Digital Transformations of Modern Energy Sciences

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Abstract

In 2024, two Nobel Prizes, in Physics and Chemistry, were awarded for breakthrough achievements that symbolize a new era in science – an era in which the combination of classical sciences, digital transformations, and artificial intelligence (AI) becomes a decisive factor for new scientific breakthroughs. The prizes, both academia-generated and market-generated ones, illustrate how the integration of Physics, Chemistry, Biology, Genetics, and Cybernetics allows solving interdisciplinary problems that previously seemed intractable. Later on, the world leaders noted the perspective professions – coders (the architects of AI), biologists (the explorers of life), energy experts (the guardians of power). Responding to the contemporary challenges, the Digital Nuclear Reactor Initiative Project (Europe) partners rely on a variety of simulation software and dozens of computational codes (created at different times for different IT-environments) capable of modeling various phenomena occurring in the reactor. A digital representative should be produced not only for a generalized type of reactor, but also for each individual installation. The Digital Nuclear Reactor Initiative Project requires the integration of data specific to each facility, including design data, operational records, real-time measurements. Such data need to be verified for completeness and consistency. The aim of digital transformation in the nuclear industry is to restructure supply and innovation chains using digital technologies. The aim on the international arena is to maintain a global strategy for the domestic nuclear industry, focusing on improving its position on the global world and creating a portfolio that meets the current needs of the international market. In the new millennium, much attention is paid to the development of innovative code combinations and multiphysics solutions to support reactor operation and the development of related new concepts.

Keywords

integration, scenarios, workbench, code couplings, uncertainty platforms

1. Introduction

In 2020, France launched a large-scale R&D Project, the Digital Nuclear Reactor Initiative, involving leading players in its nuclear industry. The first phase of the Project ran from 2020 to 2023. The Project is led by EDF (Électricité de France; founded on 8 April 1946 as a result of the nationalisation of around 1,700 smaller companies producing, transmitting and distributing energy; fully renationalised on 8 July 2023), which has a fleet of 56 active nuclear reactors across 18 nuclear power plants (NPPs) in France. This research Project will enable the industry to collaborate on the development of digital twins for the country's NPPs. Industry organisations are pooling their R&D expertise to develop digital twins for NNPs that can be used at all stages of the life cycle, from design to decommissioning. The Project's scope is equivalent to the full-time employment of 184 professionals. The Project also includes industrial and academic partners:

- CEA (Commissariat à l'énergie atomique et aux énergies alternatives; Alternative Energies and Atomic Energy Commission; founded on 18 October 1945 after the Second World War);

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- CORYS (COmpagnie de Réalisation Industrielle de Simulateurs; manufacturer of training and engineering simulators; established in 1997);
- CRNS (Centre National de la Recherche Scientifique; National Centre for Scientific Research; founded on 19 October 1939 during the Second World War) and CRAN (Centre de Recherche en Automatique de Nancy; Research Centre for Automatic Control of Nancy; founded in 1980);
- Framatome (Franco-Américaine de Constructions Atomiques; Franco-American Atomic Construction; established in 1958);
- ESI (Engineering System International) Group (founded in 1973 by four PhD graduates from the University of California, Berkeley (established in 1868));
- Boost-Conseil for aviation and aerospace component manufacturing (founded in 2004);
- Aneo for consulting (established in 2002);
- Axone Group for engineering (established in 1998).

This Project is also supported by the GIFEN (Groupement des Industriels Français de l'Énergie Nucléaire; trade association of the French nuclear industry; established in 2018) and Nuclear Valley (cluster of French nuclear and defense industry enterprises; established in 2005). The Project is coordinated by EDF Lab Paris Saclay.

On September 1, 1976, the Council for External Nuclear Policy was created in France, and on April 21, 2008, – the Council on Nuclear Energy Policy (Conseil de politique nucléaire (CPN)), headed by the President of France, subordinate to the Council of Ministers and responsible for developing the main strategic directions of the French nuclear industry. The CPN defines the broad directions of nuclear policy and ensures their implementation in terms of exports, international cooperation, industrial policy, energy policy, scientific research, nuclear safety, and environmental protection. Based on the results of the CPN's work, in February 2011 the Strategic Contract for the Nuclear Sector (Comité Stratégique de la filière nucléaire (CSFN)) was created, which unites all players in the nuclear industry – engineering companies, service providers, equipment manufacturers, fuel cycle companies, contractors, subcontractors, trade unions, and regional associations of service providers.

France and Ukraine are similar in the role of nuclear energy for power generation: the shares nuclear energy in power supply in France and Ukraine are around 70% and 60%, respectively. The first NNP of France was constructed in 1952–1956 (Marcoule), and that of Ukraine – in 1970–1977 (Chornobyl). Therefore, the experience of France in digital transformations of modern energy sciences is useful for Ukraine [1–3], the country of the first modern computer in continental Europe and the emerging digial leader with established traditions in modern energy [4–10]. The similar research has started in China where the first NNP was constructed in 1984–1991 (Quinshan) [11]. While IT and digital transformations change the world markets [12], energy experts are viewed as the guardians of power [13].

2. Energy platform

In March 2016 the French Nuclear Platform (Platform «France Nucléaire» (PFN)) was created, which, in order to implement the decisions of the CPN, enabled the meeting of the three leaders of the French nuclear industry – CEA, EDF, Areva (founded on April 3, 2001 through the merger of Framatome, Technicatome (founded in 1972), Cogema (founded in 1976); Orano of January 23, 2018). The PFN also facilitated the exchange of information between stakeholders on the main cross-cutting themes of the French nuclear sector. In November 2017, the French Prime Minister reformatted the National Council of Industry (Conseil national de l'industrie (CNI)) to strategic industries. In February 2018, the CNI executive committee defined an initial list of 17 strategic industries, including nuclear industry. After auditing the nuclear industry, the CNI recommended the creation of a CSFN with simplified governance. In January 2019, the CSFN was signed by the

Minister of Ecological Transition and the Minister of Economics and Finance of France, focusing on employment, skills and training, digital transformation, R&D, ecological transition, international strategy. Its aim is to guarantee the skills and expertise needed in the nuclear industry which is forward-looking, safe, and competitive. It is essential to maintain and renew skills in the nuclear sector for its manageability and ability to deploy production capacities in the best conditions (especially safety conditions), its capacity to innovate and build the potential of the future. The nuclear industry objectives in the field of R&D and ecological transformation are:

- circular economy in industry, in particular in the fuel cycle and the processing of metals with sufficiently low levels of radioactivity;
- reactors and tools of the future, in particular of the «Nuclear Plant of the Future» initiative launched by EDF, CEA, Framatome, as well as the small modular reactor (SMR) model based on French technology.

In April 2021, an addendum to the CSFN was signed, delegating to industry and the French Ministry of Ecological Transition elements of the recovery plan for the French economy after the COVID pandemic. The University of Nuclear Professions (l'Université des Métiers du Nucléaire (UMN)) was created to develop the competitiveness and sovereignty of the French nuclear sector, strengthening its solidarity with small, medium and large enterprises. The UMN is a collaborative initiative launched by key players in the French nuclear industry to meet the growing need for qualified professionals. The UMN aims to promote the development of expertise in the nuclear sector, addressing the long-standing shortage of manpower. The UMN was officially established in 2021 as an association due to the collaboration of several major organizations besause of the need to strengthen nuclear programs at regional, national and interregional levels, focusing on solving the recruitment challenges for roles that are essential for the future of the nuclear industry. At the same time, the UMN is aligned with the EDF Excell plan designed to improve the quality and excellence of the nuclear sector. This plan was launched in spring 2020 to allow the nuclear sector to return to the highest standards of rigor, quality and excellence, to be ready to face the challenges associated with the operating fleet of NPPs and future nuclear projects.

In the plan, EDF and GIFEN have set out 30 clear commitments in 5 target areas (governance, standardisation, supplier relations, production and construction, skills). To attract more young people to the nuclear industry, the UMN has launched a number of initiatives, including:

- the creation of a web portal called «My future in nuclear energy» (Mon avenir dans le nucléaire) which highlights job and training opportunities in the nuclear sector;
- around 50 (competitive) scholarships worth €600 per month for students of vocational schools (bachelor-professional (Bac Pro, bac professionnel), certified senior technician (BTS, brevet de technicien supérieur), certified professional (CAP, certificat d'aptitude professionnelle)) for a career in the nuclear sector, in particular as welders, electricians and mechanics;
- supporting regional campuses and training programs, and developing innovative training methods in critical industries such as welding and machining.

In the new millennium, the French nuclear sector is facing a serious shortage of skilled personnel: only 30% of the workforce needs were met in critical positions such as welders and engineers. This sector needs 8,000 new jobs every year to meet the demand for labor, and a professional career in the sector requires proper organization and motivation. The UMN is committed to change by increasing interest in professions of the sector and providing the necessary training to ensure a skilled workforce for the future. This is facilitated by the various academic and professional programs of EDF, the Polytechnic Institute of Paris (Institut Polytechnique de Paris (founded in 1741)), and the National Institute for Nuclear Science and Technology (l'Institut national des sciences et techniques nucléaires (INSTN); founded in 1956).

The UMN website also offers resources on nuclear professions and training opportunities. The Digital Nuclear Reactor Initiative is a direct contribution to the CFSN, which aims to ensure the preservation of skills and expertise in the nuclear industry and to promote innovation through digital technologies.

By 2023, the Project expected innovations – digital twins that serve as training tools for a new generation of operators and as a simulation environment for engineering study. Such twins will be used throughout the life cycle of a NPP, from design, operation, maintenance to decommissioning. According to the CORYS plan, a digital reactor, designed to train operators, can reflect the physical phenomena during operation of the power unit and simulate different operational strategies; instead of a full-scale simulator, operators use a web interface, and instead of detailed documentation of each system, the model reflects the operation of the plant as a whole. One of the key challenges is the accurate reproduction of a specific power unit in the French NPP fleet: a digital twin allows a user to virtually imagine an operating reactor (in the EDF R&D – EPR (Evolutionary Power Reactor; European Pressurised Reactor), a water-water nuclear reactor of generation 3+) and to access any information about the behavior of its components, which is impossible to do in the real world.

3. Digital twins of energy units

Digital twins are modified according to design changes and modifications at each NPP. These codes model everything from neutronic aspects of the reactor core to Thermal Hydraulics (TH) or Chemistry. Some codes focus on a specific component and its operation, while others focus on system-wide phenomena. CEA (around 10 people from the nuclear energy and research departments) plays a key role in ensuring the interoperability of all those computer codes, which were developed separately or jointly by CEA, EDF or Framatome. CEA is also responsible for creating an advanced multiphysics platform using CATHARE (Code Avancé de THermohydraulique pour les Accidents de Réacteurs à Eau), a software for two-phase thermal hydraulic modeling on a system scale that CEA has been developing since 1979. CATHARE is used by EDF, Framatome, the Radioprotection and Nuclear Safety Institute (l'Institut de radioprotection et de sûreté nucléaire (IRSN); founded in 2001) for the general simulation of flows in the reactor and its components and for research in the nuclear safety of pressurized water reactors, as well as for training simulators of the French nuclear fleet.

Framatome manages the validation of the advanced simulation platform for the R&D and is also takes part in the testing of the training platform. The integration of the updated computer codes with others representing the latest advances in Physics will improve the accuracy of the R&D results, which widely use simulations to demonstrate the safety of equipment in different operating scenarios.

EDF believes that digital twins help to improve safety and quality of operations: grouping the different simulation tools for design and operation in a digital reactor allows better verification of EDF's emergency response strategies. The digital reactor complements existing activities by allowing EDF to repeat (simple) operations more frequently through simulation and prototype testing, such as virtual reality devices to simulate the opening or closing of valves wthin the reactor.

The Digital Nuclear Reactor Initiative research Project aims to develop an advanced digital twin, including innovative products – a service platform for advanced research and a new type of simulator in response to the growing demand for quick on-the-job training [14]. In 1945, the industrial conglomerate Matra (Mécanique Aviation Traction) was founded in France, covering a wide range of industries, including aerospace, defense, automotive, motorsport, transportation, telecommunications. In 1999, Matra Datavision decided to publish its CAS.CADE infrastructure in an open source model under the Open CASCADE Technology Public License (Open Cascade). Following the Open Cascade initiative, in September 2000 the SALOME (Simulation numérique par Architecture Logicielle en Open source et à Méthodologie d'Évolution; digital simulation by open source software architecture and evolution methodology) 1 project was launched within the framework of the French National Network in Software Technologies (Réseau National en Technologies Logicielles (RNTL)), created at the end of 1999 by the Ministry of Research and the Ministry of Industry of France (since 2005, the French National Research Agency (l'Agence Nationale de la Recherche (ANR)). The mission of the SALOME 1 project (2000–2002) was to encourage the creation of innovative R&D projects between small and large enterprises, public and academic research teams in the field of scientific computing. SALOME has managed to attract 9 partners from different sectors, including EDF and CEA. Since 2020, this partnership has focused on industrial applications in the energy sector. The workbench, based on the SALOME components, provides access to multiphysics and multiscale simulations, relying on specialized code couplings that can be used to develop new methods and expertise to support reactor design and operation.

The modular structure of the workbench presumes certain architectural options. The functionalities of the service platform can be illustrated in some scenarios, including multiphysics and multi-scale approaches. Based on these scenarios, it became possible to meet the criteria for interoperability and interchangeability of codes, as well as their combinations with uncertainty platforms (for example, URANIE and OpenTURNS). URANIE is a software framework (CEA) designed for quantitative uncertainty assessment, sensitivity analysis, calibration and/or generation of surrogate models, optimization, and so on. Written in C++, URANIE is largely based on the ROOT software framework, developed by the CERN since the 1990s. The ROOT framework is designed to help with processing large amounts of data and providing many services. URANIE relies on visualization solutions, data processing through complex and optimized trees, a C++ compiler with code execution while writing, automatic method transcription in a Python module, and so on. OpenTURNS is an open source initiative for Treatment of Uncertainties, Risks'N Statistics.

At the same time, interoperability and interchangeability of codes, achievable through user-friendly approaches, as well as the transition to High Performance Computing (HPC) applications, are becoming the main driving force for code development and R&D. One example is the Consortium For Advanced Simulation Of Light Water Reactors (CASL), the first energy innovation hub, established in 2010 by the US Department of Energy. The CASL has connected basic research and technological development through an integrated partnership of government, academia, and industry, which has spread to nuclear power enterprises.

Another example is the applications based on the MOOSE (Multiphysics Object Oriented Simulation Environment; created in 2008) platform. The MOOSE is an object-oriented finite element framework in C++ for developing tightly coupled multiphysics solvers from the Idaho National Laboratory (USA), which uses the PETSc nonlinear solver package and the libmesh library to provide finite element discretization.

Another example is OpenFOAM (Open Field Operation And Manipulation; created in 2004 in the UK) – a set of tools in C++ for developing customized numerical solvers, pre-processing and post-processing utilities for solving problems in continuum mechanics, in particular computational fluid dynamics (CFD).

An example from Finland is Serpent, a multi-purpose Monte Carlo-based three-dimensional particle transport simulation code for continuous energy, developed in 2004 by the National Technical Research Centre of Finland (Valtion teknillinen tutkimuskeskus (VTT); founded on 16 January, 1942) [15–17]. VTT is a non-profit limited liability company controlled and owned by the state, the largest science and technology company (research centre) conducting applied R&D in Finland. In Reactor Physics, the development of couplings between advanced codes is used.

The Digital Nuclear Reactor Initiative Project is supported by the French Public Investment Bank (Banque publique d'investissement (BPI); founded in 2012). The Project aims to provide the French nuclear industry with an advanced multiphysics and multiscale simulation workbench, as well as a modular and configurable full-scale NPP simulator. Of note is the advanced multiphysics and multiscale modeling workbench, designed to provide a common coupling platform capable of incorporating the main advanced codes used by the Project partners and extending to other codes. This is done by aggregating the expertise of the main partners CEA, EDF, Framatome to define needs in performance requirements, verification strategies, architecture options, and relevant R&Ds.

4. Software architecture and infrastructure

The workbench architecture is important to support code interchangeability and to provide a framework for HPC environments [18–22]. Several codes from neutronics and thermal hydraulics (including core and system), used by the partners, have been successfully connected to the workbench and used to run typical scenarios [14]. These scenarios cover a wide range of transients, from a Rod Ejection Accident (REA), which requires integration with neutronics and core thermal hydraulics, to a Steam Line Break (SLB), where it becomes critical to consider system response and asymmetry. The development of the workbench is carried out taking into account the relevant verification strategy established on the basis of the evolution of French regulations, in particular for the couplings. It is therefore envisaged to integrate into the workbench the accessibility of the aforementioned URANIE and OpenTURNS uncertainty platforms. The functionalities of the workbench demonstrate the flexibility of its application from full-scale reactors to smaller reactor configurations, typical of SMRs, and indicate future prospects, in particular for the transition to HPC applications:

- REA transient on a small core (interoperability and interchangeability of codes);
- House Load Operation (HLO) transient on a full-scale system (uncertainty platforms);
- SLB transient (workbench interoperability using a multi-physics and multi-scale approach).

The integration bench for safety studies has key components:

- the command file editor and semantic analyzer EFICAS (Editeur de FIchier de Commandes et Analyseur Sémantique; developed by EDF R&D (covering 1800 researchers in France and 282 researchers outside France by 2025) in the context of the SALOME platform – data interface developer and dynamic dataset validation module) as a common data model to define the values used in multiphysics. EFICAS includes technological, model, scenario data;
- the C3PO (Collaborative Code Coupling PlatfOrm) library, intended for code coupling. C3PO includes the main scenario data, the neutronics driver, the thermal hydraulics driver.
- EFICAS and C3PO are complemented by codes, each dedicated to a separate physical simulation.

Several neutronics and thermal hydraulics codes (for core and system resolution) are available on the workbench. Each neutronics code with a common dataset (thermal hydraulics with a common dataset and data pre-processing) is connected to the neutronics (thermal hydraulics) driver C3PO via a dedicated PhysicsDriver available on the workbench. EFICAS is a common data model selected within the Digital Nuclear Reactor Initiative Project, which allows centralizing all relevant data for a common reactor and scenario description. This data is then linked to the different codes via the CodeDatabase. The common data model includes:

- process data (assemblies, geometric descriptions of the core, main reactor characteristics (for instance, core power));
- operational data to describe the pre-accident (scenario) state;
- scenario data to describe the transient process to be calculated;
- model data (modeling options adopted in each physical model (for example, neutronics spatial mesh, energy groups, an so on).

In the common scenario data model, the data become inputs to individual models, each of which has a name, type, default value. The examples of names: initial thermal power of the core; unit corresponding to the specified power; initial water temperature at the inlet of the core; initial boron concentration; initial water pressure at the inlet of the core; initial water pressure at the outlet of the core; initial rod position.

The common data is then stored in a special catalog file that includes a tree data structure. This file is then converted to XML format (a standard W3C (World Wide Web Consortium; founded in 1994 by WWW inventor Tim Berners-Lee) format) using EFICAS and processed by a specific Python program developed in this Project to generate input data for each code with its specific Python API. The Python program then attaches the internal state of each code to a PhysicsDriver object for C3PO, which corresponds to a specific Python API code with the ICoCo (Interface for Code Coupling) API format.

The second key component, C3PO, is a Python library for code couplings. It provides tools for program execution control, data exchange, as well as advanced convergence algorithms and message passing interface (MPI) management tools. The C3PO platform has been developed at CEA for various activities. To connect via C3PO, a PhysicsDriver is required, which corresponds to the ICoCo format for each code. ICoCo by its nature allows for universal couplings. Therefore, C3PO is the basis for interchangeability for the workbench. C3PO provides data exchange between codes by transferring scalar values and fields. The chosen field format is the MED (Modèle d'Échange des Données; data exchange model) format of the SALOME platform [14]. The MEDCoupling library, which is used to process spatial meshes and perform projections, was chosen for the Project. MEDCoupling was developed by CEA and EDF R&D for the SALOME platform. According to this approach, each program can use its own 3D spatial mesh to solve individual physics equation; projections allow the exchange of fields necessary for combining similar meshes (for example, moderator density, neutron power, and so on).

Within the framework of the Digital Nuclear Reactor Initiative Project, codes developed by CEA have been integrated into the workbench and successfully applied to various scenarios. These programs include APOLLO3® (an updated version of APOLLO II), THEDI (THErmohydraulique DIphasique; a program for calculating two-phase thermal hydraulic flows), FLICA-4 (a program for thermal hydraulic calculations for the design and thermal safety analysis of nuclear reactor cores), CATHARE3 (an updated version of CATHARE). Other nuclear process and thermal hydraulics simulation programs developed by the Project's industrial partners (EDF and Framatome) were also integrated into the workbench, allowing for the demonstration of codes interoperability and interchangeability. In total, two neutronics codes, three core thermal hydraulics codes and one system thermal hydraulics code were considered. Other codes that meet the specifications given (API implementing the ICoCo format) may be added in the future.

5. Data analysis

The architectural solutions made for the multiphysics workbench allow for the easy integration of several neutronics and thermal hydraulics codes, relying on a simple plug-in approach and conducting control exercises that can support the integration verification strategy [23]. It should be noted that the neutronics calculations implemented in the workbench are based on a two-stage approach (lattice/core), where the second stage is the only one that is combined with thermal hydraulics. Therefore, the Project assumes that neutronics codes using the two-step approach have their own multi-parameter data libraries (compatible in type and format). When conducting control exercises and checks, special attention should be paid to ensuring that calculations are performed with compatible cross-sectional data. Within the framework of this Project, several typical scenarios were integrated into the workbench:

- REA transient mode;
- HLO transient mode;

- SLB transient mode.

These three scenarios have increasing complexity and allow for several approaches to the combination and coupling. The REA transient mode scenario assumes a combination of neutronics codes and core thermal hydraulics codes. Several code couplings were considered to successfully demonstrate the codes interoperability and interchangeability. Among the codes, a coupling with CATHARE3, which is used for core thermal hydraulics, was also considered.

Two examples were investigated:

- a PWR core (1300 MWe) in low dimensionality (32 assemblies);
- a PWR core in full dimensionality (193 assemblies).

The first example, characterized by a shorter computational time, allowed the first version of the workbench to be set up before moving to full-scale typical applications. The REA scenario was also considered for the full-scale case, starting from Hot Zero Power (HZP) conditions at the beginning of cycle with of control rod groups inserted at different levels. The transient process, during which the control rod in the peripheral position is ejected in 0.1 s, required a total simulation time of 2 s [14]. The REA scenario was also used to demonstrate the integration of uncertainty platforms on the workbench.

The second scenario, the HLO transient, requires coupling with the system of thermal hydraulics and control. In this Project, the HLO transient was used to validate the coupling approach before analyzing the SLB transient (for such transients, there are tools that can be used to support the validation strategy). In this case, the main focus is on the initial phase of transient, i.e. the first 200 s, during which no operator action is expected. The transient process was modeled for a full-scale PWR. The main focus was on studying the main Quantities of Interest (QoIs) after identifying the influence parameters, using the PIRT (Phenomena Identification and Ranking Table) methodology. Running the scenario with different programs allowed verifying the feasibility of coupling to the level of the entire system of thermal hydraulics and control programs.

The third scenario, the SLB transition regime, requires a coupling between neutronics, core thermal hydraulics, and system thermal hydraulics codes. The CATHARE3 program has been adapted for this transition process. In order to improve the core boundary conditions (mixing before core entry), a combination with CFD programs could be considered. This activity is under development.

At the beginning of the Project, a specific activity was launched to establish and adopt a possible validation strategy. This part was led by the industrial partners of the Project to take into account their needs and experience. The workbench as a whole is considered a scientific computing tool, which also requires its own verification, validation, and uncertainty quantification (VVUQ) process implemented for each given calculation. The workbench as a whole produces:

- a summary document that synthesizes the knowledge of the verification and validation facts for each existing individual physics code and for the coupling components;
- qualification document for each given transient mode.

During the Project, some structural aspects of this documentation were prepared as an example, without describing all the details needed for the real qualification process. The workbench is based on existing codes, although it was planned to be extended with other programs. The workbench will allow for convenient control exercises and comparisons under appropriate scenarios. The Project allowed for progress in the development of a common integration platform capable of incorporating many advanced codes currently used by the Project partners and being extended with other codes. One of the main goals of developing the workbench structure was to demonstrate the interoperability and interchangeability of codes, so that the user could access modeling tools with different degrees of resolution (dimensionality) using the same workbench.

These capabilities can be demonstrated on the three above-mentioned scenarios REA (0.2 s neutron-physical power plot), HLO (100 s neutron-physical power plot and liquid temperature plot), SLB (200 s kinetic reactivity plot and water temperature plot) and comparisons of several combinations of code couplings. The similarity of the simulation trends confirms the validation of the proof-of-concept (POC) concept. Some differences may be due to different physical resolutions (e.g., the TH program uses a porous media (multi-1D) approach for the core) and neutronics data (multi-group cross-section data) provided by different codes. For the workbench, access was obtained to different uncertainty platforms to support the analysis of the coupling bias as well as verification and validation (V&V) strategies. OpenTURNS and URANIE platforms were tested to have access to additional methods for assessing sensitivities and uncertainties. The SLB scenario was considered to demonstrate the capability of the workbench to perform multiphase couplings. A combination of TH and high-resolution CFD programs is being developed to improve the aforementioned boundary conditions, in particular to account for coolant mixing in different areas. This is done using the NeptuneCfdDriver in Python. Multiscale and multiphysics solutions are key topics for the workbench to remain competitive, to meet new industrial needs of enterprise operation and competition [24, 25], to substantiate licensing requirements and safe operating limits.

6. Conclusions

The development of innovative solutions will contribute to increasing the robustness of traditional multiphysics couplings, providing analysis support and bias reduction. This Project fits into this concept by offering an advanced multiphysics and multiscale modeling workbench, built on the experience of collaboration among leading industrial and academic partners of France in the field of nuclear energy. The proposed workbench, based on the capabilities of the SALOME platform, ensures easy interoperability and interchangeability of codes through simple plug-in approach. The main computational tools for the French nuclear industry, developed by CEA and industrial partners, have been connected to the workbench, in particular two neutronics codes, three core thermal hydraulics codes and one system thermal hydraulics code. The structure of the workbench will allow the connection of other codes in the future, for example open codes that have appropriate integration characteristics. The architecture of the workbench is flexible enough to be extended to other scenarios and to be used to work with other innovative reactor concepts. To demonstrate and support the development of the workbench, several typical scenarios of multiphysics and multiscale analysis were defined and implemented – from the REA transient mode, which includes a coupling of only neutronics and core thermal hydraulics, to the SLB transient mode, which includes the system response. These scenarios were proposed as a demonstration of the workbench to support services for carrying out all types of research (design, dimensionality and measurability studies, providing expertise, etc.). Integration of the OpenTURNS and URANIE uncertainty platforms was also considered. The main goal of the workbench development was to ensure interoperability and interchangeability of codes. It is planned to use HPC, which will become a further driving force for code development and R&D organization.

Declaration on Generative AI

The authors have not employed any Generative AI tools.

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