methods are most easily applied. Global methods are appropriate if the range of input information is known, for example in risk calculations for fire safety engineering.

Even though it is possible to define the sensitivities and establish various methods for their computation, there are still difficulties associated with performing a sensitivity analysis. Iman and Helton [7] note some of the following properties of complex computer models that make analysis difficult.

- There are many input and output variables.
- Discontinuities can exist in the behaviour of the model.
- Correlations can exist among the input variables, and the associated marginal probability distributions are often non-normal.

- Model predictions are nonlinear, multivariate, time-dependent functions of the input variables.
- The relative importance of individual input variables is a function of time.

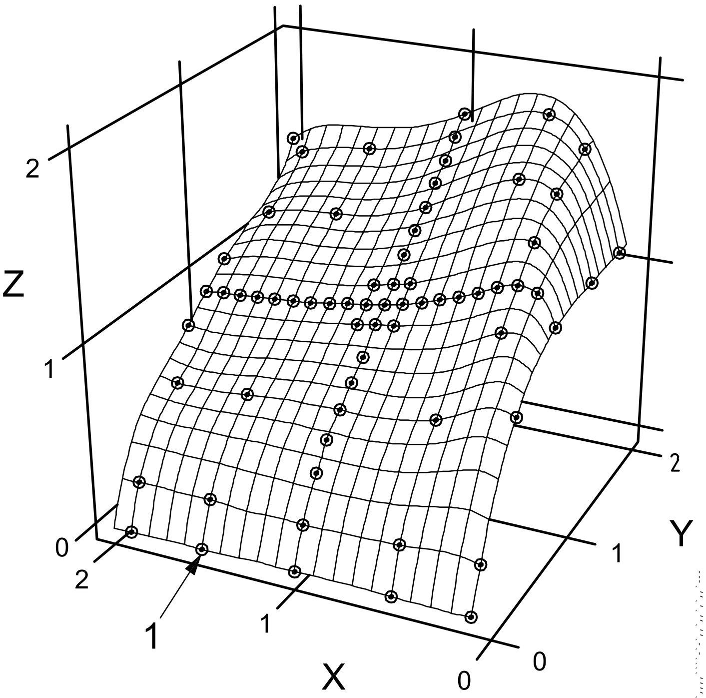
In addition, the sensitivity equations have similar properties. For a given model output and a given model input, there can be regions of time where the model output is sensitive to the input and also regions where the model output is insensitive to the same parameter.

At least two broad questions can be addressed with a sensitivity analysis of a fire model. First: “How sensitive is the model to a specific input?” This is an attempt to gain an overall appreciation of the importance of an input relative to all other inputs. For this question, the range of model inputs may be chosen as broad as possible, representing the range of applicability of the model. A subsequent analysis of model outputs for such broad changes then provides insight into the relative importance of a given input variable on selected outputs. Such an analysis provides an overall picture of model behaviour.

The second question is “How closely is necessary to specify a specific input?” Rather than understanding the overall behaviour of the model, it is an effort to obtain an understanding of the effect on the model outputs of uncertainties in selected inputs. For this question, small perturbations in the inputs may be examined. If a specific scenario is of interest, perturbations of the inputs for this scenario can be examined.

As suggested by Iman and Helton [7], an average relative difference can thus be used to characterize the model sensitivity for comparing individual inputs and outputs.

Figure 3 is a response surface for a fire model showing the effect of a changing heat-release rate (HRR) and vent size on the upper layer temperature [8]. It presents the effect of both peak HRR and vent opening (in the fire room) on the peak upper-layer temperature. In this figure, actual model calculations are normalized to the base scenario values as indicated by circles overlaid on a surface grid generated by a spline interpolation between the data points. From the surface, it is clear that HRR has more of an effect on the peak temperature than does the vent width. Until the fire becomes oxygen-limited, the trends evident in the surface are consistent with expectations: temperature goes up with rising HRR and down with rising vent width. The effects are not, of course, linear with either HRR or vent opening.



Key

X	normalized vent width
Y	normalized HRR
Z	normalized peak temperature
1	basic scenario values to which the actual model calculations are normalized

NOTE This figure shows the effect of a changing heat-release rate and vent size on the upper-layer temperature.

Figure 3 — Response surface for a fire model to characterize the model sensitivity for comparing individual inputs and outputs

5.5 Quality assurance

Evaluation of computer programs for the purpose of certifying quality assurance is advisable. The quality of such programs can be assessed by applying quality-assurance models. These make use of procedures that lead to an evaluation of both external quality, important for the end-user, and internal quality, important for the proper functioning of the program. Software quality attributes are categorized into six characteristics (functionality, reliability, usability, efficiency, maintainability and portability), which are further subdivided into sub-characteristics (see Figure 4). For each characteristic and sub-characteristic, the quality of the software should be determined by a set of measured internal attributes. The characteristics and sub-characteristics should be measured externally by the extent to which the capability is provided by the system containing the software.

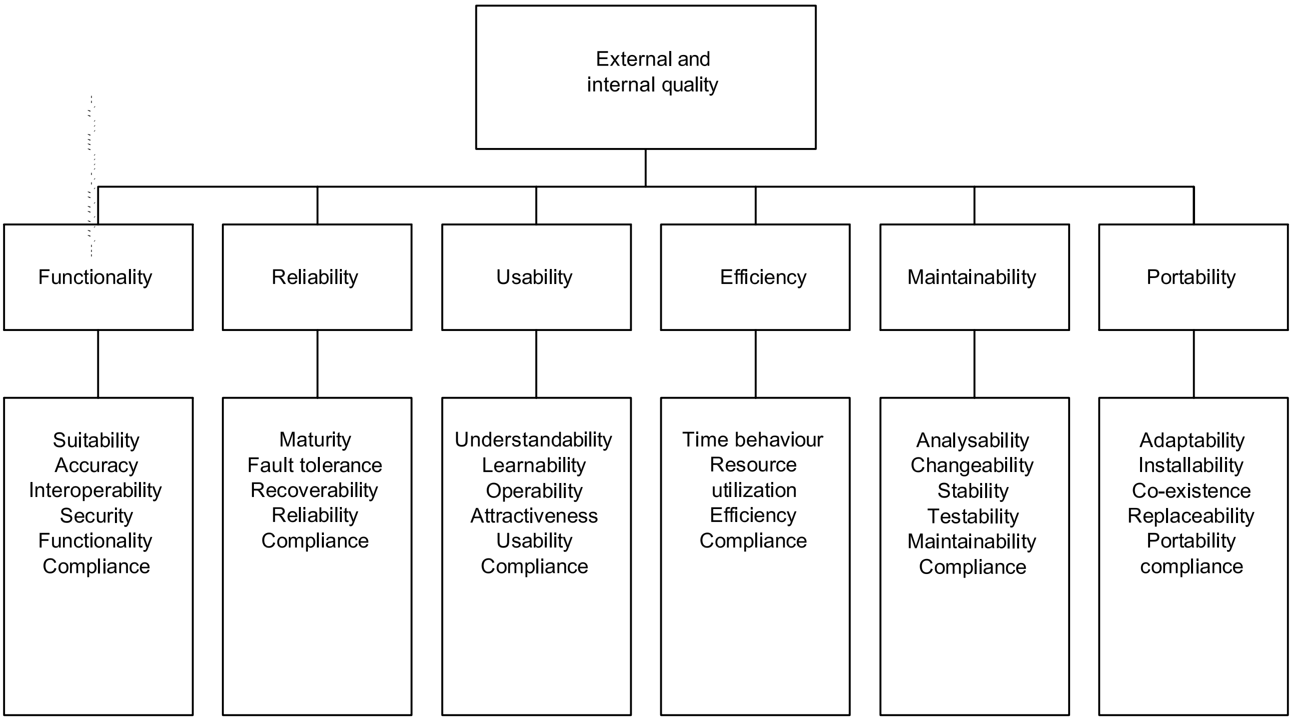


Figure 4 — Quality model for external and internal quality showing characteristics and sub-characteristics

For the assessment or evaluation of the quality of a calculation method, the procedures as outlined in the ISO/IEC 25000 series of standard documents based on ISO/IEC 9126-1 and on ISO/IEC 14598-1 apply. A short abridged version of the procedure is found in Annex C.

6 Requirements for reference data to validate a calculation method

Reference data to validate a calculation method can be obtained from experiments, surveys on (a) single or multiple similar, well documented fire event(s), or other validated calculation methods, as appropriate to the parameters and other quantities to be validated.

Data used to define, set or estimate a quantity in a calculation method cannot be used to validate that quantity. It is necessary that independent data be used for validation.

Differences between a calculation-method quantity and data used to validate that quantity can be due to errors in the quantity or errors in the data.

To support conclusions about the validity of the calculation method, it is necessary that the validation exercise assess the magnitude and nature of errors in the reference data and assess the impact of those errors on the differences between quantities and data. Therefore, it is necessary that the completeness, quality, precision and bias of the reference data be characterized, for example, by one of the following, before it can be used for validation.

- For experimental data, it is necessary that the repeatability and reproducibility of the test procedure that is the source of the data be assessed. Precision and bias characterizations of the reference data can be obtained from available precision and bias characterizations of the apparatus or measurement device that was used to generate the data.
- For (statistical) survey data, it is necessary that the representativeness of the survey design and achieved sample be assessed. It is also necessary to determine the uncertainty due to sample size.
- For forensic analysis data, it is necessary to state how these data were collected.
- For data from other validated calculation methods, the evidence from the validation of those methods, together with characterization of its precision, bias, and sources and magnitudes of error are required.

An assessment is needed of the correspondence between the conditions of reference-data collection and the conditions assumed by the calculation method. This includes initial and boundary conditions. For example, if experiments provide reference data on the evacuation performance of a population composed exclusively of young, healthy adults, then those data do not suffice to validate a calculation method applied to a more mixed population.

It is necessary to validate the whole calculation method and to validate its subsystems and sub-models separately. It is necessary that appropriate data be identified and acquired for each of these levels of validation.

It is necessary to assess any reduction, conversion or interpretation procedure applied to the raw data in order to produce reference data suitable for use in validation. For example, if raw survey data are available only for selected high-rise office buildings in a single city, then its applicability to other types of buildings of other heights in other cities in other countries is uncertain. It is necessary that this imperfect match be noted and assessed.

It is necessary to assess the independence of the reference-data generation and review from the development of the calculation method.

Full validation of a calculation method requires assessment of the full range of outputs for a full range of cases and conditions. Reference data are needed to support as complete an assessment as possible, and it is necessary that any limitations on the range of outputs and cases assessed be explicitly noted, if possible in the form of limitations on applications of the calculation method for which validation has been successfully completed. For example, if experimental data are available only for ceiling temperatures, then calculation-method predictions of temperatures elsewhere in a room have not been directly validated.

Annex A
(informative)

Uncertainty

A.1 Measurement uncertainty of data

A.1.1 General

Much of Clause A.1 is taken from Reference [1].

Clause A.1 is provided to assist experimenters in expressing the uncertainty of their measurements, and model users in judging the usefulness of experimental data when making an empirical validation of the model. Not all published experimental data include information on the uncertainty of the data.

In general, the result of measurement is only the result of an approximation or estimate of the specific quantity subject to measurement and, thus, the result is complete only when accompanied by a quantitative statement of uncertainty. The uncertainty of the result of a measurement generally consists of several components that, in the approach used by the International Council on Weights and Measures, may be grouped into two categories according to the method used to estimate their numerical values:

- type A: those that are evaluated by statistical methods;
- type B: those that are evaluated by other means.

Uncertainty is commonly divided into two components: random and systematic. Each component that contributes to the uncertainty of a measurement is represented by an estimated standard deviation, termed standard uncertainty, with a suggested symbol, u_i, and equal to the positive square root of the estimated variance, u_i^2. An uncertainty component in category A can be represented by a statistically estimated standard deviation, s_i, equal to the positive square root of the statistically estimated variance, s_{i2}, and the associated number of degrees of freedom, v_i. For such a component the standard uncertainty, u_i, is equal to s_i. In a similar manner, an uncertainty component in category B is represented by a quantity, u_j, which may be considered an approximation to the corresponding standard deviation; it is equal to the positive square root of u_{j2}, which may be considered an approximation to the corresponding variance and which is obtained from an assumed probability distribution based on all the available information. Since the quantity u_{j2} is treated like a variance and u_j like a standard deviation, for such a component, the standard uncertainty is simply u_j.

A.1.2 Type A evaluation of standard uncertainty

A type A evaluation of standard uncertainty may be based on any valid statistical method for treating data. An example is calculating the standard deviation of the mean of a series of independent observations using the method of least squares to fit a curve to data in order to estimate the parameters of the curve and their standard deviations. This report does not attempt to give detailed statistical techniques for carrying out statistical evaluations. See References [9] through [12] for comparison.

A.1.3 Type B evaluation of standard uncertainty

A type B evaluation of uncertainty is usually based on scientific judgment using all the relevant information available, which may include

a) previous measurement data,

b) experience with, or general knowledge of, the behaviour and property of relevant materials and instruments,

c) manufacturer's specifications,

d) data provided in calibration and other reports, and uncertainties assigned to reference data taken from handbooks.

Because the reliability of the evaluation of the components of uncertainty depends on the quality of information available, it is recommended that all parameters upon which the measurement depends be varied to the fullest extent practicable so that the evaluations are based as much as possible on observed data. Whenever feasible, the use of empirical models of the measurement process founded on long-term quantitative data, and the use of check standards and control charts that can indicate that a measurement process is under statistical control, should be part of the effort to obtain reliable evaluations of components of uncertainty.

A.1.4 Combined standard uncertainty

The combined standard uncertainty of a measured result, suggested symbol u_c, is taken to represent the estimated standard deviation of the result. It is obtained by combining the individual standard uncertainties, u_i, whether arising from a type A or a Type B evaluation, using the usual method for combining standard deviations. This method is often called the “law of propagation of uncertainty” or the “root-sum-of-squares method”. Combined standard uncertainty, u_c, is a widely used measure of uncertainty.

A.1.5 Expanded uncertainty

Although the combined standard uncertainty, u_c, is used to express the uncertainty of many measurement results, what is often required is a measure that defines the interval about the measurement result, y, within which the value of the measurement Y can be confidently asserted to lie. This measure is termed expanded uncertainty, suggested symbol U, and is obtained by multiplying $u_c(y)$ by a coverage factor, suggested symbol k. Thus,

$$U = kU(y) \tag{A.1}$$

and it can be confidently asserted that

$$y - U \leqslant Y \leqslant y + U \tag{A.2}$$

which is commonly written as

$$Y = y \pm U \tag{A.3}$$

In general, the coverage factor, k, is chosen at the desired level of confidence. Typically, k is in the range 2 to 3. When the normal distribution applies and u_c has negligible uncertainty, assigning k a value of 2 defines an interval having a level of confidence of approximately 95 %, and assigning k a value of 3 defines a level of confidence greater than 99 %. Current international practice is to use the value k equals 2.

A.1.6 Reporting uncertainty

To report measurement uncertainty, report U together with the coverage factor, k, used to obtain it, or report u_c. When reporting a measurement result and its uncertainty, include the following information in the report itself or refer to a published document:

- list of all components of standard uncertainty, together with their degrees of freedom, where appropriate, and the resulting value of u_c; the components should be identified according to the method used to estimate their numerical values (statistical or other means);
- detailed description of how each component of standard uncertainty was evaluated.

Annex B
(informative)

Example validation procedure

The key to validation of fire models is the ability to quantify the difference between model predictions and experimental measurements or between two model predictions or two experimental data sets. These techniques are considered useful in comparing models and experiments, comparing models to one another and comparing model predictions with sensor data for use in fire detection and prediction in real-time systems. The means to do this is through a mathematical technique known as functional analysis. Functional analysis is a generalization of linear algebra, analysis and geometry. It is a field of study that arose around 1900 from the work of Hilbert and others. Functional analysis is becoming of increasing importance in a number of fields including theoretical physics, economics and engineering to answer questions on differential equations, numerical methods, approximation theory and applied mathematical techniques. Problems are described in vector notation and appropriate operations on these vectors can be defined to allow quantitative analysis of the properties of the underlying physical system. The primary vector operations of interest are the norm, a measure of the length of a vector, and the inner product, a measure of the angle between two vectors.

To obtain an overall comparison of two curves, this single-point comparison can be extended to multiple points. Each of these curves can be represented as a multidimensional vector, with each point in time defining an additional dimension. Using such a vector notation, a direct extension of the simple comparisons of maximums is the norm of the difference of the vectors of experimental and model data.

The concept of a norm provides a definition of the length of a vector. The distance between two vectors is simply the length of the vector resulting from the difference of two vectors. The symbolic representation is written as $\|\vec{x}\|$ where $\vec{x}$ is the notation for the n-dimensional vector (x_1, x_2, …, x_{n-1}, x_n). For this example, the comparison of peak values is called the sup norm, or a norm based on maximum absolute values. To extend the sup norm, all of the data can also be represented by a vector of values measured at each time point, $\vec{E}$. The model predictions at the same time points can be represented by a vector $\vec{m}$. The distance between these two vectors is the norm of the difference of the vectors, or $\|\vec{E}-\vec{m}\|$. It is convenient to normalize this as a relative difference to the experimental data by the expression given in Equation (B.1):

$$\frac{\|\vec{E}-\vec{m}\|}{\|\vec{E}\|} \tag{B.1}$$

The difference vector is calculated just as it was for the simple example comparing the maximums of the two curves, taking the difference between the experiment and model at each time point. Initially, the Euclidean norm is most intuitive for computing length, as given in Equation (B.2):

$$\|\vec{x}\| = \sqrt{\sum_{i=1}^{n} x_i^2} \tag{B.2}$$

As discussed later, other geometries can also be useful for real-time comparisons. For the example in Figure B.1, the distance between the two vectors, $\|\vec{E}-\vec{m}\|$, is 14,1 and the relative difference is 0,056. For these simple curves, the comparison of peak values provides a good measure of the overall agreement, nearly identical to the overall comparison from Equation (B.1) since the two curves were chosen to differ only at the peak. For more complex curves, a comparison of the maxima might not be as good an indicator. Several examples are presented later in this annex.

While the difference, $\|\vec{E}-\vec{m}\|$, and the relative difference, $\|\vec{E}-\vec{m}\|/\|\vec{E}\|$, provide measures of the difference between experimental data and model predictions, other calculations provide useful information on the source of the difference. When comparing vectors, there are basically two geometric components to consider: a difference in length between the two vectors and the (non-zero) angle between the two vectors. The inner product, $\langle \vec{x}, \vec{y} \rangle$, of two vectors is the product of the length of the two vectors and the cosine of the angle between them, as given in Equation (B.3):

$$\langle \vec{x}, \vec{y} \rangle = \|\vec{x}\| \|\vec{y}\| \cos\left[\angle\left(\vec{x}, \vec{y}\right)\right] \tag{B.3}$$

which can be rearranged as given in Equation (B.4):

$$\cos\left[\angle\left(\vec{x}, \vec{y}\right)\right] = \frac{\langle \vec{x}, \vec{y} \rangle}{\|\vec{x}\| \|\vec{y}\|} \tag{B.4}$$

Choosing the inner product to be the standard dot product gives results consistent with typical Euclidean geometric perception as given in Equation (B.5):

$$\langle \vec{x}, \vec{y} \rangle = \sum_{i=1}^{n} x_i y_i \tag{B.5}$$

For this example, the $\cos\left[\angle\left(\vec{x}, \vec{y}\right)\right] = 0{,}99$. Visually, this angle between the two vectors represents a measure of how well the shapes of the two vectors match. As the cosine of the angle approaches unity, the overall shape of the curves becomes identical.

In general, an inner product is simply a function that takes two vectors and returns a number. The number can be either real or complex; for our purposes, only real inner products are considered. The axioms given in Table B.1 provide a sufficient definition of the inner product and norm to be able to perform the vector calculations [13].

Table B.1 — Axioms defining the inner product and the norm

Axiom	Inner product	Norm
I	$\langle \vec{x}, \vec{x} \rangle \geqslant 0$	$\|\vec{x}\| \geqslant 0$
II	$\langle \vec{x}, \vec{x} \rangle = 0 \Leftrightarrow \vec{x} = 0$	$\|\vec{x}\| = 0 \Leftrightarrow \vec{x} = 0$
III	$\langle \alpha\vec{x}, \vec{y} \rangle = \alpha \langle \vec{x}, \vec{y} \rangle$	$\|\alpha\ \vec{x}\| = \lvert\alpha\rvert\ \|\vec{x}\|$
IV	$\langle \vec{x} + \vec{y}, \vec{z} \rangle = \langle \vec{x}, \vec{z} \rangle + \langle \vec{y}, \vec{z} \rangle$	$\|\vec{x} + \vec{y}\| \leqslant \|\vec{x}\| + \|\vec{y}\|$
V	$\langle \vec{x}, \vec{y} \rangle = \overline{\langle \vec{y}, \vec{x} \rangle}$	—

These axioms provide appropriate rules to define the inner product and norm for other geometries in addition to Euclidean space. Three additional definitions, Hellinger, secant and a hybrid of Euclidean and secant, are considered. For consistency, the norm can be defined in terms of the inner product. This ensures that appropriate, consistent definitions for the norm and inner product are used in calculations. Since the angle between a vector and itself is by definition zero, Equation (B.6) follows from Equation (B.3):

$$\langle \vec{x}, \vec{x} \rangle = \|\vec{x}\|^2 \text{ or } \|\vec{x}\| = \sqrt{\langle \vec{x}, \vec{x} \rangle} \tag{B.6}$$

The Hellinger inner product for functions x, such that $x(0) = 0$, is defined based on the first derivative of the function, as given in Equation (B.7):

$$\langle x(t), y(t) \rangle = \int_0^T x'(t) y'(t) dt \tag{B.7}$$

For discrete vectors, this can be approximated with first differences as given in Equation (B.8):

$$\langle \vec{x}, \vec{y} \rangle = \frac{\sum_{i=1}^{n} \left(x_i - x_{i-1}\right)\left(y_i - y_{i-1}\right)}{t_i - t_{i-1}} \tag{B.8}$$

Based on the first derivative or tangents to the curves, the Hellinger inner product and norm provide a sensitive measure of the comparison of the shape of two vectors. A variation of the Hellinger inner product can be defined based on the secant rather than the tangent, as given in Equation (B.9):

$$\langle x(t), y(t) \rangle = \int_{pT}^{T} \frac{\left[x(t) - x(t - pT)\right]\left[y(t) - y(t - pT)\right]}{\left(pT\right)^2} dt \tag{B.9}$$

where $0 < p \leqslant 0{,}5$ defines the length of the secant. The limit of the secant inner product as $p \to 0$ is the Hellinger integral. For discrete vectors, this can be approximated analogous to the Hellinger geometry as given in Equation (B.10):

$$\langle \vec{x}, \vec{y} \rangle = \frac{\sum_{i=1,s}^{n} \left(x_i - x_{i-s}\right)\left(y_i - y_{i-s}\right)}{t_i - t_{i-s}} \tag{B.10}$$

When $s = 1$, the secant definition is equivalent to the discrete Hellinger inner product. Depending on the value of p or s, the secant inner product and norm provide a level of smoothing of the data and thus better measures large-scale differences between vectors. For experimental data with inherent small-scale noise or model predictions with numerical instabilities, the secant provides a filter to compare the overall functional form of the curves without the underlying noise. Finally, a hybrid of the Euclidean and secant inner product provides a balance between the rank ordering of the Euclidean norm and the functional form comparison of the secant. From the axioms above, the sum of two inner products is also an inner product. In this International Standard, a simple weighted sum of the Euclidean inner product and secant inner product is considered, or as given in Equation (B.11):

$$\langle \vec{x}, \vec{y} \rangle = \frac{1}{n} \sum_{i=1}^{n} x_i y_i + \frac{1}{n - s} \frac{\sum_{i=1,s}^{n} \left(x_i - x_{i-s}\right)\left(y_i - y_{i-s}\right)}{t_i - t_{i-s}} \tag{B.11}$$

The weighting factors equalize the contribution of the Euclidean inner product and the secant inner product to the combination.

Figure B.2 shows a simple example of data compared with three model predictions. Model 1 is simply the experimental data multiplied by 0,9. Model 2 has the same peak value as model 1, but with the peak shifted –25 s. Model 3 has the same peak as model 1 and model 2, but with a 20 s plateau centered around the peak of the experimental data. The comparison only of maxima shows that all three models are identical with a relative difference of 0,1. Clearly, this comparison fails to capture the differences between the three models. Table B.2 shows the relative difference and cosine between the vectors of experimental data and model predictions for the three models using other definitions for the inner product and norm.

All of the metrics rank the models in the same order, with model 1 closest to the experimental data, followed by models 2 and 3. The rank order matches a visual interpretation of the comparisons. Model 1 is clearly the best, with the same functional form and a peak timed correctly but slightly lower than the experimental data. Conversely, model 2, with its peak significantly offset from the experiment, appears the worst. Although model 3 does not have the correct type of peak (an elongated plateau rather than a sharp peak), it does have the right general form; changing to match the experiment.

The relative difference for model 1 is the same for all of the metrics, as it should be. By choice, the vector form of model 1, $\vec{m}$, is simply $\vec{m} = 0{,}9\vec{E}$. Thus, the relative difference, $\left\| \vec{E} - \vec{m} \right\| / \left\| \vec{E} \right\|$, regardless of the definition of the norm, is just $\left\| \vec{E} - 0{,}9\vec{E} \right\| / \left\| \vec{E} \right\|$ or 0,1. Similarly, the cosine of the angle between model 1 and the experiment is 1,0 for all of the comparisons.

While both the Euclidean relative difference and cosine have the appropriate ranking for all of the models, the cosine does not provide much differentiation between the model predictions. The Hellinger and secant values provide a wider range since they specifically compare the functional forms of the experiment and models.

As an example, a comparison of the model CFAST with five different real-scale fire tests is shown in Table B.3, using this technique. They consist of the following.

a) A single-room test using upholstered furniture as the burning item was selected for its well-characterized and realistic fire source in a simple single-room geometry; see Reference [14].

b) A single-room fire test using furniture as the fire source [15] provided a test similar to the first test with a more realistic fire source.

c) A three-room configuration, for which the average of a series of 11 replicate tests with simple steady-state gas-burner fires is cited.

d) A series of tests conducted in a multiple-room configuration with more complex gas-burner fires [16] than the previous data set is considered.

e) A series of full-scale experiments is conducted to evaluate zoned smoke-control systems, with and without stairwell pressurization [17]. This latter test was conducted in an eight-story hotel with multiple rooms on each floor and a stairwell connecting to all floors. A selection of data from these same tests is used in this International Standard to provide examples of equivalent comparisons quantified using the norm and inner product. Details of the geometry, experimental measurements, and model predictions are available [18]. Table B.2 presents the hybrid relative difference norm, Equation (B.1), and cosine of the angle between the vectors of experimental data and model predictions for a selection of the data from these five tests. To better understand these quantified comparisons, Figure B.3 shows the experimental data and model predictions for one of the variables included in Table B.3.

Figure B.3 shows a comparison of upper-layer temperatures for a single-room test. In this test, two measurement positions are available from the experimental data. The predicted temperatures show obvious similarities to the measured values. Peak values occur at similar times with comparable rise and fall for both measurement positions. For both positions, peak temperatures are higher than the model predictions, with one position somewhat higher than the other position. Both the relative difference norm and cosine reflect these trends. The relative-difference norm is somewhat higher for one of the experimental positions (0,36 versus 0,31), reflecting the higher temperature at this measurement position. With the shapes of all the curves similar, the cosine shows similar values for both curves (0,93 and 0,95).

For the experiments and models examined, the techniques provide the ability to quantify the comparison of the magnitude and functional form consistent with visual examination of the comparisons.

Table B.2 — Comparison of “fictional” experimental data with three model predictions using several different inner product definitions

Geometry	Model	Relative difference	Cosine
Euclidean	1	0,10	1,00
	2	0,40	0,92
	3	0,20	0,98
Hellinger	1	0,10	1,00
	2	0,94	0,58
	3	0,74	0,77
Secant	1	0,10	1,00
	2	0,92	0,58
	3	0,66	0,83
Hybrid	1	0,10	1,00
	2	0,64	0,78
	3	0,43	0,91

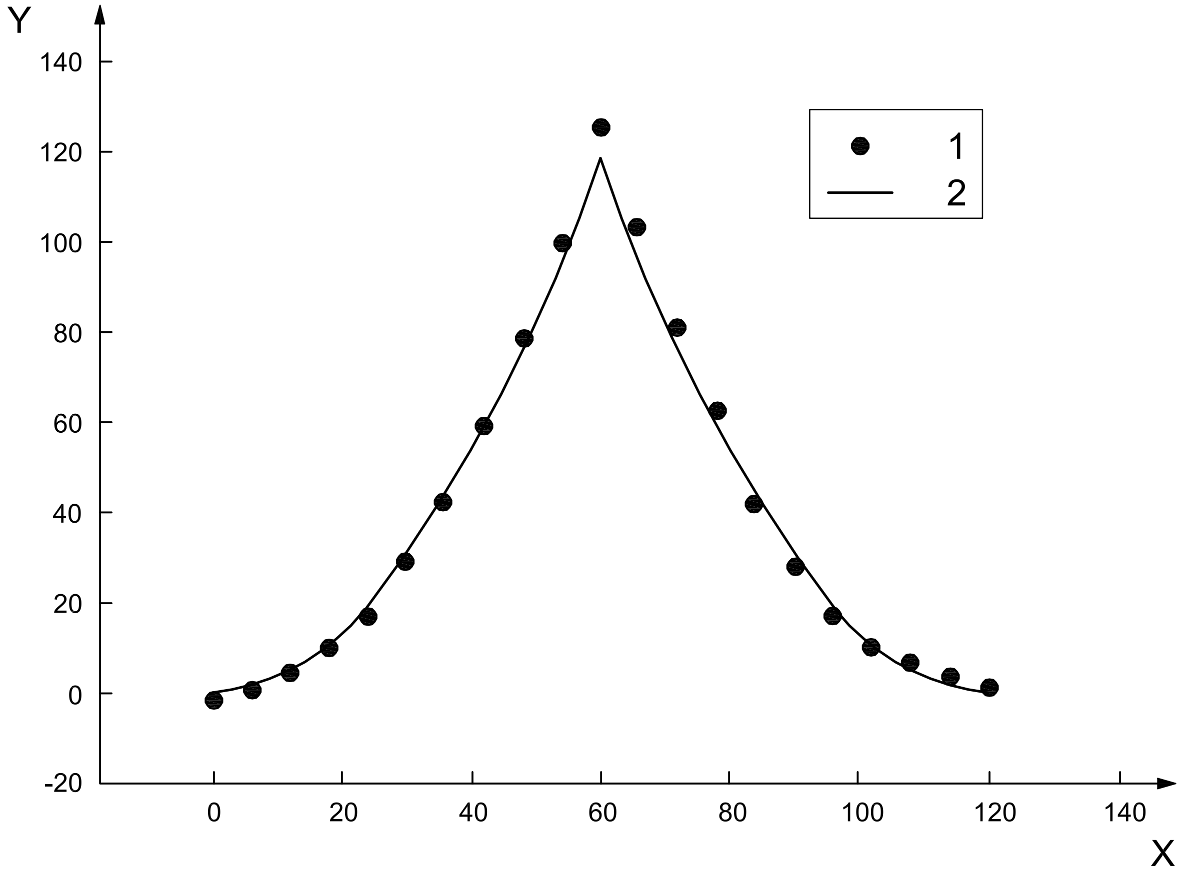
Table B.3 — Comparison of experimental measurements and model predictions for several tests

Upper- and lower-layer temperatures and interface position							
Test model	**Position/ compartment**	**Upper-layer temperature**		**Lower-layer temperature**		**Interface position**	
		Relative difference	**Cosine**	**Relative difference**	**Cosine**	**Relative difference**	**Cosine**
Single-room furniture tests	1	0,31	0,95	0,47	0,92	1,38	– 0,60
	2	0,36	0,93	0,63	0,78	0,63	0,78
Three-room tests with corridor	1	0,25	0,97	[a]	[a]	[a]	[a]
	2	0,26	0,99	[a]	[a]	[a]	[a]
	3	0,26	0,98	[a]	[a]	[a]	[a]
Four-room tests with corridor	1	0,51	0,93	0,33	0,95	2,26	0,06
	2	0,54	0,91	0,52	0,87	[a]	[a]
	3	0,36	0,97	0,78	0,86	[a]	[a]
	4	0,20	0,98	[a]	[a]	[a]	[a]
Multiple-story building	1	0,28	0,97	[a]	[a]	[a]	[a]
	2	0,27	0,96	[a]	[a]	[a]	[a]
	7	2,99	0,20	[a]	[a]	[a]	[a]

Gas concentrations							
Test model	**Position/ compartment**	**Oxygen**		**Carbon monoxide**		**Carbon dioxide**	
		Relative difference	**Cosine**	**Relative difference**	**Cosine**	**Relative difference**	**Cosine**
Single-room furniture tests	1	0,48	0,90	0,93	0,66	0,69	0,93
Four-room tests with corridor	1	0,85	0,53	1,05	0,61	1,16	0,63
	2	0,93	0,39	1,02	0,57	0,90	0,63
Multiple-story building	2	0,74	0,68	0,72	0,90	0,87	0,93

Heat-release, pressure and vent flow							
Test model	**Position/ compartment**	**Heat release**		**Pressure**		**Vent flow**	
		Relative difference	**Cosine**	**Relative difference**	**Cosine**	**Relative difference**	**Cosine**
Single-room furniture tests	—	0,19	0,98	[a]	[a]	0,61	0,79
Single-room tests with wall burning	—	0,21	0,98	1,31	0,80	—	—
Three-room tests with corridor	1	0,43	0,96	0,15	0,99	0,14	0,99
	2	[a]	[a]	0,68	0,98	0,20	0,98
Four-room tests with corridor	—	[a]	[a]	6,57	0,74	[a]	[a]
Multiple-story building	1	[a]	[a]	1,12	–0,41	[a]	[a]

[a] Data for the comparison are not available.

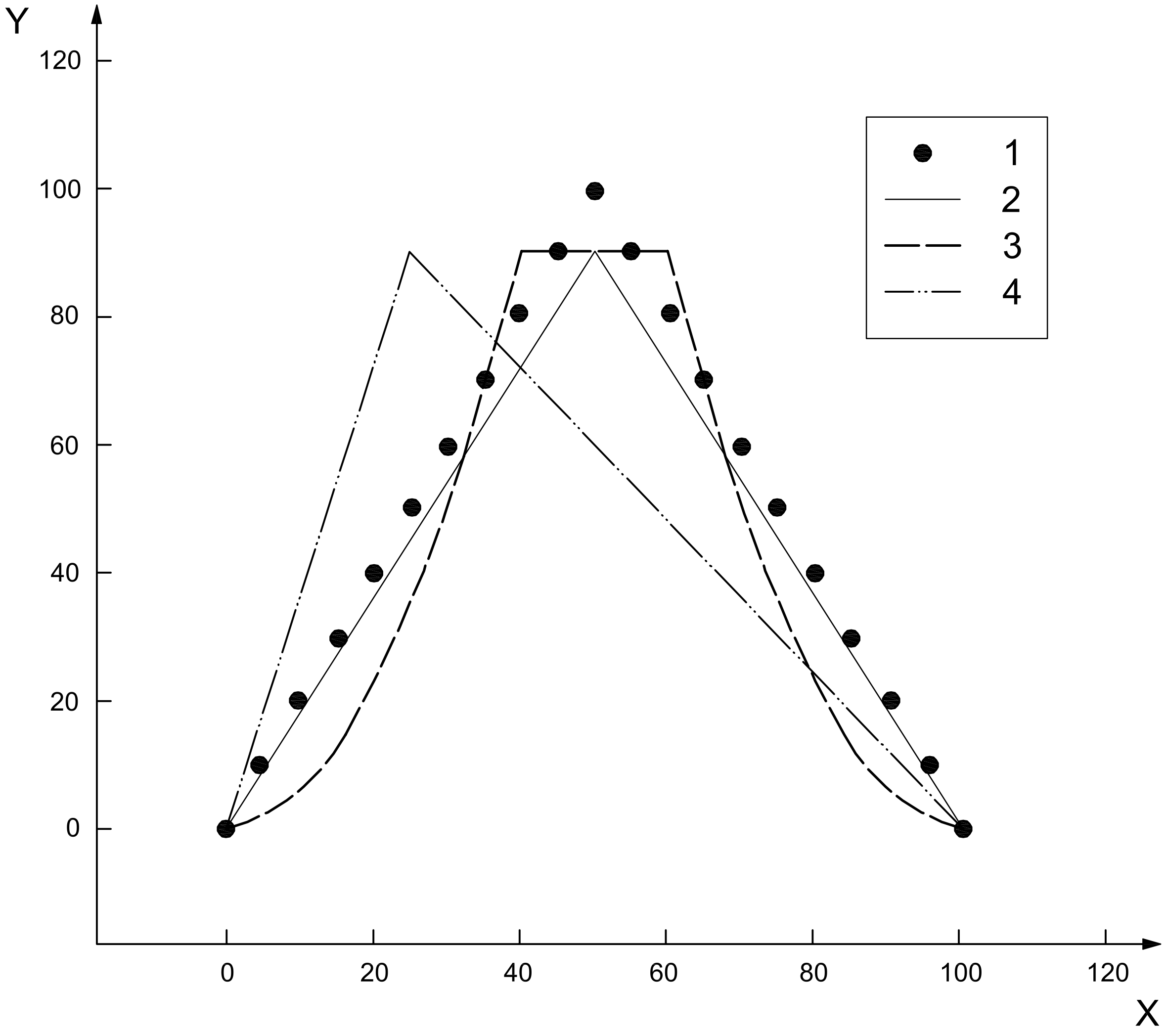


Key

X time
Y measurement

1 experimental data points
2 model

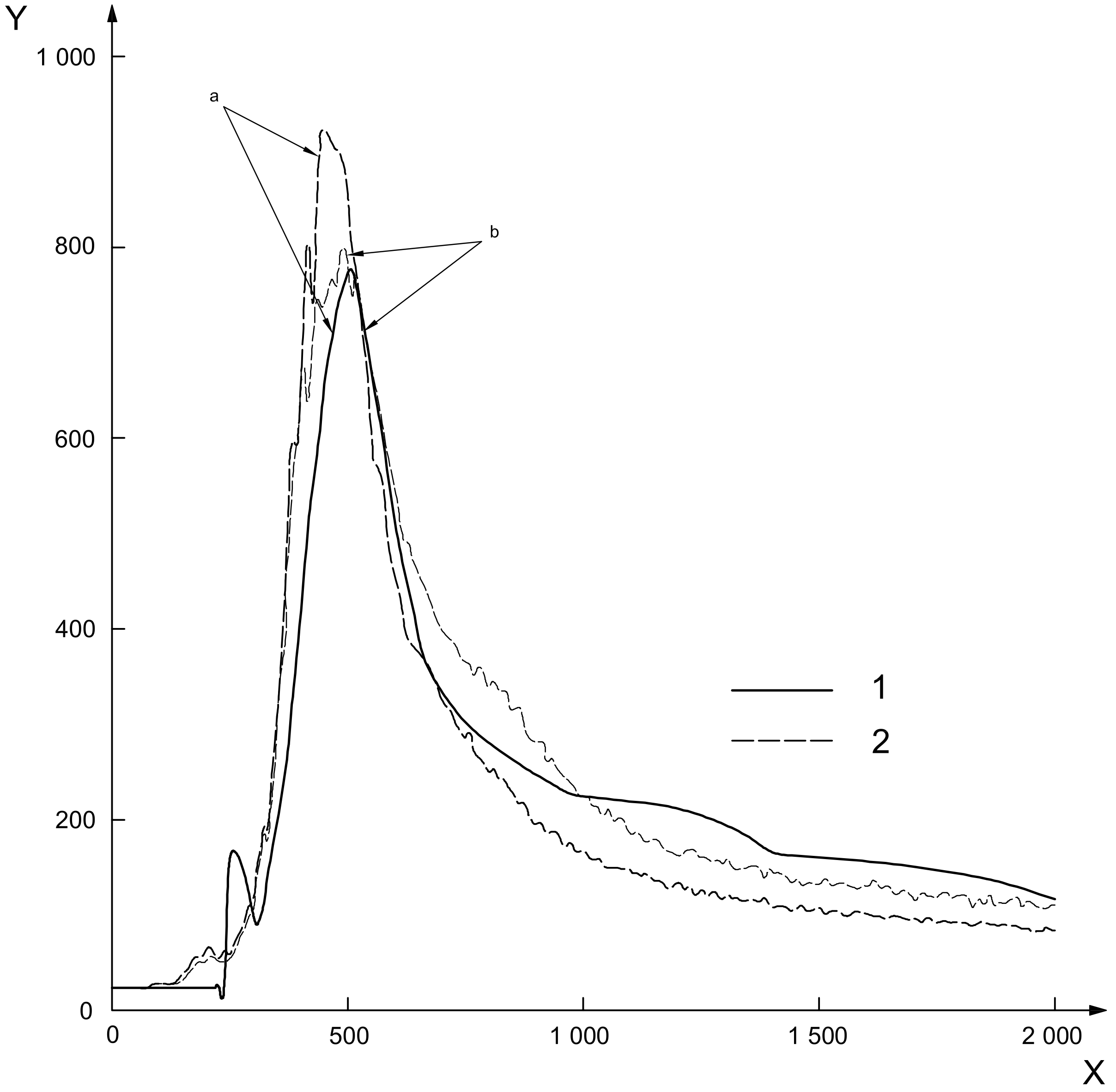
Figure B.1 — Simple example of experimental data compared with a model prediction



Key

X	time
Y	measurement
1	Col 6 vs Col 7
2	Col 6 vs Col 9
3	Col 6 vs Col 11
4	Col 6 vs Col 13

Figure B.2 — Three possible model predictions for an example of experimental data



Key

X time (s)
Y temperature (°C)

1 model
2 experimental data

[a] Relative difference equals 0,36; cosine equals 0,95.

[b] Relative difference equals 0,31; cosine equals 0,93.

Figure B.3 — Comparison of the upper-layer temperature for a single-room test

Annex C
(informative)

Quality-assurance methodology

C.1 General

The process of evaluation is outlined in Figure C.1 and Clauses C.2 to C.5 (see also 5.5.).

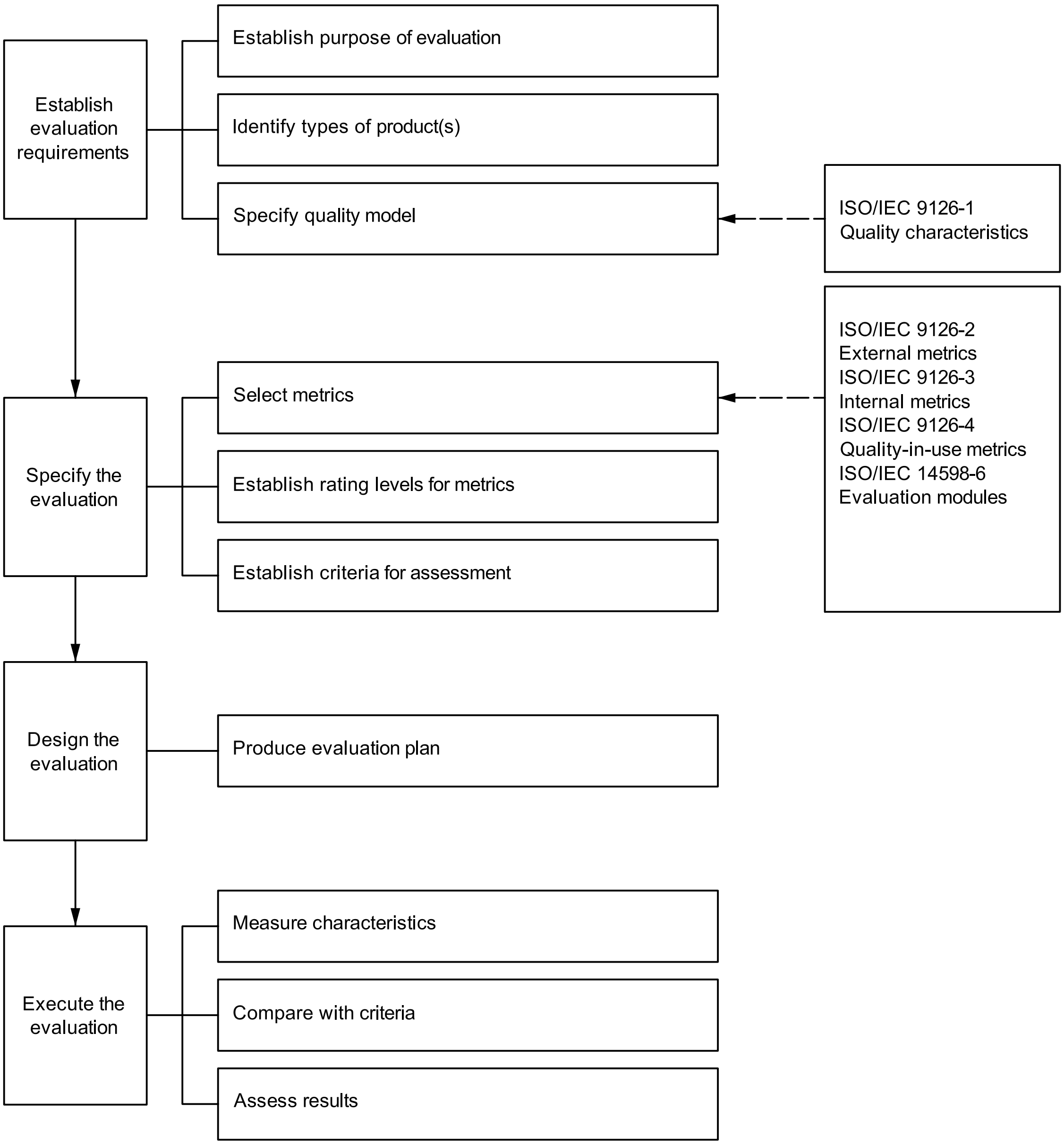


Figure C.1 — Process of evaluation (taken from ISO/IEC 14598-1)

C.2 Establish evaluation requirements

C.2.1 Establish the purpose of evaluation

The purpose of software product evaluation is, in general, to compare the quality of a software product against quality requirements that express user needs, or even to select a software product by comparing different software products, or ranking a product with regard to its competitors. This general objective can be better specified when considering the point of view of the software product evaluation, such as acquisition, during development, or under operation conditions.

C.2.2 Identify types of product(s) to be evaluated

The types of products being evaluated depend on the purpose of the evaluation. As a first step, the evaluator should define the products being evaluated as intermediate (during the development life cycle) or final products. Products being evaluated can be measured using: external metrics, when the product is a part of a complete hardware/software system under operation; internal metrics that can be applied to measure internal properties of the software (e.g. specification or source code); and quality-in-use metrics, which measure the effect of the use of the software in a specified environment.

C.2.3 Specify quality model

The quality model specified for the evaluation is the reference for the software product requirements definition. At this evaluation step, the requirements are described for relevant quality characteristics, being prioritized according to the user needs.

C.3 Specify the evaluation

C.3.1 Select metrics

The quantitative specification and measurement of the software product quality requirements can be made only by using metrics that are associated with desired quality characteristics. Metrics may be

- internal, e.g. associated with the software product architecture and allowing a prediction of the final product quality;
- external, e.g. measurable when the product is under operation;
- quality-in-use, e.g. for evaluating the effect of the software-product use.

The choice of metrics for use during the software-product evaluation depends on the purpose of the evaluation, the selected quality characteristics and on how easy and economical it is to apply the measurements. The metrics used for comparisons should also be valid and sufficiently accurate to allow reliable comparisons to be made. This means that measurements should be objective, empirical, using a valid scale, and reproducible.

C.3.2 Establish rating levels for metrics

For each selected metric, the rating values shall be defined for the related scale, where the required level of the attribute being measured is expressed. The adopted scale can indicate limits for each attribute, identifying whether the measured value is, for instance, unacceptable, minimally acceptable, within the target range or whether it exceeds the requirements.

C.3.3 Establish criteria for assessment

The assessment criteria do not require summarizing the measurement values to generate a unique indicator which represents the product quality, since the quality is characterized by the adherence to established requirements. In such manner, the cost and schedule can be sensitive to each established requirement and its measured value. When the evaluation process is used to make a choice among different products, it can be necessary to establish a model that represents the perceived commercial value of each product from the measured values, in order to make more objective comparisons.

C.4 Design of the evaluation and production of an evaluation plan

Documenting evaluation methods and producing a draft plan requires addressing issues such as

- technical constraints related to the measurements or verifications,
- evaluation methods for each measurement or verification that shall be documented,
- identification of software tools used for measurements,
- identification of products components on which the method is to be applied,
- specification of interpretation of results, when necessary,
- description of the environment,
- optimizing the evaluation plan addressing issues, such as the revision of the draft evaluation plan to avoid duplicating evaluator actions,
- scheduling evaluation actions with regard to available resources, addressing issues such as the measurement and the schedule of planned actions, and taking into consideration
  - the delivering schedule for the product and components,
  - the relation between the evaluator and the developer,
  - access to development and operational sites.

NOTE It is advisable for the users of this International Standard to start reading the related clauses from ISO/IEC 14598-2 and consider the information in the other parts of ISO/IEC 14598 in order to have a broader comprehension of this issue when intending to prepare an evaluation plan.

C.5 Execute the evaluation

C.5.1 Take measures

The selected metrics are for application to the software product, resulting in values on the scales of the metrics.

C.5.2 Compare with criteria

The measured values are compared with the criteria established in the specification. For end-product measurements, the values shall be compared with target values.

The measured values shall be used to identify

- each deficiency of the product and how each deficiency can be resolved,

- any additional evaluations required to resolve any identified deficiencies; this additional evaluation can, for instance, confirm that there is no deficiency, or be used to verify the correct and acceptable performance of the software once a design change or changes have been made to correct deficiency,
- whether it is necessary to limit or control the use of the software product and, in this case, whether the limitation, for instance, impacts on the mandatory requirements, requires additional evaluation work or impacts on the application design, budget or schedule,
- any exclusions from the scope of evaluation and/or restrictions on the results for each evaluation, such as: “This evaluation does not include a detailed review of the functionality of the product.”,
- the integrated results of all the evaluation activities to allow an overall conclusion for the evaluation of the software product to be made.

C.5.3 Assess results

In the assessment activity, a set of rated values is summarized and a statement of the extent to which the software product meets quality requirements is made. This summary is then compared with other aspects, such as time and cost. Finally, based on managerial criteria, a managerial decision is made on the acceptance or rejection or on the release or non-release of the software product. The evaluation results influence the next software development life-cycle steps; for instance, “should the requirements be changed or are more resources necessary for the development process?”

It is necessary to draw conclusions that can be explained by two complementary approaches:

a) by formalizing the conclusions using a “statement of requirements compliance” that clarifies how each requirement has been met;

b) by making a final decision either to accept or not to accept a software product for use and consider possible alternatives; for instance, if the decision is to not accept, consider modifying the product or changing the requirements.

It is also necessary to consider that, although the evaluator is responsible for the evaluation conclusion, he can accomplish the final assessment only if this is stated in the evaluation specification. The evaluator usually delivers to the requester the evaluation report, which may contain some conclusion, and then the requester finishes the assessment based on this report. This occurs because the final assessment can take into consideration strategic decisions for the organization, such as cost, adaptations to be implemented and time to deliver.

C.6 Examples

NOTE Taken from ISO/IEC TR 9126-2.

C.6.1 Choice of metrics and measurement criteria

The bases on which the metrics are selected depend on the business goals for the product and the needs of the evaluator. Needs are specified by criteria for measures. The model in ISO/IEC 9126-2 supports a variety of evaluation requirements, for example

- a user or a user's business unit may evaluate the suitability of a software product using metrics for quality in use,
- an acquirer may evaluate a software product against criterion values of external measures of functionality, reliability, usability and efficiency, or of quality in use,
- a maintainer may evaluate a software product using metrics for maintainability,

- a person responsible for implementing the software in different environments may evaluate a software product using metrics for portability,
- a developer may evaluate a software product against criterion values using internal measures of any of the quality characteristics.

NOTE ISO/IEC 9126-4 provides requirements and guidance for the choice of metrics and measurement criteria for software-product evaluation.

C.6.2 Rating levels for metrics

Quantifiable features can be measured quantitatively using quality metrics. The result, i.e. the measured value, is mapped on the scale. This value does not itself show the level of satisfaction. For this purpose, it is necessary to divide the scale into ranges corresponding to the different degrees of satisfaction of the requirements. Examples are

- dividing the scale into two categories: unsatisfactory and satisfactory,
- dividing the scale into four categories bounded by the current level for an existing or an alternative product, the worst case, and the planned level. The current level is stated in order to control that the new system does not deteriorate from the present situation. The planned level is what is considered achievable with the resources available. The worst case level is a boundary for user acceptance, in case the product does not fulfil the planned level (see Figure C.2).

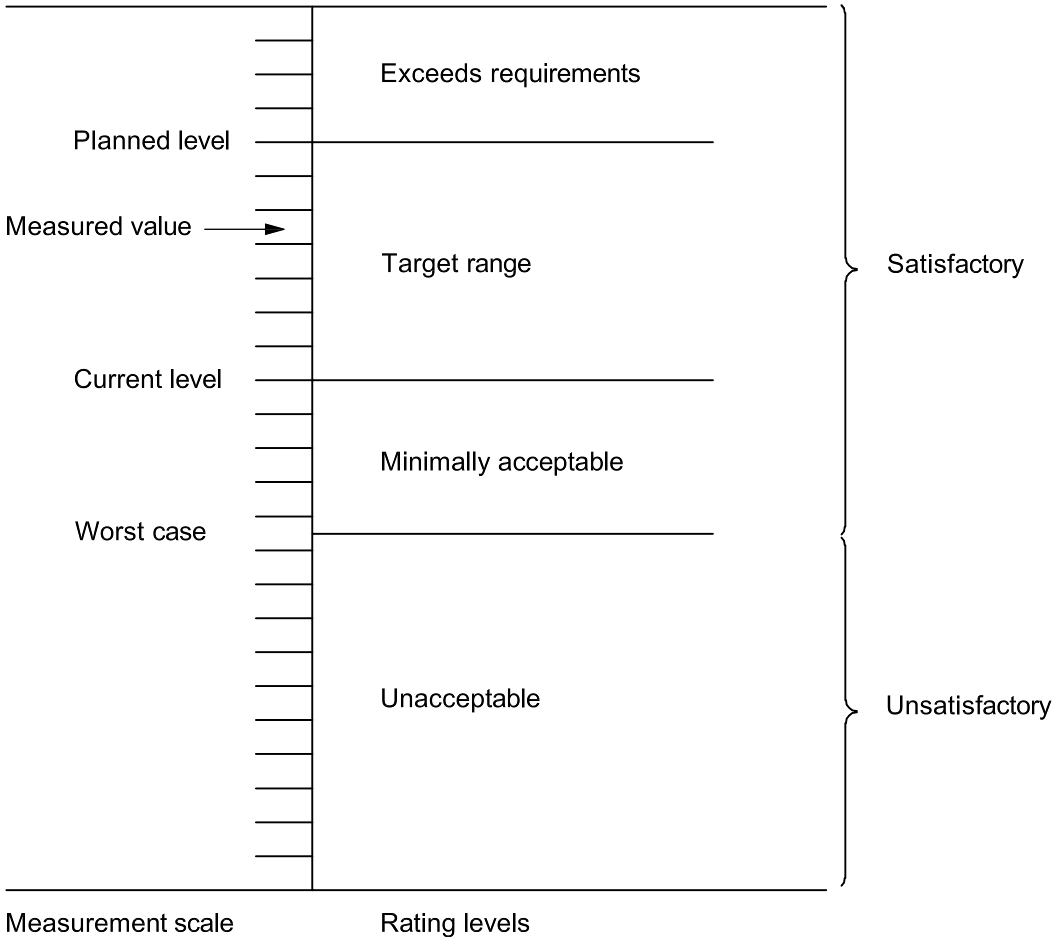


Figure C.2 — Rating level for metrics

C.6.3 Metrics for assessment — Establishing assessment criteria

Software-quality-requirements specifications shall be defined using an appropriate, well-defined quality model. For this purpose, the quality model and definitions in ISO/IEC 9126-2 should be used, unless there is a particular reason to use another model.

To assess the quality of the product, it is necessary to summarize the results of the evaluation of the different characteristics. The evaluator should prepare a procedure for this, with separate criteria for different quality characteristics, each of which may be in terms of individual sub-characteristics, or a weighted combination of sub-characteristics. The procedure usually includes other aspects, such as time and cost, that contribute to the assessment of the quality of a software product in a particular environment.

Bibliography

[1] TAYLOR, B.N. and KUYATT, C.E., *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results*, NIST Technical Note 1297

[2] COX, G., *Combustion Fundamentals of Fire*, Academic Press, London, 1995

[3] ASTM E1591–07, *Standard Guide for Obtaining Data for Deterministic Fire Models*1)

[4] BEARD, A., The Limitations of Computer Models, *Fire Safety Journal*, **18**, pp. 375-391, 1992

[5] BEARD, A., Evaluation of Deterministic Fire Models: Part I — Introduction, *Fire Safety Journal*, **19**, pp. 295-306, 1992

[6] WIERZBICKI, A., *Models and Sensitivity of Control Systems*, Wiley and Sons, New York, 1984

[7] IMAN, R.L. and HELTON, J.C., An Investigation of Uncertainty and Sensitivity Analysis Techniques for Computer Models, *Risk Analysis*, **8**, No. 1, pp. 71-90, 1988

[8] PEACOCK, R., RENEKE, P. and FORNEY, C., Issues in Evaluation of Complex Fire Models, and M. Kostreva, *Fire Safety Journal*, **30**, p. 103, 1998

[9] PATANKAR, S.Y., Numerical Heat Transfer and Fluid Flow, *Hemisphere*, Washington, 1980

[10] MANDEL, J., *The Statistical Analysis of Experimental Data*, Interscience-Wiley Publishers, New York, NY, 1964 (out of print; corrected and reprinted, Dover Publishers, New York NY, 1984)

[11] NATRELLA, M.G., Experimental Statistics, *NBS Handbook 91*, U.S. Government Printing Office, Washington DC, 1963; reprinted October, 1996

[12] BOX, G.E.P., HUNTER, W.G. and HUNTER, J.S., *Statistics for Experimenters*, John Wiley & Sons, New York, NY, 1978

[13] KREYSZIG, E., *Introductory Functional Analysis with Applications*, John Wiley and Sons, New York, pp. 63-64, 1989

[14] BABRAUSKAS, V., Upholstered Furniture Room Fires — Measurements, Comparison with Furniture Calorimeter Data, and Flashover Predictions, *J. Fire Sci.*, **4**, pp. 5-19, 1984

[15] LEE, B. T., *Effect of Wall and Room Surfaces on the Rates of Heat, Smoke, and Carbon Monoxide Production in a Park Lodging Bedroom Fire*, Natl. Bur. Stand. (U.S), NBSIR 85-2998, 78 pp., 1985

[16] HESKESTAD, G. and HILL, J.P., Propagation of Fire and Smoke in a Corridor, Proceedings of the 1987 ASME:JSME Thermal Engineering Joint Conference 1987, Honolulu, HI, pp. 371-379

[17] KLOTE, J.H., *Fire Experiments of Zoned Smoke Control at the Plaza Hotel in Washington DC*, Natl. Inst. Stand. Technol., NISTIR 90-4253, 75 pp., 1990

[18] PEACOCK, R.D., JONES, W.W. and BUKOWSKI, R.W., Verification of a Model of Fire and Smoke Transport, *Fire Safety Journal*, **21**, pp. 89-129, 1999

[19] BABUSKA, I., ODEN, J.T., Verification and validation in computational engineering and science: basic concepts, *Computer methods in applied mechanics and engineering*, **193**, pp. 4057-4066, 2004

---

1) ASTM, Philadelphia.

[20] Patrick, J., Roache, P.J., *Verification and Validation in Computational Science and Engineering*, Hermosa publishers, 1998

[21] ISO/IEC TR 9126-2:2003, *Software engineering — Product quality — Part 2: External metrics*

[22] ISO/IEC TR 9126-4:2004, *Software engineering — Product quality — Part 4: Quality in use metrics*

[23] ISO/IEC 14598-2:2000, *Software engineering — Product evaluation — Part 2: Planning and management*

[24] ISO/IEC 14598-3:2000, *Software engineering — Product evaluation — Part 3: Process for developers*

[25] ISO/IEC 14598-4: 1999, *Software engineering — Product evaluation — Part 4: Process for acquirers*

[26] ISO/IEC 14598-5:1998, *Information technology — Software product evaluation — Part 5: Process for evaluators*

[27] ASTM E1355-05, *Standard Guide for Evaluating the Predictive Capability of Fire Models*

[28] ASTM E603-07, *Standard Guide for Room Fire Experiments*

[29] ASTM E1472-07, *Standard Guide for Documenting Computer Software for Fire Models*

[30] Atkinson, K.E., *An Introduction to Numerical Analysis*, Singapore, John Wiley & Sons, 1988

[31] Babrauskas, V., Peacock, R.D., Janssens, M. and Batho, N.E., Standardizing the Exchange of Fire Data — The FDMS, *Fire and Materials*, **15**, pp. 85-92, 1991

[32] Babuska, I. and Oden, J.T., Benchmark Computation: What is the Purpose and Meaning. *IACM Bulletin*, **7**, No. 4, Oct.-Dec. 1992

[33] Beard, A., On Comparison Between Theory and Experiment, *Fire Safety Journal*, **19**, pp. 307-308, 1992

[34] Beard, A., Reliability and Computer Models, *Journal of Applied Fire Science*, **3**(3), pp. 273-279, 1993-94

[35] Belytschko, T., Hughes, J.R.T., *Computational Methods for Transient Analysis*, North-Holland, Elsevier Science Publishers, 1983

[36] BS 476-32, *Fire tests on building materials and structures. Guide to full scale fire tests within buildings*[2]

[37] Cilia, M.A. and Gray, W.G., *Numerical Methods for Differential Equations*, Prentice-Hall, 1992

[38] Davies, A.D., Some Tools for Fire Model Validation, *Fire Technology*, **23**, pp. 95-114, 1987

[39] Fire Modelling, *BRE Digest*, p. 367, 1991

[40] Friedman, R., An International Survey of Computer Models for Fire and Smoke, *Journal of Fire Protection Engineering*, **4**, p. 81-92, 1992

[41] Guidelines for Model Developers, Model Evaluation Group, European Communities Directorate-General XII Science Research and Development, Commission of the European Committees DG X11/0/1 Rue de la for, 200 B-1049, Brussels, Belgium, May 1994

---

[2] British Standards Institution, London,

[42] JACOBS, D.A.H., ed., *The State of the Art in Numerical Analysis*, Academic Press, London, 1977

[43] JARVIS, J.P., KOSTREVA, M.M. and FORNEY, C.L., Tools for Validation and Analysis of Fire Models Combustion Institute/Eastern States Section. Chemical and Physical Processes in Combustion. 20th Fall Technical Meeting. Abstracts. 2-5 November, 1987, Gaithersburg MD, **103**, pp.1-4

[44] JOHNSON, C., *Numerical Solutions of Partial Differential Equations by the Finite Element Method*, Studentlitteratur, Lund, Sweden, 1987

[45] KAHANER, D., MOLER, C. and NASH, S., *Numerical Methods and Software*, Prentice-Hall, Inc., USA, 1989

[46] KHOUDJA, N., *Procedures for Quantitative Sensitivity and Performance Validation of a Deterministic Fire Safety Model*, NBS-GRC-88-544, National Institute of Standards and Technology

[47] MAGNUSSON, S.E., FRANTZICH, H. and HARADO, K., *Fire Safety Design Based on Calculations — Uncertainty Analysis and Safety Verification*, ISSN 1102-8246, ISRN LUTVDG/TVBB–3078–SE, Department of Fire Safety Engineering, Lund University

[48] MICHELL, A.R. and GRIFFITHS, D.F., *The Finite Difference Method in Partial Differential Equations*, John Wiley and Sons, 1980

[49] MITLER, H.E., Mathematical Modelling of Enclosure Fires. Numerical Approaches to Combustion Modelling, ed. ORAN, E.S. and BORIS, J.P. *Progress in Astronautics and Aeronautics*, **135**, pp. 711-753, American Institute of Aeronautics and Astronautics, Washington, 1991

[50] Model Evaluation Protocol, Model Evaluation Group, European Communities Directorate-General XII Science Research and Development, Commission of the European Committees DG X11/0/1 Rue de la for, 200 B-1049, Brussels, Belgium, May 1994

[51] NELSON, H.E. and DEAL, S., Comparing Compartment Fires with Compartment Fire Models, Fire Safety Science, Proceedings of the Third International Symposium, ed. by COX, G., and LANGFORD, B., pp. 719-728, Elsevier, New York, 1991

[52] NORDTEST Method NT FIRE 025, Surface Products: Room Fire Tests in Full Scale, NORDTEST, Helsingfors, Finland, 1986. PEACOCK, R.D. and BABRAUSKAS, V., Data for Room Fire Model Comparisons, *Journal of Research of the National Institute of Standards and Technology*, **96**(4), July-August 1991

[53] PORTIER, R.W., Fire Data Management System FDMS 2.0 Technical Documentation, NIST TN 1407, National Institute of Standards and Technology, USA, Feb. 1994

[54] PORTIER, R.W., Programmers' Reference Guide to FDMS File Formats, NISTIR 5162, National Institute of Standards and Technology, USA, April 1993

[55] RAHAKRISHNAN, K., Combustion Kinetics and Sensitivity Analysis Computations. Numerical Approaches to Combustion Modelling, ed. ORAN E.S. and BORIS, J.P., *Progress in Astronautics and Aeronautics*, pp. 83-128, American Institute of Aeronautics and Astronautics, Washington, 1991

[56] ISO/TS 16733:2006, *Fire safety engineering — Selection of design fire scenarios and design fires*

[57] ISO 16734, *Fire safety engineering — Requirements governing algebraic equations — Fire plumes*

[58] ISO 16735, *Fire safety engineering — Requirements governing algebraic equations — Smoke layers*

[59] ISO 16736, *Fire safety engineering — Requirements governing algebraic equations — Ceiling jet flows*

[60] ISO 16737, *Fire safety engineering — Requirements governing algebraic equations — Vent flows*

[61] ISO 16731, *Fire safety engineering — Data needed for fire safety engineering*

[62] ISO/TS 16732, *Fire safety engineering — Guidance on fire risk assessment*

[63] ISO/IEC 14598-1:1999, *Information Technology — Software product evaluation — Part 1: General overview*

[64] ISO/IEC 14598-6, *Software engineering — Product evaluation — Part 6: Documentation of evaluation modules*

[65] ISO/IEC 9126-1, *Software engineering — Product quality — Part 1: Quality model*

[66] ISO/IEC TR 9126-3, *Software engineering — Product quality — Part 3: Internal metrics*

[67] ISO/IEC 25000, *Software Engineering — Software product Quality Requirements and Evaluation (SQuaRE) — Guide to SQuaRE*

ICS 13.220.01

Price based on 38 pages