Summary

This thesis has the double objective of proposing new methods, mainly concerning the safety and stability analyses of nuclear reactors, and, at the same time, extending available techniques to comply with the industrial requirements concerning the adoption of qualified computational codes. The development of new methods is mostly carried out in the first part of the thesis, where they are applied to simplified systems in order to better grasp their physical and mathematical features but without losing track of real-life applications.

First, the classical P_N and S_N approximations are presented, in order to approach numerically the solution of the neutron transport eigenvalue problems, which is performed with an in-house Python package, called TEST. After verifying the implementation of the code with some numerical benchmarks taken from the literature, some old-fashioned but still relevant questions are addressed concerning the angular parity order, the equivalence between odd and even angular orders and the numerical acceleration of the angular convergence.

Then, the classical eigenvalue formulations to the neutron transport equation are presented and discussed, focusing on their physical and mathematical peculiarities and on their eigenvalue spectra. Afterwards, a novel eigenvalue formulation, focusing on the neutron capture, is introduced and discussed as well. Furthermore, an example regarding the application of the eigenvalue spectrum for the optimal selection of the energy group for the energy collapsing is presented and discussed.

Exploiting these results, the eigenfunctions associated with the various formulations are proposed as alternative weighting functions for the generation of the few-group constants. The behaviour of the different weighting functions is assessed by comparing the main integral parameters obtained by multi- and few-group calculations. The major outcome of this analysis is that better alternatives to the multiplication eigenfunction commonly adopted to perform the collapsing exist, despite their performances depend on the calculation parameters.

Then, the first part of the thesis is concluded by proposing a generalisation of the standard eigenvalue formulations, with the final aim of deriving a new eigenvalue problem, which allows acting on specific portions of the phase space and nuclides, for design-oriented applications. After discussing the main physical and mathematical aspects of this formulation, relevant engineering problems like the determination of the

critical boron concentration are evaluated using this new approach, showing its efficiency and its capability to find all the possible critical configurations for a given initial off-critical system. This last feature is particularly important for safety analyses, since it allows to explore the physical conditions that may lead a system to re-criticality. In the determination of the possible critical configurations of the system, emphasis is also put on the usual figure of merit used to assess the neutronic stability, i.e. the eigenvalue separation.

In the remaining chapters, more realistic systems are analysed, focusing on 2D and 3D models of some Gen-III+ and Gen-IV reactor concepts. This last part of the work mainly aims at proposing computationally efficient methods for the safety analyses of the neutronic behaviour of the core, trying to reduce as much as possible any intervention in the code. This goal is accomplished by means of Non-Intrusive Reduced-Order Modelling (NIROM) techniques, which permit a fair reduction of the computational time without any code modification at the price of small approximations. This model, which is based on a combination between a feature extraction technique and a high-dimensional interpolation technique, is then applied to three different problems of industrial interest, with the goal of proving the its effectiveness in reducing the computational cost of the model evaluations.

The first application deals with the spatial stability of large Gen-III+ cores such as the EPR. In particular, this study aims at training an efficient NIROM to analyse the power tilt behaviour at the full-core level with respect to a random, space-dependent input perturbation. Due to complexity of the core and to the great number of free parameters, some extensions of the NIROM are devised, like proposing the adoption of the Polynomial Chaos Method to compute the perturbed multi-group constants for the full-core diffusion calculation. Afterwards, the need for a new metric to evaluate the distance between the training data is highlighted, proposing a more accurate algorithm to accomplish this task. Finally, the NIROM performances are successfully tested, both in terms of memory and computational time, exploiting the bootstrap method.

The second application concerns the parametric safety analysis of accidental transient scenarios in Lead Fast Reactors. Also in this case, some of the NIROM steps are suitably modified and extended, for taking into account the time-dependent behaviour of the model. Finally, the accuracy of the NIROM is demonstrated by comparing its results with a validation dataset.

In order to show that the methods proposed have a wide applicability range also outside the nuclear field, the last application focuses on the safety analysis of accidental high-pressure gas releases in industrial, congested environments. In this case, the ROM is combined with statistical methods, namely the bootstrap and unscented transform, to efficiently estimate the uncertainty of the ROM in the safety-critical simulation output quantities of interest.

Finally, the last chapter focuses on the nuclear data uncertainty quantification, which is a relevant topic in the safety analysis of nuclear system. The study focuses both on methodological aspects and on the nuclear data uncertainty propagation for the lead fast reactor ALFRED design, providing also the epistemic uncertainty induced by the nuclear data featuring the fissile isotopes on the capture and fission multi-group cross sections.