IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received February 21, 2022, accepted February 28, 2022, date of publication March 23, 2022, date of current version May 2, 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3161626

A Unified Approach to Digital Twin Architecture–Proof-of-Concept Activity in the Nuclear Sector

DAVID BOWMAN[1], LYNN DWYER[1], ANDREW LEVERS[1], EANN A. PATTERSON[2], SALLY PURDIE[1], AND KONSTANTIN VIKHOREV[1]
[1]Virtual Engineering Centre, University of Liverpool, Sci-Tech Daresbury, Daresbury, Liverpool WA4 4AD, U.K.
[2]School of Engineering, University of Liverpool, Liverpool L69 3GH, U.K.

Corresponding author: David Bowman (Bw03212@liverpool.ac.uk)

This work was supported by the U.K. Government Department of Business Enterprise and Industrial Strategy through the Nuclear Innovation Program—Digital Reactor Design Project.

ABSTRACT Many approaches are currently being considered to develop digital twins and integrated digital frameworks. These approaches concentrate on an industrial sector or a single product, with the obvious risks of a lack of interoperability at differing levels of abstraction. However, a unified approach is required to truly realize the benefits of digital twins and is achievable at their current stage of development. We present proof-of-concept case studies where a digital twin architecture has been developed using standard techniques and adopting a systems-based approach. This architecture has demonstrated technical benefits such as a step-change in processing efficiency, a reduction in traditional manual interventions, an ability to integrate risk and uncertainty, and a perceived cost benefit despite the necessary up-front investment. This approach also allows for the integration of models and simulations at differing levels of detail within an overall value chain. Several wider benefits to an organization such as improved communication and recording of implicit expert knowledge were identified. These benefits we believe will offset the upfront resource required for the development of the architecture. Challenges to adopting the technology were also identified and should be addressed in parallel with future technology development. This work is a first step in establishing a practical approach to realizing a digital twin architecture that demonstrates the flexibility and scalability that can be applied universally. We discuss the wider application of this architecture to a wide range of industry sectors by adopting this unified approach and thereby realize the major benefits a digital twin can provide.

INDEX TERMS Digital threads, digital twin, high-level architecture, horizontal integration, integrated digital framework, systems architecture.

I. INTRODUCTION

The dream of conceptualizing, designing, testing, operating, and disposing of objects in an integrated virtual environment has existed for decades; proposals for an ‘analytical hierarchy of models’ for simulating complex battlefield scenarios have existed since the 1970s [1]. Further advancements have led to the concept of a digital twin but consensus on a definition of this concept has not yet been reached [2], [3]. In this paper, we apply a recent definition which considers a digital twin to be a simulation of a real-world object or system that exchanges data with its real-life counterpart and subsequently proposes behavior changes based on real-time data [3]. Since this definition includes a requirement for data manipulation that will influence organizational practices such as decision making and training, we recognize that, to truly realize the benefits of digital twins, this definition must include a framework to integrate the simulation into organizational practices; a digital framework can be thought of as an infrastructure that unites a sector, requiring training and wide scale deployment to turn it from a digital toolkit to an embedded culture that captures the accepted way of working.

Zheng *et al.* [4] proposed that a digital twin must fully describe the potential or actual physical product from the atomic to the macro geometrical level. This touches on the living nature of digital twins. They must be continually updated with data transferred from their real-world counterpart so that the twin maintains its replication of the physical entity

The associate editor coordinating the review of this manuscript and approving it for publication was Okyay Kaynak.

throughout its lifecycle (if updates cease then the twin reverts to a digital representation of its counterpart). Another commonly accepted definition is from Glaessgen and Stargel [5]: a digital twin being an ultra-realistic, integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding real twin. However, the quantity and complexity of sensors and bandwidth required to capture the necessary information for this complete or ultra-realistic replication of an object, quickly becomes prohibitive. For example, Google's self-driving car is estimated to produce 1 gigabyte of data per second, whilst today's Bluetooth connections can only transmit 0.03% of this data [6]. A digital twin is then required for each car and so on. The computational power required to manipulate such a growth of data quickly erodes the economic benefits gained from the simulation. The cost and complexity of developing digital twins of complex engineered systems has been likened to the next Manhattan Project. Estimates for the development of such technology for the Department of Defense's Next Generation Air dominance aircraft, were projected to be $1-2 trillion and take up to 250 years to complete, even with a team a third of the size of Microsoft [7]. This led NASA to conclude that these concepts are impractical to fully implement.

For most situations, an exact replica that is accurate down to the atomic level (commonly referred to as a digital clone) is not required. A simplified representation (or abstraction) can often enable the user to address the specific questions or decisions required particularly when integrated with narrower, more detailed models that run when required. This mirrors the way that the human brain works, allowing a focus on a particular item of interest whilst maintaining an overall awareness of the environment. To illustrate, a pedestrian crossing a thoroughfare is conscious of the detail of traffic close by and will be analyzing the risk of stepping onto the road. Simultaneously, they will have some, less detailed, knowledge of distant traffic (the context) and the behavior of other pedestrians which might affect the overall scenario. By adopting a similar approach, the framework allows for detailed modelling to be linked to (less detailed) contextual modelling to satisfy the 'purpose' without demanding massive computing resource. For example, the digital twin required to optimize a vehicle's fuel efficiency could be significantly different to one simulating the deterioration of the tires; both may require a simplified representation of the car, and its environment but with unique elements/functionality to assess the impact on the item of interest within the defined purpose. It is more computationally efficient to have different models to address these differing questions rather than one model that seeks to address all possible questions.

A digital twin would therefore require: (i) a specified purpose or scenario that it is established to analyze; (ii) validation versus its real-world equivalent and resultant accuracy found to be within the limits required by the purpose defined in (i); (iii) continual updating and optimization based on the input of 'real-world' data from its physical counterpart, as required to continue delivering the purpose defined in (i); and (iv) the ability to link to other digital twins relating to the same product.

A digital twin can exist at any stage in the product lifecycle, provided that it interacts with a physical counterpart, to provide improvements to the physical product [8]. Many different scenarios are of interest through the product lifecycle and again the use of simplified integratable models provides many efficiencies compared to a single complex monolithic model. For the foreseeable future complex engineering systems will likely need to be represented by multiple digital twins, representing unique points on the product lifecycle, different levels of the system, subsystem or component level to address specific scenarios. Multi-physics models describing processes or systems at different scales will usually be required to be integrated into digital twins to describe and analyze an engineered object to sufficient resolution and certainty. To maintain their status as true digital twins they must not only be connected, but also be regularly updated to reflect the changes happening in the real-world. Digital twins and other digital assets with the functionality to interconnect independently would also therefore allow cross-sector use.

Many studies have explored the theoretical benefits of moving to this more virtual, integrated way of working [4], [6], [9]. One of the most attractive benefits, particularly in high-cost economies, is the reduction in manual interventions as this lowers cost, accelerates development and decreases the likelihood of human error. There is further potential for cost and time savings through the rapid evaluation and optimization of alternate designs, increasing the rate and scale of innovations. The increased use of simulation and modelling also reduces the number of physical prototypes needed, thus reducing associated costs.

'Digital twins' enable virtual verification, failure mode prediction and analysis of designs, whilst extending the benefit stream into manufacture, operation, maintenance and repair, and also into policy and planning. An improved understanding of critical operations can be gained from exploring what-if scenarios through the digital twin, leading to better informed decision making and improved management of physical assets [10].

Although the benefits of integrated digital frameworks are well established, there is a significant gap in understanding the best approach for realizing these frameworks. Example approaches have previously been presented for applications such as manufacturing using mechatronics [11], manufacturing as a service [12] and for the generation of electricity from nuclear power stations [13], [14], [15] while other studies have provided analysis across lifecycles for a variety of applications [16]. Such examples demonstrate that a variety of approaches are under consideration within different sectors. Many sectors, such as manufacturing, aerospace, and electricity generation, are highly complex and becoming ever more so. In aerospace, a Boeing 747-800 requires over 6 million separate parts, with sub-assemblies of the aircraft being manufactured by supply chain partners and only the final assembly being conducted by Boeing [17]; the digital twin of an in-operation aircraft must contain and allow for individual twins from each supply chain partner. Rossen *et al.* [11] points out that a digital twin of a manufacturing plant can provide links to externally hosted datapoints suggesting that this evolution could involve ongoing digital communication between Boeing and the supply chain. As electricity generation technologies shift from fossil fuels to renewables, control systems requirements to balance the electricity distribution grid must adapt, predicating the rise of a control system digital twin [18]. Interfaces between the electricity generation points and the control system must allow sufficient data flow to allow the electricity grid to be balanced and this requires information on the performance of each electricity generation source, i.e., the digital twin of a nuclear reactor or solar farm must interface with the digital twin of the electricity grid. Many of these products, whether they be an aircraft or an electricity generation plant, will be in use for decades and may be upgraded or modified during that time; hence, any digital twin must also have the flexibility to accommodate these changes. Therefore, it is clear that a common unified and integrated approach would be beneficial i.e., one that provides standardized interfaces across industry sectors, applications and supply chains. We take this term 'unified approach' to mean having such a consistent, or standard way of dealing with the issue of assembling digital twins so that interoperability along the supply chain, at differing levels of the system and between systems provides cost effective construction and deployment of the 'twin'. Any approach to integration must also be scalable, enable knowledge sharing, allow economies of scale while protecting intellectual property.

In section II of this paper, we further define a digital twin and outline the different approaches to integration with reference to this ultimate aim.

In section III, we apply a particular approach of High-Level Architecture (HLA) integration to two case studies from the UK civil nuclear power sector. Previously, an HLA has been applied at a component or sub-system level, and DTs have been described as the backbone of future innovations e.g. Jiang *et al.* [19] for a plant-wide monitoring system. However, these are a subset of the Proof of Concept (POC) reported in this paper and are not scalable, becoming too complex and unwieldy if used to model organizations, sectors, or large geographies. They also do not provide the necessary IP, governance, or stewardship needed for such high-level digital twins.

Other previous approaches to create digital twins at a higher level have primarily utilized star and vertical integration [5], [7], [20]. These approaches have some advantages, as they require fewer resources for the initial creation, however, they have significant disadvantages in terms of high computational power requirements and reduced flexibility and scalability, which have limited their wide scale adoption. The approach in these case studies represents an advancement for integration for this sector and we believe this is the first time that an HLA framework has been applied at the component behavior level. The opportunities and challenges for the broader application of this approach, and requirements for further work, are laid out in section IV. Although the case studies are from a particular sector, this approach to integration could be applied across sectors and represents an important first step in developing an integrated digital framework that can be made available to all, with sufficient flexibility to evolve and develop with time.

II. INTEGRATED DIGITAL FRAMEWORKS AND DIGITAL TWINS

A digital twin can be defined as an instance where there is fully integrated, two-way flow of data between an existing physical object and a digital object [3], however, this is a narrow definition. For data to be exchanged between a physical entity and the digital twin, and manipulated by the digital twin, a framework must be in place. As stated above, we consider a framework to be not just the architecture that allows the digital twin to interact with the physical entity; an integrated digital framework is the architecture needed to unite and integrate all hardware, software, user, and organizational interfaces to allow seamless operability for an application. It is often missed that these frameworks *must* include the protocols and procedures needed to define this common way of working in addition to the technology elements. In this context, a digital twin without a framework is unlikely to be sustainable or may only be operated by a limited pool of users. Hence, in a field where there is no consensus on definitions, defining the framework is a key research outcome. As a first step to defining this framework, the approach to building the digital twin and the architecture for integration with the physical entity and end user must be considered, as detailed in the following sub-sections.

A. BUILDING A DIGITAL TWIN

A digital twin can be either data-based or systems-based. In a data-based approach, the data are structured according to certain criteria, for example organizing them by different functionalities [2]. The focus is on the flow of data as it is received from the object's sensors, analyzed and then the output of the analysis fed back to the object which means that all data required in the modelling and analysis must be accessible. A data-based digital twin does not require complete technical information; only access to sensors is required for analysis. In contrast, a systems-based digital twin combines various models along with complete technical information and data on individual components to arrive at a single, complete representation of the physical object. The data that are fed back to the object could be used to provide modification of the object. For example, in closed-loop control for manufacturing, corrective or preventative actions can lead to automatic mitigation of defects [21]. The data produced by the digital twin could also be reviewed by a human operator to aid in decision making and then apply corrective action, effectively utilizing an open-loop approach.

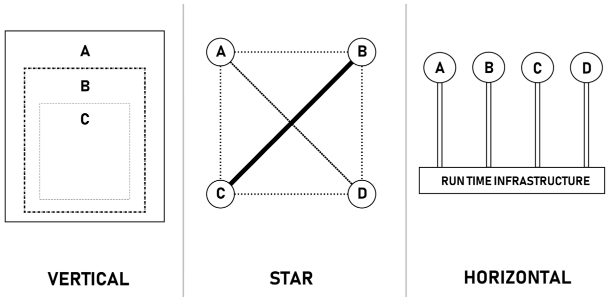


FIGURE 1. **Illustration of three common methods of system integration: vertical, star and horizontal.**

Regardless of whether the approach is data-based or systems-based, open-loop or closed-loop, mapping out systems characteristics requires consistency and a standardized way of storing and retrieving information. Both approaches have different benefits: a data-based approach lends itself to automation and so can improve productivity; a systems-based approach lends itself to simulations and so makes it most suitable for prediction of behavior and what-if analysis which is ideal for managing uncertainty. A hybrid approach where some elements of the digital twin use a data-based approach whereas others use a systems-based approach can realize the benefits of both approaches. As well as deciding the approach to how the data are processed, the architecture for data flow must also be considered. Various approaches are detailed below.

B. APPROACHES TO INTEGRATING DIGITAL FRAMEWORKS

Systems integration is the mechanism by which components and subsystems are connected into one aggregate system. Three common methods to integrate large systems are illustrated in Fig. 1 and described in the following sections.

1) VERTICAL INTEGRATION

This method integrates subsystems with a stack-like structure (analogous to Russian dolls), creating a single inseparable monolithic system, depicted in Fig. 2, where changes to any individual subsystem would normally affect all linking subsystems. Data from sensors are passed through layers, interpreted in some way and then information is supplied back to the physical object. In a data-based approach, since the data are organized according to criteria, all sensor data on a particular aspect of the physical object, for example servos or temperature, follow the same route through these layers and are acted on in the same way; the monolithic architecture is akin to a 'black box' where data are processed without a need for the user to understand how the data have been analyzed. In the systems-based approach, each sensor is treated as a unique entity, assigned an identifier, and the data from it flows through the layers until it reaches the subsystem that acts on it.

In practice, vertical integration can be performed more quickly than other methods; however, as Fig. 2 illustrates, it requires more effort to evolve and upgrade the subsystems, introduce new functionality, and scale up the system, due to the tight coupling and monolithic nature of the integration. In many sectors the object or physical plant may be in operation for decades and be modified repeatedly during this time. Therefore, there is a need to develop a flexible approach to integration if the digital twin is to be sustainable i.e. to ensure that future modifications to the physical entity are reflected by the digital entity. Indeed, if the digital entity cannot be updated and pass data back and forth with the physical object, it does not meet the criteria for a digital twin.

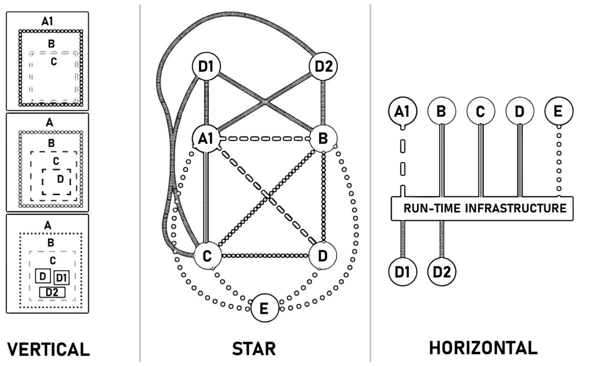


FIGURE 2. **An illustration of the additional complexities required for vertical, star or horizontally integrated systems to upgrade and evolve, A1 (shown in dashes lines); or add new subsystem, E (shown in dotted lines); or to scale-up by adding more subsystems, D1 & D2, with the same interface. In vertically integrated systems, all elements are tightly coupled into a single, inseparable, monolithic (stacked) system so any change to one of the sub-systems will affect all connected systems and subsystems in the stack.**

2) STAR INTEGRATION A.K.A SPAGHETTI INTEGRATION

This approach integrates subsystems with a point-to-point structure. It uses the concept of external interfaces to link subsystems to each other according to their own needs. This improves the integrated system's ability to evolve as there is no need to modify the whole integrated system with each change. However, as Fig. 2 illustrates, the interface complexity, and associated times and costs increase exponentially when adding additional subsystems as data flow must be specified for each connection between the subsystems. Coming back to the idea of a sustainable digital twin, any future modification of the digital entity to reflect any modification to the physical entity can become unwieldy for the same reasons outlined above in relation to vertical integration.

In the data-based approach, data flow is dictated by the classification of the data; for example, if one subsystem requires temperature data from a particular location in the physical object or plant system, then it must be classified accordingly in order to be passed to the subsystem that will analyze it. This introduces an additional up-front cost to setting up the digital twin as data classification must be considered at the outset.

3) HORIZONTAL INTEGRATION

This method uses a specialized subsystem dedicated to communication between other systems or subsystems, which is analogous to a data-bus. This reduces the number of connections to only one per system or subsystem (the direct connection to the communication subsystem), as shown in Fig. 2. A key advantage of the horizontal integration is that it allows independence of the models with regards to physical scale and timing schedules, albeit with a defined, controlled interface. Not only does this reduce some of the challenges associated with integration, but it requires less computational effort as only the required module needs to run, and it can be easily updated with data input files from the other modules.

The key disadvantage with horizontal integration is that initial development times may increase as the dedicated communication module must be developed, as well as common protocols for defining and managing interfaces. A temporal management plan is also required at the outset to define the frequency, granularities, and input/output requirements. As with star integration, consideration to data classification increases the upfront development time if a data-based approach is used.

III. CASE STUDY – DEVELOPING INTEGRATED DIGITAL FRAMEWORKS FOR THE UK NUCLEAR SECTOR

Being the first nation to achieve industrial scale electricity production from a nuclear reactor, the UK represents an interesting case. Here, the regulations and procedures originally developed against a backdrop of post-war secrecy in the 1950’s evolved over the intervening decades to their present high standard. The industry is highly regulated with safety being of paramount concern and any new development requires significant buy-in from the regulatory bodies. These safety and security issues are seen as the main discriminators of the nuclear sector from others, but at heart designing, building, and operating nuclear plants is little different from other sectors designing, building, and operating (DBO) complex systems.

In the UK, the industry is undergoing a renaissance; the drive for net zero and the aspiration to implement smart grids requires a flexible mix of green electricity generation and this includes nuclear energy [11]. Digital twins would help drive this renaissance: moving toward a systems approach to a digital twin will lead to improvements in efficiency and will provide a means of uncertainty quantification that is much needed in safety analysis.

The civil nuclear power industry in the UK encompasses the complete lifecycle for the power plants: fuel fabrication, construction, electricity production, used fuel management, decommissioning and waste management. Decommissioning of some facilities is expected to take decades and so requires elements of asset management. The supply chain for this industry is geographically diverse and, with the renaissance only just beginning, there is a skills gap associated with an ageing workforce [22]. Some areas of the civil nuclear power industry have begun to explore virtual prototyping, with some attempts to virtually represent reactor components [23], [24]. There have been notable attempts to integrate different tools and produce digital frameworks for nuclear power plant design at an international level while recognizing that widespread adoption of digital twins will require acceptance by regulators, must have robust cyber security, and be able to deal with emerging threats while providing protection of intellectual property. Hence, a digital twin for applications within the nuclear industry must be secure and meet the demands of the emerging workforce requirements to safeguard knowledge and deliver resource efficiencies while evolving as the technology develops [25]. A vision for one such digital framework is introduced in section A and the driver for its development is described in section B while the high-level architecture is depicted in section C. Technical details of the use cases are provided in the remainder of this section.

A. A VISION FOR AN INTEGRATED DIGITAL ENVIRONMENT

A conceptual approach for the application of digital frameworks to the nuclear sector, the Integrated Nuclear Digital Environment (INDE), has previously been proposed [26]. This idealized the real-world lifecycle into five stages: design, operations, end of life, waste packaging for interim storage, and waste disposal, as illustrated in Fig. 3. A parallel digital world is constructed which mirrors those five stages, starting with a virtual prototype and combining real-world data from Building Infrastructure Modelling (BIM) data, non-destructive testing and monitoring data to create digital twins. Included in this framework is a series of interconnected, multiscale, multiphysics computational models that link to real world data throughout the complete lifecycle. In comparison, other frameworks used by the industry, such as baseline VERA [13] and NURESIM SALOME [15], explained in more detail below are heavily focused on solving specific engineering/physics problems associated with reactor operation. Although Advanced VERA and DaVinci [27] contain tools that are designed to model hypothetical reactor design, their current limitations and lack of connection to the downstream lifecycle of these reactors mean that there may be certain safety or economic factors that are missed.

The vision of the INDE framework is to provide tools to support the analysis of the whole nuclear industry lifecycle; this ‘top-down’ approach provides an opportunity to address the limitation of other existing approaches. Part of the rationale for proposing the INDE was to create a driver for industry investment by linking technical challenges to the potential benefits.

The UK Government recognized the need for such an integrated approach in the domestic nuclear sector. As a result, through the Department of Business, Energy and Industrial Strategy (BEIS), it funded the Nuclear Virtual Engineering Capability Project (NVEC) [previously known as Digital Reactor Design] [25] as a driver for further work on the INDE and a proof of principle. The initial aim was to create a

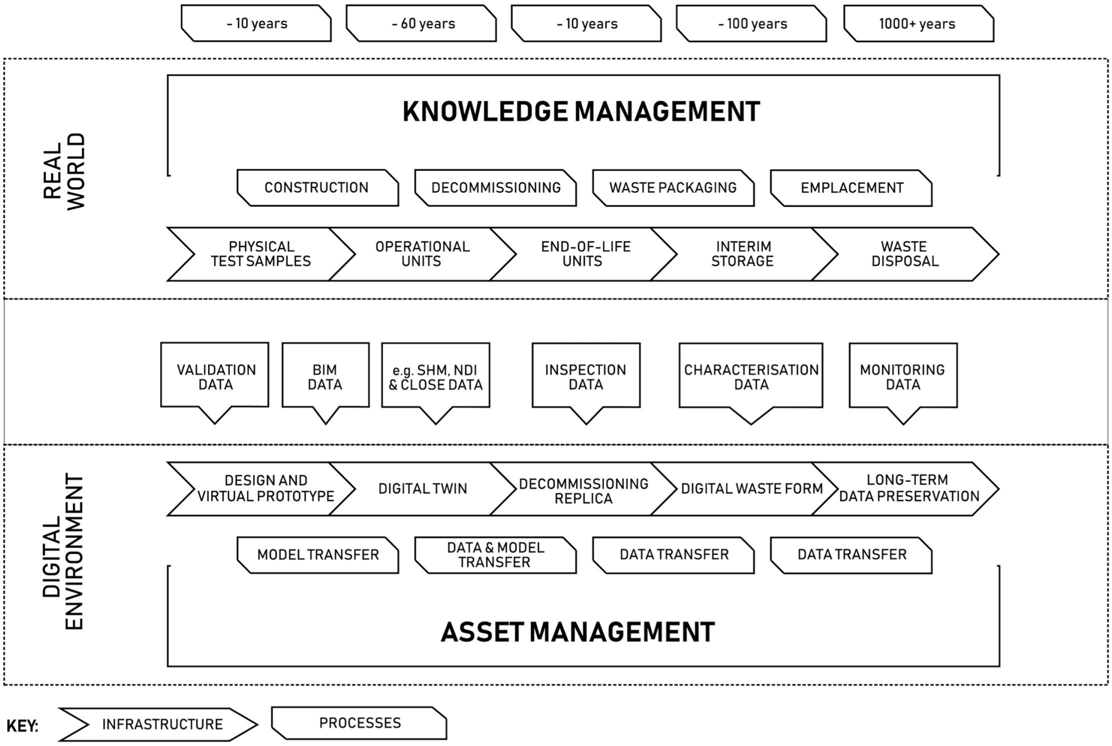


FIGURE 3. Schematic diagram of the INDE showing the digital environment, its relationship to the real world and the potential added value.

software environment with the potential to ‘plug and play’ multiple different software applications. A key element of the project was to create an open framework architecture to enable multiple organizational users across the nuclear lifecycle to collaborate between sites to deliver economic benefit. The resultant use cases are seen as important stepping-stones to the future realization of a complete INDE.

B. THE CURRENT LANDSCAPE

As part of the NVEC project, the UK Government (BEIS) funded a project to map the existing virtual engineering capability, both in the UK and internationally. A review of the current status of UK and international virtual engineering (VE) capabilities was completed [27] and a summary of the findings is included in Table 1. The capability review concluded that existing tools could be broadly split into two categories: (a) frameworks for industrial applications that couple licensed codes within an integrated platform with the purpose of providing more accurate and easier to use systems, e.g. Oak Ridge National Laboratory’s Baseline VERA [13] and AREVA’s ARCADIA®systems [14]; and (b) frameworks developed for research purposes that are designed to test next generation technologies and approaches [15]. They aimed to ultimately become verified and validated to then be incorporated into future industrial grade tools e.g., VERA [13].

C. THE DIGITAL ARCHITECTURE APPROACH

A critical requirement identified for the NVEC proof of concept was to address specific problems through the integration of high-fidelity modelling and simulation within the integrated framework. This need for simulations dictated a systems-based approach. The highly regulated nature of the nuclear industry meant that the full technical information was already available, and the systems architecture of a powerplant in existence, offsetting some of the inherent disadvantages of this approach.

To provide connectivity between the computational models, the framework uses horizontal integration. As the physical assets being twinned have decade or longer lifecycles, an ability to update, improve and sustain any digital framework is imperative. Horizontal integration provides the necessary flexibility, easy extension and scalability that is considered necessary to create a sustainability digital twin for such long-lifecycle products. One clear need was to ensure the retention of Intellectual Property (IP) by the IP generator and not allow ‘leakage’ across organizational/supply chain boundaries. This led to an adoption of HLA as the core of the POC activity. The digital framework was therefore developed in accordance with IEEE 1516-2010, the standard for Modelling and Simulation (M&S) HLA generation and IEEE 1730-2010, the recommended Practice for Distributed Simulation Engineering and Execution Process. The framework

TABLE 1. **Overview of existing nuclear digital framework capabilities [27].**

Tool	Description	Key Users	Strengths	Weaknesses	Status
Baseline VERA	Closely coupled star integrated toolkit for reactor safety, licensing and sustainability- focused in industry standard tools for core reactor unit operations (neutronics, thermal hydraulics, etc)	US & some international partners	• Shared IP based on open-source licensing • Developed with industrial engagement • Based on industry standard license grade tools – verified	• High computational demand out of reach of most industrial users • Focus on technical challenge problems • Restrictions on some component modules make release outside US difficult • Star integration makes switch out of specific elements difficult	Limited adoption – slow update industrially
VERA	Vertically integrated toolkit concerned with the development of advanced codes covering fuel performance and in-silico neutron physics	Primarily US-based research organisations	• Advanced capabilities for future reactor design	• As above – but not yet verified	Limited to research organisations
NURESIM SALOME	Star integrated toolkit for reactor safety, licensing and sustainability	EU (18 countries & 23 research & industrial partners)	• Open framework • Easy coupling between different codes • Includes uncertainty quantification • Interoperability between CAD models and computational simulation • User friendly interface • Reduces training time	• Focus on technical challenge problems	Project dormant after 3 rounds of funding
ARCADIA	Integrated industrial toolset to support reactor safety & licensing	AREVA	• Emphasis on professional software development • Industrial standard unit codes	• Focus on workflow and optimisation • Expensive license cost & unavailable to general users	Commercial product
DaVinci	Industrial toolset to support reactor safety & licensing build integrating from Excel spreadsheets to FEA software	Rolls-Royce	• Built using commercial software	• No Cloud solution • Individual tool execution • Currently focussed on design phase – although plans to expand manufacturing, certification and operation during later phases	In use

integrates several elements: (a) a real-time infrastructure (RTI): a component or software module that provides a standardized set of services through different programming languages. In simple terms, the RTI is a universal translator allowing otherwise dissimilar software and simulations to communicate. This could include information exchange, synchronization and federation management, where a federation is a set of integrated yet individual simulations using the same RTI services. (b) Graphical user interface (GUI) – a simple interface to allow operators to access the framework; (c) Sim Manager – the control system for the federates (individual codes or simulations that can link together to address a specific issue); (d) Database – the storage mechanism for records and results (note this can be distributed rather than a single permanent database); (e) uncertainty quantification capability which was a later addition to the framework in the form of a module for the assessment of uncertainty within the framework; (f) visualization of outputs. The resultant framework is shown in Fig. 4.

The unproven nature of digital frameworks led to skepticism about the ability to achieve effective integration and a reluctance to modify existing code before the integration and its benefits were proven. Therefore, it was not possible to create a true HLA using a standard approach and protocol set. For this reason, a workaround was developed, by using adaptors to interface between the real-time infrastructure and the extant analytical toolset.

In the use cases below, various computational tools are brought together under a single framework to accurately simulate certain aspects of two different nuclear reactor technologies. In addition, a concept model for the generic top-level nuclear power plant-based was developed.

D. CONCEPTUAL MODEL FOR NUCLEAR POWER PLANT

A plant level simulation was created to prove the concept of a distributed model for multiple site working and system level optimization. The resultant high-level architecture is shown in Fig. 5, connecting abstracted models of the nuclear island,

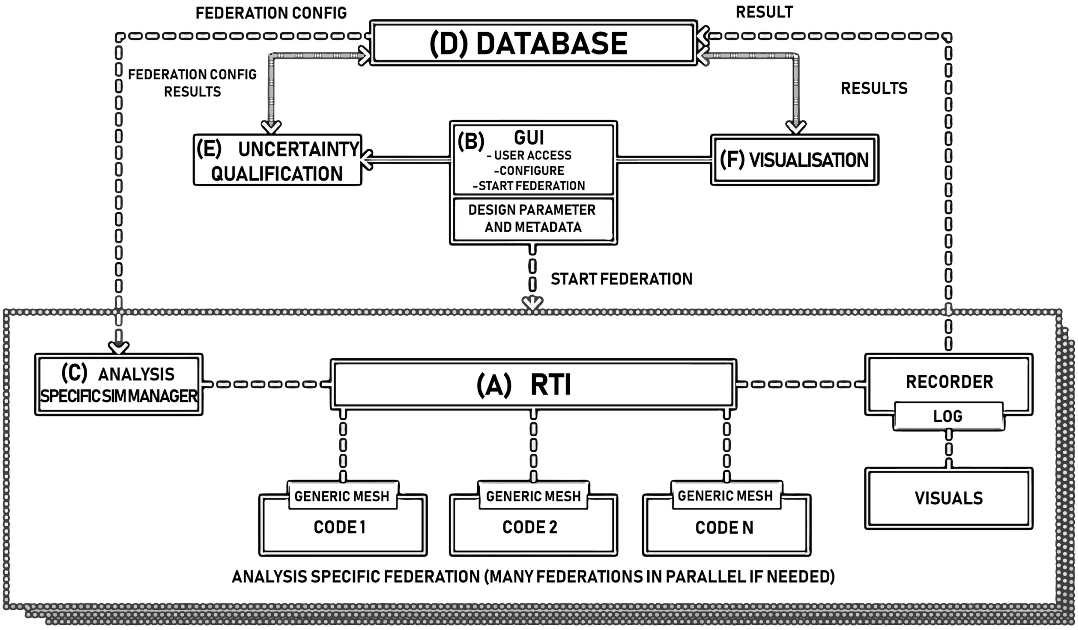


FIGURE 4. Generic software framework developed under the Digital Reactor Design project including (a) A real-time infrastructure (RTI); (b) Graphical user interface (GUI) - a simple interface to allow operators to access the framework; (c) Sim Manager - the control system for the federates; (d) database - the storage mechanism for records and results (note this can be distributed rather than a single permanent database); (e) uncertainty quantification capability & (f) visualisation for outputs.

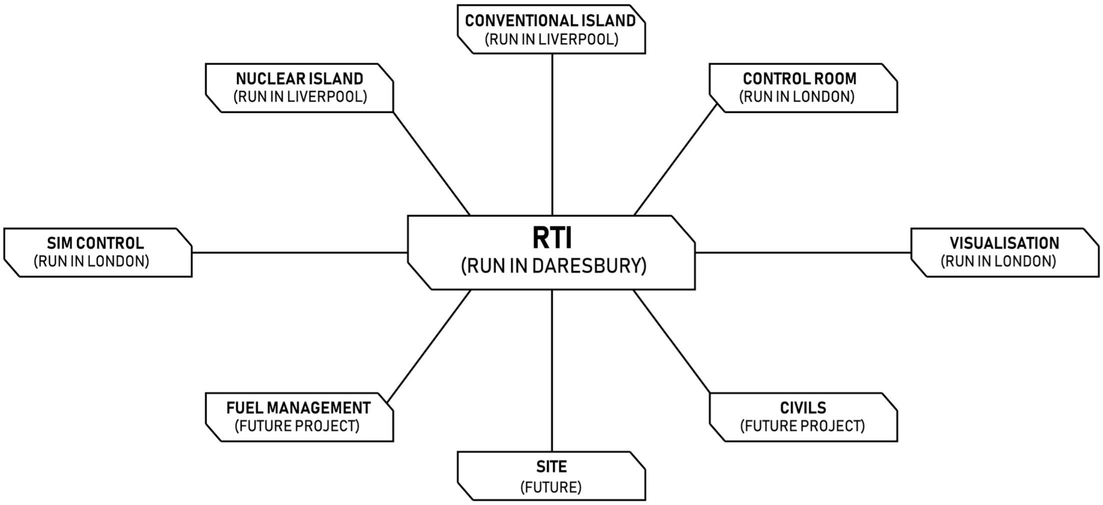


FIGURE 5. HLA for Power plant (system) level simulation. The nuclear island represents the components that are unique to a nuclear reactor (safety systems, reactor core, coolant system and steam generators). The conventional island represents components of the plant that are generic to electricity generation (the turbine, generators, condenser and secondary coolant system).

conventional islands, control room, etc. The key parameters could then be adjusted, enabling users to understand the impact of these on the top-level system design. For example, changing the design of a generator turbine would have an impact on overall plant performance. Although no structured design exercises were undertaken, this demonstrated that the use of integrated digital frameworks for design optimization is feasible. It also demonstrated that that this model could be operated at multiple geographically dispersed sites.

E. USE CASES

The INDE framework was substantiated through two detailed use cases: the through-life assessment of cracking of graphite fuel bricks in an Advanced Gas Cooled Reactor (AGR); and a

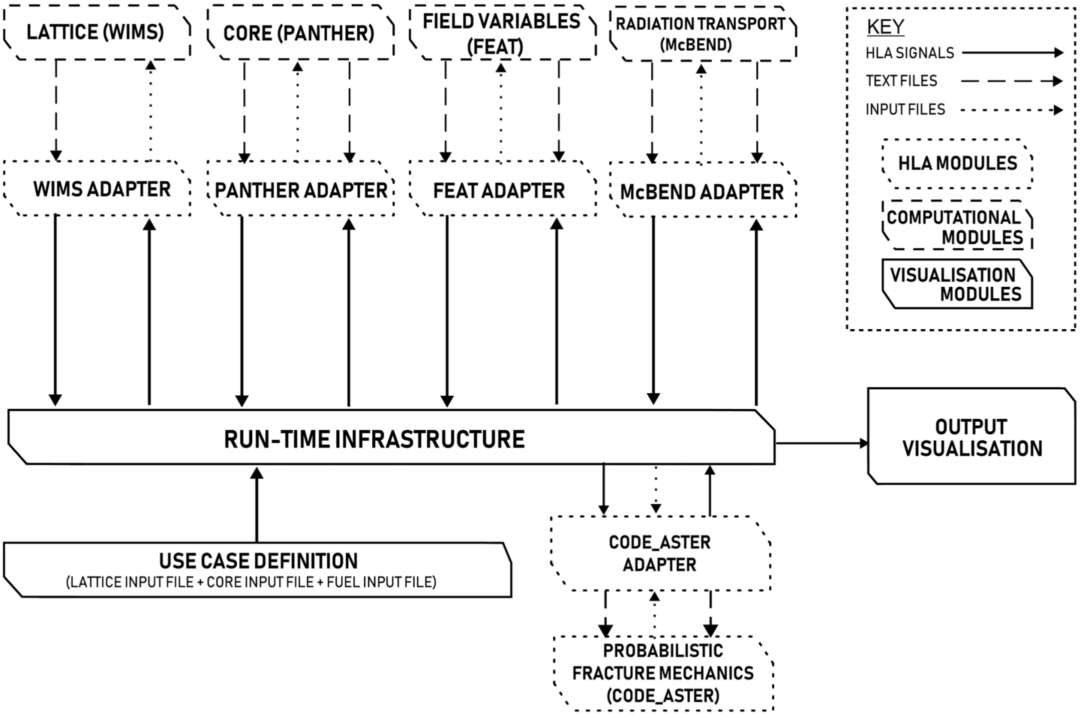


FIGURE 6. Integrated software framework for Advanced Gas-Cooled reactor (AGR) use case.

control rod ejection scenario for a Pressurised Water Reactor (PWR). In both use cases, the intent was to demonstrate the benefits of such frameworks by supporting the decision-making process with rapid and accurate analysis, i.e., to create optimized open-loop systems. The highly regulated nature of the nuclear industry means that it is considered likely that for the foreseeable future all such frameworks would be open-loop; so, no consideration has been given to the additional mechanisms and protocols that would be required to allow the overall control of any physical systems.

The first use case sought to simulate the change in graphite properties through the operating life of a real-life advanced gas cooled reactor (AGR). To model the different physics and damage mechanisms, including fast neutron irradiation and radiation-induced graphite weight loss, four codes were coupled together and then executed in an iterative fashion. The codes were:

- PANTHER [28] (PWR and AGR Neutronic and Thermal-Hydraulic Evaluation Route) was used for assessing the neutron flux, the power production and the heat distribution within the reactor cores. As the name suggests, the code is used for both PWRs and AGRs but was also used for Magnox reactors.
- MCBEND [29] is a general-purpose Monte Carlo radiation transport code to model the behavior of neutrons, photons and high energy electrons through materials and voids.
- FEAT-GRAPHITE [30] is a graphite condition assessment tool used to predict graphite weight loss, material properties and stresses within individual graphite bricks of an AGR core. It is a suite of macros which are run using the Finite Element Analysis Toolbox (FEAT) and used to compute graphite weight loss based on the MCBEND results and considering other factors, such as the chemistry conditions in the core.
- CODE_ASTER [31] to take field variable data from MCBEND and FEAT-GRAPHITE, including neutron damage, temperature and graphite weight loss, and project them onto a suitable finite element mesh for non-linear structural analysis.

The resultant integrated software framework is shown in Fig. 6.

The traditional way of working with the codes used in this case study requires users to manually generate input files for each code, passing data from the output of one code to the input of the next code in the sequence. At project conception, it was considered that there was a high risk that integration via a software framework would not be possible, making these activities true proofs of principles. Prior to commencement of the coding and activity to integrate software, the organizations supplying data and code for the INDE case studies had to agree on a common set of interfaces to define the sequencing, timing, formats and the usage of the simulation. This proved almost as challenging as integrating

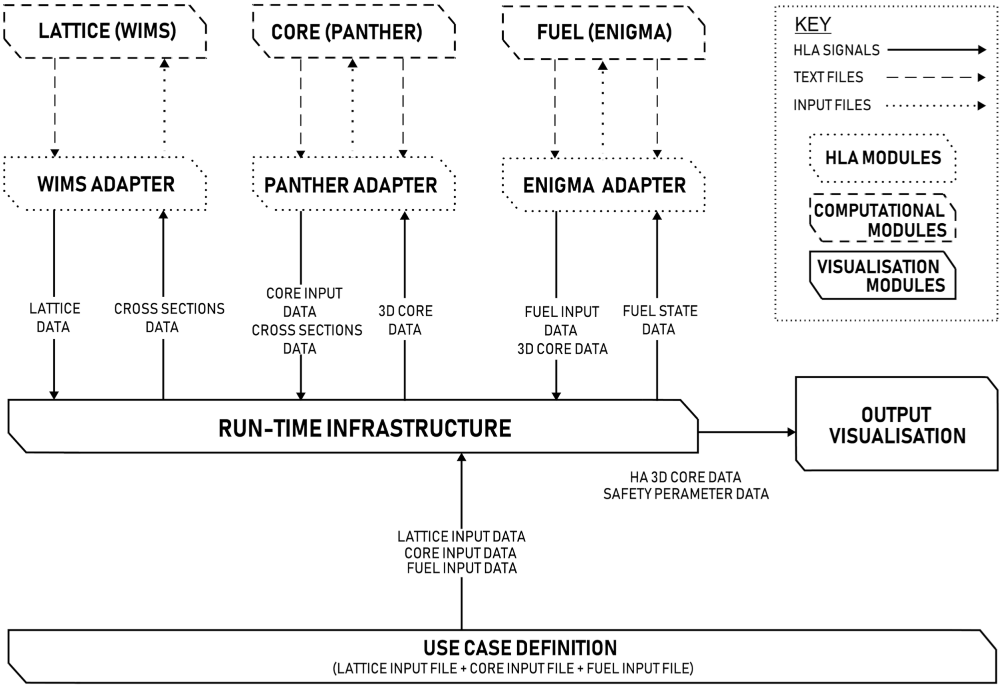


FIGURE 7. Integrated software framework for Pressurised Water Reactor (PWR) rod ejection use case.

the simulations. The end result was an integrated simulation that linked complementary analytical capability by connecting independent organizations on remote sites and enabling them to collaborate and compare results in real-time. The processing time for analysis was reduced from 4 days to approximately 4 hours. This was reduced further when the operators became experienced in running the new analysis. Outputs from the manual and networked analyses were compared and found to be within acceptable limits by the end-user.

The second use case, a control rod ejection in a Pressurized Water Reactor (PWR), was chosen to both demonstrate the multi-physics capabilities of the framework and the addition of new fuel codes within the calculations. Whilst a solution can be developed using a single tool (e.g. DYN3D [32]), the usual industrial practice is to use a number of codes from different sources and this can introduce a lack of efficiency. Once set up, the framework allowed more rapid analysis of differing scenarios with no loss of accuracy. The codes used in this use case were:

- WIMS [33] is a 2D lattice solver operating on unstructured mesh geometry that utilizes fine geometrical details, isotopic evolution and generic multi-group, multi-energy tabulated neutron cross-sections to generate homogenized few-group data (Flux Weight Constants) for a single fuel pin or an assembly.
- PANTHER (as above) is a coupled nodal diffusion and thermal hydraulic solver used to provide distributions of neutron flux, power and irradiation in a reactor core and perform analyses of steady-state and transient operations.
- ENIGMA [34] models the evolution of the thermal and mechanical state of the fuel and the changes caused by the generation and redistribution of fission products. The calculated parameters included temperatures, stresses, strains and corrosion.

The resultant integrated software framework is shown in Fig. 7. Once implemented, the analysis time was reduced from approximately 8 days to 12 hours [35]. Simplified models were initially substituted in the nuclear island of the PWR use case and the standard protocols used (defining the data input and outputs) meant that these abstracted models could easily be replaced by the high-fidelity codes by actioning a simple drop-down box.

In both use cases, the benefits were offset by the initial overhead to create the code, i.e., the requirement for a common standard and approach that is agreed by the multiple project partners. In the PWR example, the time to develop and run the initial simulation was comparable to the current manual process. However, subsequent runs could be completed in minutes, leading to an exponential increase in benefits with each subsequent iteration. It was found that the development time for modular elements such as adaptors and real-time infrastructure could be reduced by reusing and modifying existing codes rather than starting from scratch.

Prior to implementing the framework, the approach to implementing the codes in these use cases involved multiple human touch points or 'tweaks.' Fig. 8 illustrates these for

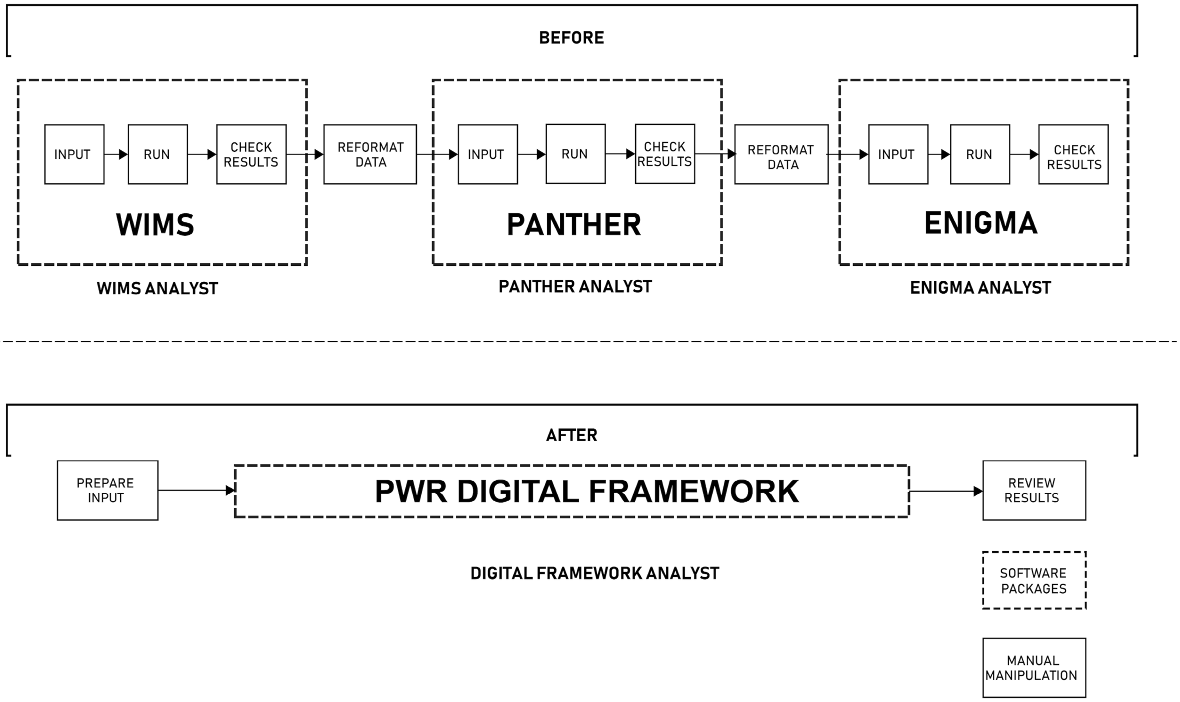


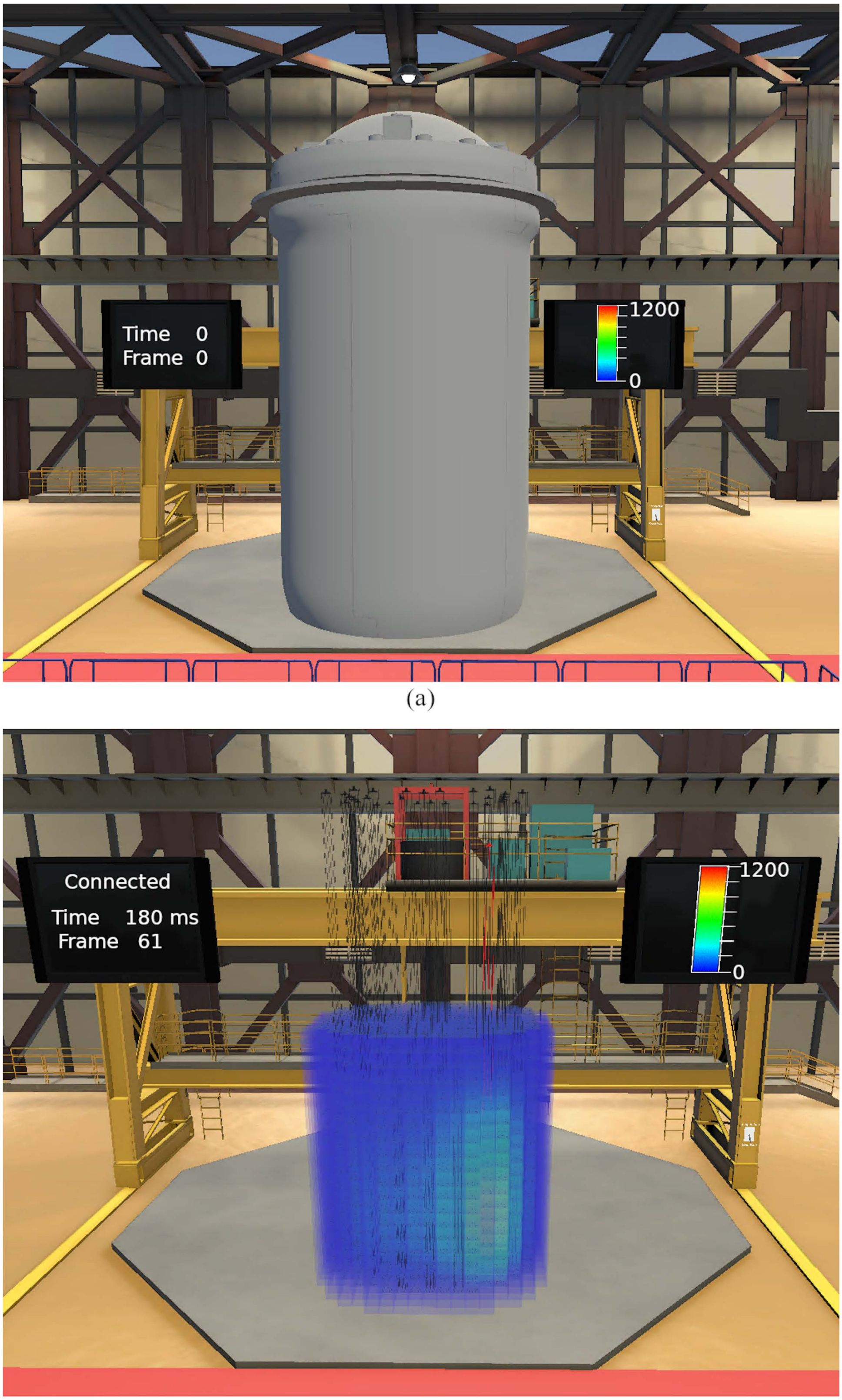
FIGURE 8. Comparison of manual interventions of existing for PWR use case. The "before" image illustrates the disparate software packages and manual manipulations that were required with the existing process. The "after" illustrates the streamlined process after integration using the concept software architecture.

the PWR use case. The complexity and implicit knowledge required for these interventions meant different specialists were required for each specific code, and these specialists could be located in different departments and/or physical locations. In the PWR example, eleven manual manipulations were replaced by two minor input and output checks. Quality checks confirmed the results were still acceptable to the end user. The capability of monitoring at each stage was retained. This significantly reduced the opportunity for the introduction of human error, in addition to the obvious resource efficiency improvements. Initial concerns that the accuracy might suffer when these manual adjustments were removed were disproved when results were found to be comparable to at least two decimal places. As the integration required the codification of knowledge, this made it explicit and has the added benefit that this would then be available for the life of the product. As a result, the entire operation can be completed by a single analyst, as opposed to the three specialists required before, as shown in Fig. 8. It also reduces the time to competency required of the analyst completing the work, as the simple GUI took the analyst step-by-step through what was required.

Various visualization options were developed for these use cases. This included 2D graphics, 3D visualization, and immersive, full-scale virtual reality (VR) visualizations as shown in Fig. 9 and the supplemental videos. The simulations were built up with standard protocols. The user interface allowed side by side, real-time comparison of results from different codes, as illustrated in Fig. 10. The VTK library [36] was used to create the user interface and visualize data.

F. EXTENSION OF USE CASES

To demonstrate the 'plug and play' capability of these frameworks, an extension to the PWR use case was carried out. This involved the substitution of the PANTHER code with DYN3D, which are different codes that provide the same simulation capability, as illustrated in Fig. 11. On completion, the results from DYN3D were found to be equivalent to those obtained using the integrated framework containing PANTHER. This demonstrated the key advantage of the horizontal integration: it lends itself to customization by allowing the simple replacement/modification of the modular simulations. Although there was a set-up time of approximately a person-week (35 hours) to create the initial interface representation, once this was established the DYN3D/PANTHER modules could be interchanged instantaneously via a drop-down menu. It should be noted that, during this proof of concept, adapter modules were used to interface all proprietary codes (except DYN3D). These were necessary to mediate and act as an interface between HLA and a specific code, as there was a reluctance to modify the base codes without evidence that the approach would work. Any further development should integrate the HLA communication interface as part of the code. However, the horizontal integration meant that no other modules had to be changed to make this substitution. This is seen as a key advantage over existing integrated



(a)

(b)

FIGURE 9. Snapshots from full-scale immersive Virtual Reality output: showing the plant as is (a) and an overlay of power distribution and control rod position (b).

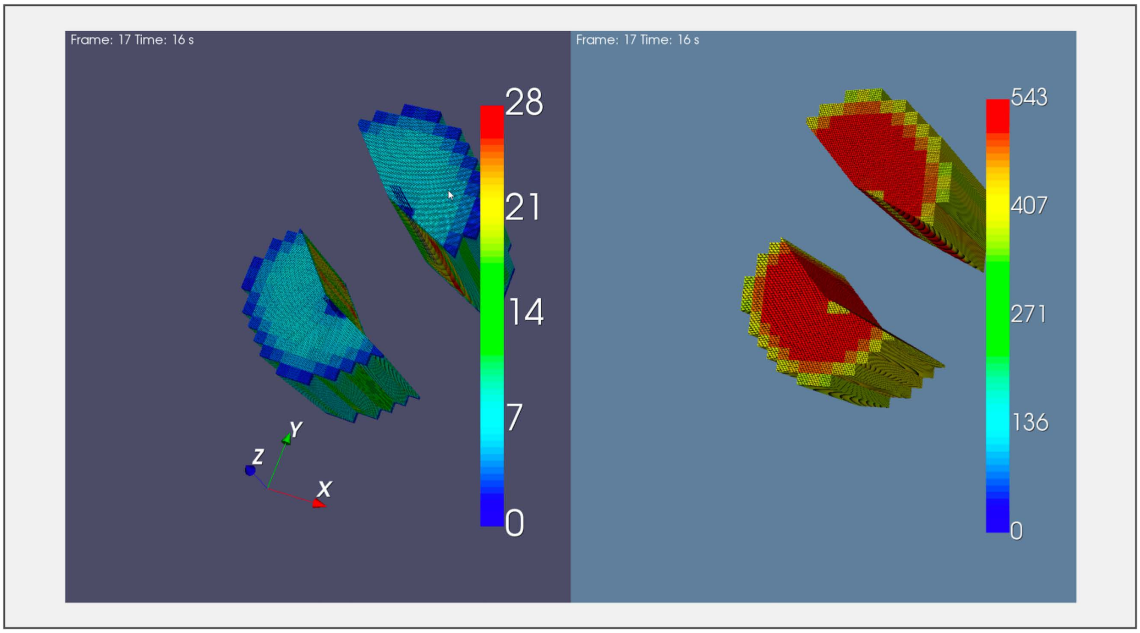


FIGURE 10. **Simulation outputs allowed side-by-side comparison of results. In this example from the PWR use case, linear rod power results obtained from PANTHER are contrasted with the fuel centre temperatures obtained from ENIGMA.**

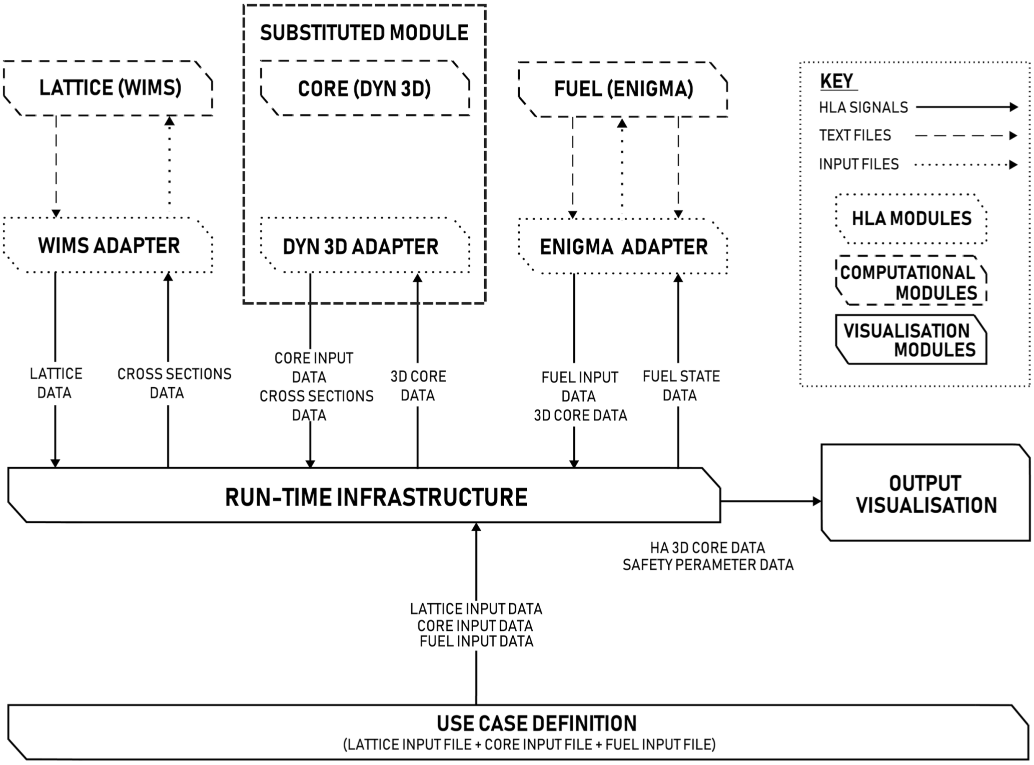


FIGURE 11. **Demonstration of 'module' interchangeability for Rod Ejection of PWR Use Case Simulation (compared to original in FIGURE 7).**

code systems such as NURESIM and VERA. An additional advantage was that the potential to execute codes while physically separated by hundreds of miles was demonstrated. The locations used are included in Fig. 5.

Automated and integrated uncertainty quantification was applied to specific aspects of the use cases. Uncertainty quantification is a key capability to define the appropriate boundaries of processes, critical safety parameters, allow-able tolerances, concession limits, and appropriate safety margins using the best estimate plus uncertainty approach. The full technical results were published in [33] and so only briefly summarized here while more consideration is given to the wider benefits in the discussion section below. In the AGR case study, the effects of uncertainty on the fracture mechanics of the fuel bricks was based on a constitutive law describing the material behavior of graphite and derived from hundreds of materials properties. In the PWR use case involving DYN3D, computation tools for uncertainty quantification were selected from pre-existing algorithms within the OpenCossan library [37]. In both cases equivalent accuracy to the manual methods were achieved with the PWR case generating comparable results to within a factor of 10^{-7} of the existing methods. Sensitivity analysis was completed for various computational outputs which enabled an increased understanding of critical parameters, e.g. for generated power, initial power had very limited impact on the output, whilst the thermo-hydraulic parameters and fuel assembly manufacturing tolerances played a crucial role. These insights offer the potential of opening up the design space or reducing conservatism on non-critical factors. The initial set-up time was comparable to the manual processes and now this capability has been established, reductions in analysis time would be achieved for future calculations, however, until approval from regulators can be gained, manual methods would still need to be carried out.

G. OUTCOMES

As far as we are aware, this work represents the 'first of a kind' usage of an HLA framework at the component behavior level and the first application of HLA to a UK civil nuclear scenario. Integrated simulations that have previously been created for the nuclear sector have primarily utilized star and vertical integration [13]–[15]. These previous approaches had some advantages, such as requiring fewer resources for the initial creation, however, there are also significant disadvantages in terms of high computational power requirements and reduced flexibility and scalability, which limited their wide scale adoption. Therefore, any new integrated digital framework should offer a solution that can be made available to all, with sufficient flexibility to evolve and develop with time. Based on these initial use cases, the framework that has been tested here provides a foundation for this solution and so warrants further development and testing.

The resultant software framework is an important proof of principle for the realization of the INDE, increasing the confidence that there is a viable approach for developing and scaling such a framework for the civil nuclear industry. To date, this work does not have the dynamic connectivity to real-world assets that would qualify as a digital twin. However, the horizontal integration approach used would lend itself to the addition of real-world data in a straightforward and modular fashion.

IV. DISCUSSION

The aspiration for a digital framework is a new way of working where hardware, software, user and organizational interfaces are interlinked and allow a fully joined-up approach to product development, business management and operations. It is not enough for one organization or sector to develop its own approach; the interconnected nature of various sectors, where supply chain partners contribute to aspects of manufacturing or product development and, in the case of electricity generation, where disparate power generators must interface with a central control system, demonstrates that a unified approach is required that must be adaptable over the decades that some products may be in use for. The guiding light to achieving this aspiration of a unified approach is to consider how dissimilar systems can be connected; where different approaches to the architecture for the digital twin are possible, the case study indicates that horizontal integration of a systems-based approach led to a favorable outcome. The development of this architecture is an important first step to realizing this aspiration. The many positive early indications of success, and the challenges associated with meeting this aim, can be explored in relation the technical and non-technical aspects. Although these benefits and challenges, explored below, are derived from use cases from the nuclear industry, they would also apply to any industry with similar requirements.

A. TECHNICAL BENEFITS

There are many expected technical benefits from these frameworks [38]. The use cases demonstrated increased efficiencies: in particular, step-change reductions in the elapsed time for simulation, processing times and a threefold reduction in the number of analysts needed to complete the task. The removal of a large number of manual interventions increased confidence that the capability would perform as expected. The HLA concept for the software framework has delivered the flexibility and scalability that would be needed to ensure the long-term sustainability of such a framework. However, a detailed cost/benefit analysis has not been undertaken. With horizontal integration, the scale of the initial investment required to agree standard protocols and approaches between collaborative partners should not be underestimated, especially when few precedents exist. Any future work should seek to quantify this fully.

The resultant software framework required relatively few resources to run. Analyses were completed on a small cluster ($n<4$) of off-the-shelf PCs as opposed to requiring dedicated High Performing Computing (HPC) power as a standard which is expensive and out of reach of many industrial users. As these are only small-scale proof of concepts, it is not yet possible to formally conclude whether HPC would be required for running the full system framework.

There is little quantitative data in the published literature on the benefits that have been achieved from digital frameworks which makes it difficult to compare these results to

TABLE 2. Summary of benefit streams from digital frameworks [4], [6], [9], [38], [39], [40].

Benefits	
Harder	Softer
• Reduction overall lead-times and cost	• Improved knowledge management through the capture & validation of corporate knowledge
• Reduced run-times	• Training and education platform
• Increased quality through decreased number of human interactions	• User-friendly interface allowing improved access for non-specialists
• Increased understanding of uncertainties	• Tailored visualisations all based on single 'version of the truth'
• Rapid design optimisation – move to non-obvious/evolutionary design	• Improved communication & collaboration
• Transparency of change management – single version of the truth, leads to reduced mistakes and reduced time in version management	• Library of 'trusted simulations'
• Integration of tolerances/tolerance stack-ups	• Auditable and transparent decision-making processes
• Enabler for simulation of on-off/off-nominal events	• Driver for culture change across industry sectors
• Computation costs – cost of hardware, HPC access, etc	

other case studies. Caution is advised on treating the values quoted within this paper as representative; the examples were specially selected to offer more potential for improvement than the standard. However, even with conservatism, the step change in analyses and elapsed times offers the potential to reduce the overall timescale for design. Currently, for nuclear fission reactors, this extends to years [23]; hence, any meaningful reduction would provide a compelling case for future research in this area.

B. ORGANIZATIONAL BENEFITS

In addition to the resource efficiencies, a number of other benefits to the organization were found. The development of adaptive visualizations of outputs and the creation of a 'single version of the truth' was found to improve communication between partners at geographically isolated sites. It also made it easier for individuals to access and manipulate results while tailoring them to personal preferences. This single 'version of the truth' eliminated issues of version control and reduced the burden of configuration management. However, data are not available on the scale and impact of these improvements.

The creation of the frameworks requires the codification of otherwise implicit knowledge, thus creating a repository of knowledge that would aid long-term data preservation. As many sectors are facing challenges with ageing workforces [39], [40], these approaches would help in mitigating some of the risks as older knowledge holders retire.

Knowledge management and improved communications were just two organizational benefits found to have been improved by using these frameworks. These 'softer' benefits were harder to quantify but were still important contributors to the overall value case. Table 2 captures examples of the range of benefits that can be realized through digital frameworks [4], [6], [9], [38] and identifies those which are 'harder' (easy to quantify) or softer. It is recommended that any future work seeks to quantify these savings from the softer benefits.

The systems-based approach has the advantage that one person or organization can be responsible for part of the framework. This would allow one subsystem to be managed or operated by a single organization while still allowing integration with other parts of the digital twin. Where a unified, sector-agnostic approach is considered, there is a clear benefit in allowing development of a subsystem by subject matter experts while it remains integrated with the rest of the digital twin; the expert knowledge can be captured by the digital twin while those that have provided the knowledge can retain intellectual property rights.

C. TECHNICAL CHALLENGES

In a future where the use of digital twins may become standard practice, they would ideally be introduced at the design stage as a virtual prototype i.e. a representation of a proposed real-world object, only validated to establish the extent to which they represent the real-world with respect to their intended usage [16]. Creating these frameworks without the foundational elements of a digital prototype could be prohibitively expensive. Digital prototypes are not currently available for existing nuclear infrastructures, and many gaps exist in the BIM dataset for nuclear infrastructures [26]. As a result, it may be cost-prohibitive to create a complete digital framework for existing systems. For these reasons, it is considered that the focus should be on developing these frameworks as a key capability for future assets rather than attempting to retrofit. However, even with this aim, significant investment is required to develop these technologies now, so that they are ready in parallel with any new build timelines for the nuclear industry.

The systems-based approach applied here utilized simulations and exemplar data sets within a framework and expert knowledge of the individual components. A data-based digital twin would also be able to handle large volumes of data from sensors, software, and actuators to increase the automation of calculations and thereby improve productivity. However, the drawback to a data-based approach is that the large volumes of data can be difficult to handle and cost-prohibitive. In addition, the output of a data-based digital twin cannot easily be transferred to another similar system, having been developed from that very specific data set. This lack of transferability along with the somewhat 'black-box' nature of a data-based digital twin is at odds with the learning from experience principle that the industry operates under; the systems-based approach offers greater insight and this benefit outweighs the upfront development effort.

D. ORGANIZATIONAL CHALLENGES

The use cases presented were focused on an initial demonstration. If the software framework and benefits are to be maintained in the long-term, collective discipline is required by all partners to utilize these protocols for any ongoing development. This is considered to be one of the many organizational challenges that merit further investigation to understand the practicalities of these approaches in the future.

There was also recognition during the development of these use cases, that although the initial proof of concept has been established, the work on integrated digital frameworks cannot stop at technology development. Training, deployment and the cultural change programs required for wide scale adoption are significant considerations that should be understood in more detail. If these points were not addressed, then it is likely that only limited benefits from this approach would be obtained. NASA proposed that management support/advocacy, technical capability readiness and organizational willingness were prerequisites for the adoption of these new technologies [41]. To wait for these prerequisites to manifest organically would add to already long development times, so this may re-enforce the need to consider a 'controlling mind' or strategic deployment plan for critical areas.

Although not evident in the technical results, other challenges were experienced. Discussions during this project and during the formulation of the NVEC work highlighted differences of opinions on the commercial ownership of the framework and the routes and mechanisms for exploiting such a framework for revenue generation. Similarly, a requirement to appoint an ultimate decision-maker or establish a clear governance structure was identified, to ensure that matters pertaining to the future development and evolution of the framework could be resolved appropriately. There is also a need to define where the responsibility and resources would reside to provide routine maintenance and upkeep for the resultant framework, i.e., ensuring there is active stewardship. It is considered a gap in the literature that little has been found on the requirements to establish clear commercial frameworks, governance and stewardship for these frameworks as part of the development process. More work is required to define appropriate solutions for these areas.

E. APPLICATION TO OTHER INDUSTRIES

Given that the nuclear sector in the UK is entering something of a renaissance where new reactors are now being proposed, this provides a unique opportunity; although the industry encapsulates decades of operation, the previous technology did not incorporate widespread use of sensors and often relied on expert knowledge. The development of sensors for the nuclear industry is in its infancy and the development of a digital twin that evolves as this technology also develops while also codifying the expert knowledge could represent a step-change in how the industry works as well as providing a template for other industries to follow. Further, in a highly regulated industry that demands precise prediction of future performance, the up-front investment in a flexible digital twin architecture will pay off in the long-run and act as an example for other industries to follow.

However, cross-fertilizing the learning from the development of digital frameworks is not enough. The importance of a unified approach to building a digital twin is clear [3], [42] and the approach outlined in this paper could serve as the foundation for such unification. In particular, there is a need for a standardized way of exchanging information between the components of a digital twin, and indeed between individual digital twins, is required to truly realize the benefits [11]. Standardized data exchange would require an approach with built-in flexibility to allow for plug-and-play connectivity, and this is what the architecture used in these case studies provides; the example in section 3.6 of interchanging modules via a drop-down menu is facilitated by using a standard approach to integration. Hence, the ability to provide translation between different components of a digital twin will be instrumental in providing this flexibility. Once a module has been developed, a standardized approach would make its re-use straightforward and allow its translation into a future where current barriers to adoption such as development times and costs are reduced.

Big data analytics is increasingly used to drive efficiency and provide enhanced insight into causes of failure [43] and an approach that combines both data-based and systems-based methods is seen to add the greatest value [2]. Some aspects of the architecture presented in our study could be adapted to include a data-based approach and so would generate a hybrid approach where the best approach is selected for different aspects of the digital twin.

Further cross-sector applications can be envisioned. The visualizations used in our study are universal so can be applied to any other industry with an interest in modelling components. The framework incorporates codes that describe thermodynamic, mechanical, and structural properties, so the types of data that would be used in industries, such as aerospace, are very similar to the case studies reported here. In translation to manufacturing, the case studies used here represent scenarios relevant to Prognostic and Health Management applications: data are collected from the physical system and used to determine when preventative maintenance or diagnostics of faults are required. In this regard, the framework we have outlined would provide excellent adaptability for manufacturing as a service [12]. The horizontal integration lends itself to adaptation for other industries; a translator may be required at a node to integrate any new software into the systems-level environment, but ideally the new software would incorporate the necessary interface. To truly realize this benefit, common standards should be developed to define the interface with the translator. The up-front effort required to develop these standards will be substantial and would be offset by the economy of scale generated by the widespread adoption of this approach. The ability to run the simulations without the need for a High Performance Computing cluster would be a further advantage for wider-scale adoption.

The development of plug-and-play modules that apply across sectors could introduce a new market where code is developed specifically because of the flexibility provided by a standardized approach. We can envision a future where a library of standardized digital models is available for connecting common pieces of hardware or management systems. This approach has a clear benefit over other architectures which would require widespread adaptation of the framework to add in every extra piece of software. To support such an approach, funding models should be revised so that research can be less specific to an individual sector.

V. CONCLUSION

A. OUTCOMES

The nuclear case study presented here provides a proof-of-concept for an initial software framework for an Integrated Nuclear Digital Environment (INDE) and is the first time that HLA has been applied to a civil nuclear scenario. This approach is widely applicable to other sectors and shows promise as the basis for a unified, cross-sector approach to developing digital twins.

The framework is the first of a kind to use HLA at the component level and at the analysis tool level. The horizontal integration methodology was found to have the scalability needed to ensure that frameworks could develop, evolve, and remain relevant through time, addressing limitations of previous software frameworks. As well as resource efficiencies, several additional softer benefits, such as improved inter-site co-operation, knowledge management and time to competence, were found. The addition of automated integration of risk and uncertainty is novel and is found to be as reliable as manual methods while reducing resource requirements. Although this HLA approach to the software framework requires an increased up-front investment in resource to define common standards as well as some ongoing maintenance of these standards, this investment is considered worthwhile due to the longer-term benefits that it offers.

B. OUTLOOK

The proof-of-concept provided by this study demonstrates that there is an achievable route to implementation of an INDE and is an important first step to realizing a unified approach to implementing digital twins.

The horizontal architecture provides a significant opportunity for cross-sectoral efficiencies and so, compared to other architectures, would lend itself well to the development of a unified approach. Patterson et al have already proposed how the INDE could be developed and expanded to deal with the unique requirements of fusion power plants [44] and many elements such as the GUI, database, RTI, SIM managers, and the simulations themselves, could be used in many different sectors beyond electricity generation. This approach can be thought of as providing 'building blocks' that could then be configured as appropriate for the individual sectors. Developing a standard approach to integration allows the development of modules that can be used interchangeably and so could lead to new markets where these modules provide a revenue stream. The horizontal architecture could be adapted to provide a hybrid approach where some components utilize a data-based approach and others use a systems-based approach, depending on the level of detail and technical understanding required. The upfront cost and timescale for development are necessary to move to this approach which would truly realize a unified approach to digital twin architecture.

Further research is needed into the commercial and organization challenges that digital frameworks present. In particular, solutions will need to be found for critical issues such as the benefit distribution, commercial models, governance and stewardship, if the collaboration that underpins the benefit streams is to be realized. There is also an opportunity to create synergies and gain further efficiency improvements through consideration of a cross-sectoral approach. If adopted more broadly, the adaptable approach used by the INDE could be a key enabler to connect disparate digital frameworks, sectors, and applications over time. The organization or establishment that finds a solution for these challenges and champions the development will have the opportunity to establish a global leadership position.

ACKNOWLEDGMENT

Sally Purdie would like to thank Dr Laura Leay for her support in writing and editing this paper.

REFERENCES

[1] G. L. Harris, *Computer Models, Laboratory Simulators, and Test Ranges: Meeting the Challenge of Estimating Tactical Force Effectiveness in the 1980's*," Leavenworth, Kansas: U.S. Army Cofigmmand and General Staff College, May 1979.

[2] D. Adamenko, S. Kunnen, R. Pluhnau, A. Loibl, and A. Nagarajah, "Review and comparison of the methods of designing the digital twin," *Proc. CIRP*, vol. 91, pp. 27–32, Jan. 2020.

[3] A. Fuller, Z. Fan, C. Day, and C. Barlow, "Digital twin: Enabling technologies, challenges and open research," *IEEE Access*, vol. 8, pp. 108952–108971, 2020.

[4] Y. Zheng, S. Yang, and H. Cheng, "An application framework of digital twin and its case study," *J. Ambient Intell. Hum. Comput.*, vol. 10, no. 3, pp. 1141–1153, 2019.

[5] E. Glaessgen and D. Stargel, "The digital twin paradigm for future NASA and U.S. air force vehicles," in *Proc. 54th AIAA/ASME/ASCE/AHS/ASC Struct., Struct. Dyn. Mater. Conf.*, 2012, p. 1818.

[6] F. Tao, J. Cheng, Q. Qi, M. Zheng, M. Zhang, and F. Sui, "Digital twin-driven product design, manufacture and service with big data," *Int. J. Adv. Manuf. Technol.*, vol. 94, pp. 3563–3576, Feb. 2018.

[7] T. D. West and M. Blackburn, "Is digital thread/digital twin affordable? A systemic assessment of the cost of DoD's latest Manhattan project," *Proc. Comput. Sci.*, vol. 114, pp. 47–56, Jan. 2017.

[8] A. Levers, K. Vikhorev, S. Purdie, L. Dwyer, and D. Bowman. *Transforming Digital Twins into Digital Products that Thrive in the Real World*. Virtual Engineering Centre. Accessed: Jun. 10, 2021. [Online]. Available: https://www.virtualengineeringcentre.com

[9] Y. Lu, C. Liu, K. I. Wang, H. Huang, and X. Xu, "Digital twin-driven smart manufacturing: Connotation, reference model, applications and research issues," *Robot CIM-INT Manuf.*, vol. 61, Feb. 2019, Art. no. 101837.

[10] R. Vrabič, J. A. Erkoyuncu, P. Butala, and R. Roy, "Digital twins: Understanding the added value of integrated models for through-life engineering services," *Proc. Manuf.*, vol. 16, pp. 139–146, Jan. 2018.

[11] R. Rosen, J. Fischer, and S. Boschert, "Next generation digital twin," *IFAC PapersOnLine*, vols. 15–52, pp. 265–270, Jan. 2019.

[12] Q. Qi, F. Tao, Y. Zuo, and D. Zhao, "Digital twin service towards smart manufacturing," in *Proc. 51st CIRP Conf. Manuf. Syst.*, vol. 72, no. 1, 2018, pp. 237–242.

[13] J. A. Turner, K. Clarno, M. Sieger, R. Bartlett, B. Collins, R. Pawlowski, R. Schmidt, and R. Summers, "The virtual environment for reactor applications (VERA): Design and architecture," *J. Comput. Phys.*, vol. 326, pp. 544–568, Dec. 2016.

[14] F. Curca-Tivig, "ARCADIA and advanced methods licensing and implementation update," in *Proc. TOPFUEL*. La Grange Park, IL, USA: American Nuclear Society, 2016, pp. 755–762.

[15] C. Chauliac, J.-M. Aragonés, D. Bestion, D. G. Cacuci, N. Crouzet, F.-P. Weiss, and M. A. Zimmermann, "NURESIM—A European simulation platform for nuclear reactor safety: Multi-scale and multi-physics calculations, sensitivity and uncertainty analysis," *Nucl. Eng. Design*, vol. 241, no. 9, pp. 3416–3426, Sep. 2011.

[16] M. Liu, S. Fang, H. Dong, and C. Xu, "Review of digital twin about concepts, technologies, and industrial applications," *J. Manuf. Syst.*, vol. 58, pp. 346–361, Jan. 2021.

[17] A. Timmis, "Aircraft manufacturing and technology," in *Air Transport Management: An International Perspective*, 2nd ed. Evanston, IL, USA: Routledge, 2020, ch. 16, pp. 271–273.

[18] C. Brosinsky, D. Westermann, and R. Krebs, "Recent and prospective developments in power system control centers: Adapting the digital twin technology for application in power system control centers," in *Proc. IEEE Int. Energy Conf. (ENERGYCON)*, Jun. 2018, pp. 1–6.

[19] J. Yuchen, Y. Shen, L. Kuan, L. Hao, and K. Okyay, "Industrial applications of digital twins," *Philos. Trans. Roy. Soc. A*, vol. 379, no. 2207, 2021, Art. no. 20200360.

[20] B. Hicks. (2019). *Industry 4.0 and Digital Twins: Key lessons From NASA*. The Future Factory. Accessed: Nov. 18, 2019. [Online]. Available: https://www.thefuturefactory.com/blog/24

[21] P. Franciosa, M. Sokolov, S. Sinha, T. Sun, and D. Ceglarek, "Deep learning enhanced digital twin for closed-loop in-process quality improvement," *CIRP Ann.*, vol. 69, no. 1, pp. 369–372, 2020.

[22] *Energy White Paper: Powering Our Net Zero Future*, U.K. Government Department for Business, Energy & Industrial Strategy, London, U.K., 2020.

[23] *Industrial Strategy: Nuclear Sector Deal*, HM Government, 2018. [Online]. Available: https://www.gov.uk/government/publications/nuclear-sector-deal/nuclear-sector-deal

[24] G. Di Gironimo, C. V. Labate, F. Renno, M. Siuko, A. Lanzotti, and F. Crisanti, "An interactive design approach for nuclear fusion purposes: Remote handling system for FAST divertor," *Int. J. Interact. Des. Manuf.*, vol. 8, no. 1, pp. 55–65, Feb. 2014.

[25] B. Lindley, D. Allen, J. Lillington, A. Smethurst, P. Smith, D. Bowman, L. Dwyer, K. Lai, A. Levers, K. Vikhorev, and D. Litskevich, "Modelling and simulation activities in support of the U.K. nuclear R&D programme on digital reactor design," in *Proc. Nucl. Fuel Mater., React. Phys., Transp. Theory*, vol. 3, Jul. 2018, Art. no. V003T02A004.

[26] E. A. Patterson, R. J. Taylor, and M. Bankhead, "A framework for an integrated nuclear digital environment," *Prog. Nucl. Energy*, vol. 87, pp. 97–103, Mar. 2016.

[27] D. Bowman, K. Vikhorev, K. Lai, M. Bankhead, B. Merk, D. Litskevich, C. Jackson, and D. Faulke, "Digital reactor design—Capability mapping," Digit. React. Des. Project, Mumbai, India, Tech. Rep., VECD-AIS-DRD-EXT-003-002.B, 2017. [Online]. Available: https://n-vec.co.U.K./publications/

[28] P. K. Hutt, N. Gaines, M. McEllin, R. J. White, and M. J. Halsall, "The U.K. core performance code package," *Prog. Nucl. Energy*, vol. 30, no. 5, pp. 291–298, 1991.

[29] S. D. Richards, C. M. J. Baker, A. J. Bird, P. Cowan, N. Davies, G. P. Dobson, T. C. Fry, A. Kyrieleis, and P. N. Smith, "MONK and MCBEND: Current status and recent developments," *Ann. Nucl. Energy*, vol. 82, pp. 63–73, Aug. 2015.

[30] J. E. Coote and N. S. Headings, "Revised method for graphite weight loss prediction," in *Modelling and Measuring Reactor Core Graphite Properties and Performance*. Cambridge, U.K.: RSC Publishing, 2011.

[31] EDF. *Code Aster: Structures and Thermodynamics Analysis for Studies and Research*. Accessed: Mar. 30, 2020. [Online]. Available: https://www.code-aster.org/spip.php?rubrique2

[32] S. Tolo, D. Litskevich, K. C. Lai, D. Faulke, D. Bowman, B. Merk, K. Vikhorev, and E. Patelli, "Uncertainty in digital reactor design," in *Proc. 2nd Int. Conf. React. Plants, Struct., Risk Decommissioning (NUPP)*, 2018, pp. 1–10.

[33] B. Lindley, G. Hosking, P. Smith, D. Powney, B. Tollit, T. R. Fry, R. Perry, T. N. Ware, C. Murphy, C. Grove, M. Thomas, K. Hesketh, and D. Kotlyar, "Developments within the WIMS reactor physics code for whole core calculations," in *Proc. M&C Int. Conf. Math. Comput. Methods Appl. Nucl. Sci. Eng.*, Jeju, South Korea, Apr. 2017, pp. 1–10.

[34] G. Rossiter, "Development of the ENIGMA fuel performance code for whole core analysis and dry storage assessments," *Nucl. Eng. Technol.*, vol. 43, no. 6, pp. 489–498, Dec. 2011.

[35] A. Kyrieleis, A. Aslam, J. Draup, I. Nistor, D. Bowman, C. S. Jackson, S. Tolo, and S. Dargaville, "Digital reactor design phase 1: Final report," Digit. React. Des. Project Rep., Mumbai, India, Tech. Rep. 207134-TR-00020, 2019.

[36] W. Schroeder, K. Martin, and B. Lorensen, *The Visualization Toolkit*, 4th ed. Clifton Park, NY, USA: Kitware, 2006.

[37] E. Patelli, "COSSAN: A multidisciplinary software suite for uncertainty quantification and risk management," in *Handbook Uncertainty Quantification*. R. Ghanem, D. Higdon, and H. Owhadi, Eds. Cham, Switzerland: Springer, 2015, pp. 1–69.

[38] J. P. Hale, P, Zimmerman, G. Kukkala, J. Guerrero, P. Kobryn, B. Puchek, M. Bisconti, C. Baldwin, and M. Mulpuri, "Digital model-based engineering: Expectations, prerequisites, and challenges of infusion," NASA, Washington, DC, USA, Tech. Rep. TM-2017-219633, 2017.

[39] D. M. Blau and B. A. Weinberg, "Why the U.S. science and engineering workforce is aging rapidly," *Proc. Nat. Acad. Sci. USA*, vol. 114, no. 15, pp. 3879–3884, Apr. 2017.

[40] *Future of an Aging Population*, UK Government Office for Science, Open Government License, London, U.K., 2016.

[41] M. Grieves, *Virtually Perfect: Driving Innovative and Lean Products through Product Lifecycle Management*. Merritt Island, FL, USA: Space Coast Press, 2003, p. 133.

[42] F. Tao, H. Zhang, A. Liu, and A. Y. C Nee, "Digital twin in industry: State-of-the-art," *IEEE Trans. Ind. Informat.*, vol. 15, no. 4, pp. 2405–2415, Apr. 2019.

[43] F. Tao, M. Zhang, J. F. Cheng, and Q .L. Qi, "Digital twin workshop: a new paradigm for future workshop," *Comput. Integr. Manuf. Syst.*, vol. 23, no. 1, pp. 1–9, 2017.

[44] E. A. Patterson, S. Purdie, R. J. Taylor, and C. Waldon, "An integrated digital framework for the design, build and operation of fusion power plants," *Roy. Soc. Open Sci.*, vol. 6, no. 10, 2019, Art. no. 181847.

DAVID BOWMAN received the degree in aero engineering from The University of Manchester, U.K., in 1976.

He joined BAE Systems (then British Aerospace), in 1980, from the Marshall's of Cambridge, as a Project Engineer within the U.K. arm of Panavia. Following various roles within the Technical Directorate, including as the Head of modeling and simulation and the Deputy Chief Advanced Studies Engineer. He retired from BAES, in 2011, as a Chief Engineer Operational Aircrew Training. He joined the Virtual Engineering Centre, Daresbury, U.K., in 2011. He is currently a Honorary Fellow with the University of Liverpool.

Mr. Bowman is a Chartered Engineer and a member of the Royal Aeronautical Society.

LYNN DWYER received the B.A. degree in industrial economics from Coventry University (Lanchester Polytechnic), in 1987.

She is currently the Commercial and Partnerships Director of the Institute of Digital Engineering and Autonomous Systems and the Virtual Engineering Centre (VEC), University of Liverpool (UoL), U.K. She has a strong background and over 30 years' experience in research and development programs in industrial and digital engineering environments. She has been instrumental in the early-stage establishment and on-going development of the Virtual Engineering Centre, UoL's digitalization applied research impact center. She has been lead or co-investigator on a number of large multi-partner collaborative industrial digitalization research and development projects and has established an active network of over 500 businesses, including 300 SME's engaged in digital adoption.

ANDREW LEVERS received the M.Sc. degree in structural integrity from the University of Sheffield, U.K., in 1992, the M.Phil. degree in the application of axiomatic design principles from the University of Leeds, U.K., in 1998, and the Ph.D. degree in manufacturing engineering from Middlesex University, U.K., in 2001.

He is currently an Executive Director of the Institute of Digital Engineering and Autonomous Systems (IDEAS), University of Liverpool. Prior to this, he was the Technical Director at the Survitec Group, a designer and manufacturer of personal survival equipment and oxygen systems for fixed and rotary wing military platforms. Until May 2013, he served as the Research and Development Integration Manager at Airbus Operations. In 20 years career held a variety of senior technical and strategic positions within Airbus Operations that has led to several cutting-edge technology development projects. He has been a Project Leader for the THERM Project co-funded by the U.K. Technology Strategy Board. He has delivered several keynote and prestige lectures, including the Sir Geoffrey de Havilland Lecture to the Royal Aeronautical Society and the Bi-Annual Dickinson Lecture to the Newcomen Society.

Dr. Levers is a Chartered Engineer and a fellow of the Royal Aeronautical Society. He is an Active Member of the International Scientific Committee on Shot Peening. He was awarded the Gold Medal of the Institute of Materials Minerals and Mining, in 2004, for the implementation of the Creep Age forming process on the Airbus A380.

EANN A. PATTERSON received the B.Eng. degree in mechanical engineering and the Ph.D. degree in engineering from the University of Sheffield, U.K., in 1982 and 1985, respectively.

He has been the AA Griffith Chair of structural materials and mechanics at the University of Liverpool, since 2011. He was appointed as the Dean of the School of Engineering, in 2019. Previously, he was the Chair of the Department of Mechanical Engineering, Michigan State University, and the Head of the Department of Mechanical Engineering, University of Sheffield. His research interests include experimental mechanics and application of measurement data to support computational modeling in the aerospace, biomedical, and energy industries.

Prof. Patterson is a Chartered Engineer and a fellow of the Royal Academy of Engineering (FREng) and the Institute of Mechanical Engineers (FIMechE). He was awarded the Royal Society Wolfson Research Merit Award, in 2011.

SALLY PURDIE received the B.Eng. degree in materials, design and engineering from Newcastle University, Newcastle upon Tyne, U.K., in 1995, and the M.Sc. degree (Hons.) in tribology and machine design from the University of Leeds, U.K., in 1997.

She has over 20 years' experience translating academic research into industrial innovations in companies, including Rolls-Royce plc, Procter and Gamble, Element Six, and the U.K. Atomic Energy Association. She currently runs her own company, Seirots Engineering, U.K. She has previous published a paper on "An integrated digital framework for the design, build and operation of fusion power plants" (Royal Society Open Science). Her research interests include engineering materials, manufacturing, digital innovation, business storytelling, and creativity.

Ms. Purdie is a Chartered Engineer and a fellow of the Institute of Materials, Minerals and Mining.

KONSTANTIN VIKHOREV received the Dipl.Ing. degree from Bauman Moscow State University, in 2006, the M.Sc. degree in mechatronics from De Montfort University, U.K., in 2007, and the Ph.D. degree in computer science from the University of Nottingham, U.K., in 2010.

He is currently the Technical Lead with the Virtual Engineering Centre (VEC), University of Liverpool. He is experienced in systems engineering for complex environments and digital engineering. He oversees all technical work at the VEC, including the digital architecture development along with providing the expertise to ensure the integration of existing sector relevant digital models and advising on the structure of future new digital models for compatibility and ease of integration to ensure future and enduring scalability. He was also the Technical Lead of Track Analytics Project aimed to develop data analysis solution for Royal Navy. He worked to design a big data analysis solution for JLR Halewood factory and leading the Industrial Internet of Things (IIoT) LCR 4.0 projects, promoting digital technologies in the Liverpool City Region.

• • •