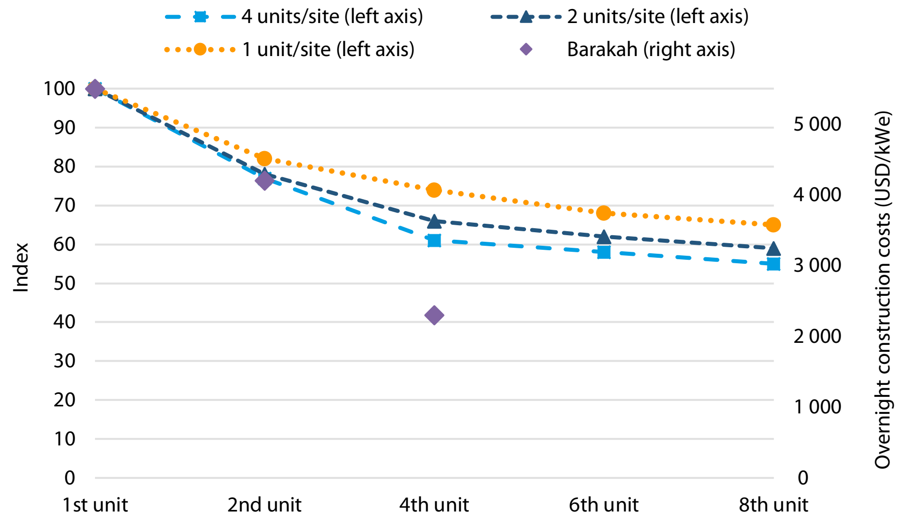
Figure 24: **Average cost of one unit in a programme of n units**



Sources: Based on NEA (2000), *Reduction of Capital Costs of Nuclear Power Plants*; and Gogan (2019), "The potential for nuclear cost reduction."

Series effect

Construction of the French fleet clearly benefitted from the series effect, with the average construction cost (EUR/kW$_e$) of a series of standardised units being less than for a single unit with the same features designed and built separately.

The series effect, a term covering all the effects related to delivering large projects, has been demonstrated in several econometric studies (Berthélemy and Escobar Rangel, 2015). To create a series effect, the technical standards, codes and norms that will be used in the design, licensing and construction of all units of the series must be stable. When there is any deviation from these conditions, for example with construction projects that involve more than one country (and are therefore subject to different safety authorities and regulations), or that have different industrial assembly lines, series effect benefits are likely to be lost.

The series effect is influenced by two distinct factors: the programme effect and the productivity effect (SFEN, 2018).

- The programme effect originates in the strategic decisions of the architect-engineer (the company managing the project and supervising reactor construction, for example EDF in France). The programme effect arises from the uniformity of studies, developments, qualifications and testing of materials for one reactor model built in a series. These nonrecurring costs are both independent of the number of units involved and are fairly independent of unit size (rated power). They are, however, strongly impacted by the level of innovation and degree of complexity introduced in a new design.
- The productivity effect is seen mostly in the supply chain, with suppliers passing on gains in productivity in their prices. It is highly dependent on the visibility given to suppliers with a guaranteed order for a series of identical components. This visibility means that the planning and use of resources and production tools can be optimised.

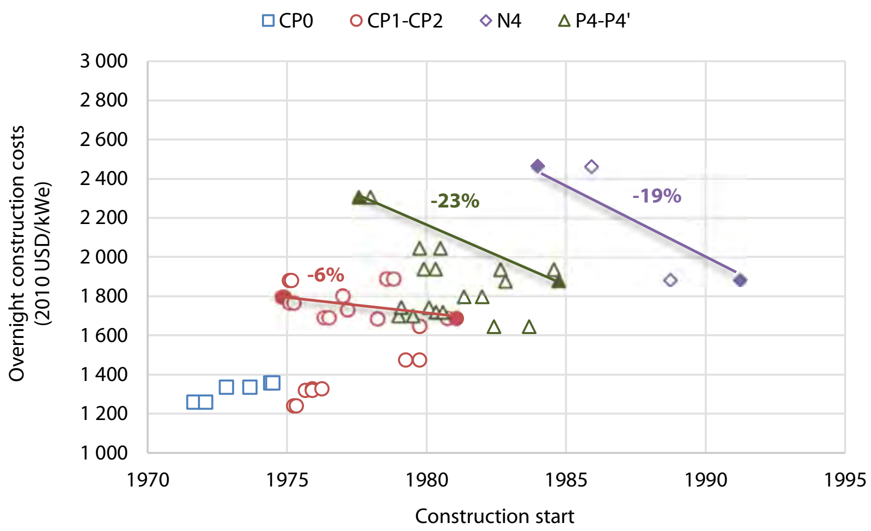
The impact of series construction of standardised reactors on OCC is quite substantial, with cost savings of 15-20% (NEA, 2000). The impact on time-related costs (IDC) is also significant (costs could decrease by more than 60%) because the construction period is substantially shorter. When time-related cost savings are combined with OCC reductions, total costs can be 25-40% lower.

Empirical evidence indicates that more than six units need to be built to take full advantage of a standardised series effect. Korean nuclear programme experience shows that the construction lead time of 75 months for the first twin units can fall to 53 months for the second pair. France's 900-MW_e series deployment demonstrates similar findings, with the last units being delivered in less than 60 months.

- France's historical nuclear programme: Benefits of series construction

The French National Audit Office's report provides a sound statistical baseline for the construction costs of France's current fleet, expressed in nominal and real terms (using a gross domestic product deflator). The data show that the strategy of standardisation for the French fleet with a vertically integrated industrial organisation (with the operator, EDF, having architect-engineer responsibility) allowed EDF to realise significant cost reductions between the first and last pair of each reactor series (Figure 25).

Figure 25: **French nuclear programme construction costs, 2012**



Source: NEA based on data from Cour des Comptes (2012).

- The UK Sizewell B and C projects: Benefits of shifting from a single- to multi-unit project

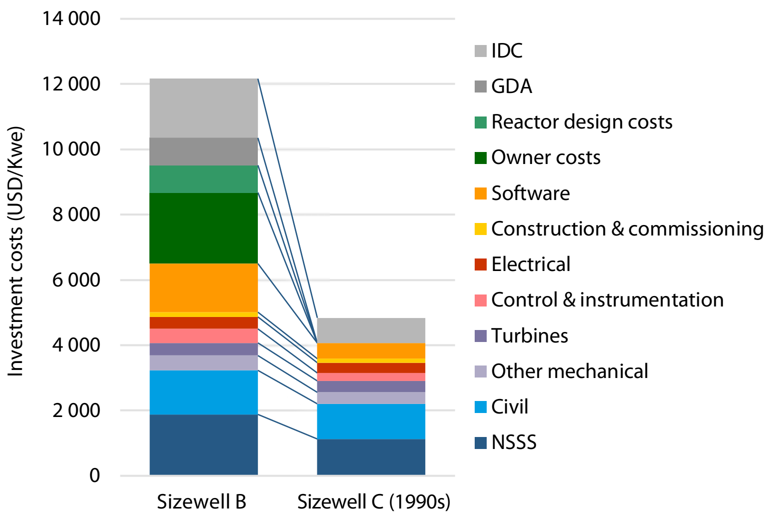
Sizewell B was the first pressurised water reactor (PWR) to be built in the United Kingdom, and it was finished on time and on budget. The single-unit reactor was commissioned in 1995, and for several years a detailed plan for a twin-unit project based on the same reactor design was considered for Sizewell C.[32]

It is estimated that the OCC would have fallen by 37% for the two projects, owing to both a reduction in indirect costs and sustained supply chain mobilisation. Sizewell C would have benefitted from the Sizewell B design phase's primary contractors and suppliers, which would have significantly reduced costs related to the reactor core (the NSSS), construction and instrumentation, and software development.

32. The current project for two EPRs at Sizewell C is based on the same site but is a different project in terms of reactor technology.

In addition, a number of nonrecurrent indirect costs related to reactor design, Generic Design Assessment (GDA) and site acquisition would have been avoided. Considering those nonrecurrent indirect costs, overall cost reductions could have reached 55% (Figure 26).

Figure 26: **Cost reductions expected between Sizewell B and proposed Sizewell C (1990s)**



Source: Based on ETI (2018), *The ETI Nuclear Cost Driver Project: Summary Report*.

Box 9: **Lessons learnt from industrial megaprojects**

Nuclear new-builds are major temporary undertakings, characterised by colossal budgets, considerable complexity and important socio-political and economic implications. Nevertheless, they are not the only projects with these features. Major transportation projects such as tunnels, bridges, ports and other massive facilities such as oil and gas platforms, liquefied natural gas platforms and power stations have similar characteristics, and they all fall into the category of industrial megaprojects.

The historical performance of megaprojects demonstrates that most of them have experienced cost and time overruns. For instance, transportation megaprojects are over budget all over the world (Locatelli, 2018). In the electricity sector, the costs of three-quarters of electricity megaprojects are higher than predicted, with an average budget overrun of 66% (Sovacool, Gilbert and Nugent, 2014). These trends suggest that nuclear projects are not unique and the poor performance of recent Gen-III FOAK projects can be explained, to some extent, by the fact that nuclear new-builds are among the most complex megaprojects.

The reasons for megaproject cost overruns have been studied extensively, and three key factors can be identified:

- Optimism bias: The combination of optimism bias and strategic misrepresentation is responsible for the underestimation of cost baselines and the deliberate overestimation of benefits to gain approval and funding. These factors are particularly important when political and social implications are significant.
- Design maturity: When the scope of work and potential risks of megaprojects are well identified in the pre-project phase, time and cost savings of roughly 20% can be realised. Detailed engineering and early validation and verification are at the core of practices that can make a difference (such as system engineering), as described in Chapter 4.

Box 9: **Lessons learnt from industrial megaprojects** *(cont'd)*

- Organisational complexity and inadequate governance: Recent studies suggest that megaproject costs escalate mainly because investments are so large and projects are very complex, particularly at the organisational level (Locatelli, 2018), involving numerous stakeholders with conflicting needs and a high number and variety of interfaces between the project and organisational entities. In these circumstances, a lack of strategic vision, ambiguity of scope and misalignment of stakeholder interests can be very damaging. It is therefore largely the governance of all these interactions that will determine the final performance of nuclear megaprojects.

Another challenge is low productivity. While the manufacturing sector has approximately doubled its productivity over the past two decades, construction productivity has remained flat or even declined. Wages, however, have continued to rise more quickly than inflation in many markets, resulting in higher costs for the same results (McKinsey, 2015).

These findings suggest that the organisational dimension may be key to the success of megaprojects. Organisational theory offers practical solutions to find the organisational optimum needed to cope with the complexity and changing conditions of megaprojects (i.e. hierarchies versus networks). As indicated in Box 6, practitioners also highlight the importance of leadership, organisational skills, mindsets, attitudes, behaviour and organisational culture. These "soft" issues, which are often overlooked but represent a non-negligible source of additional costs, are further explored in Section 4.2.1.

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4. Short-term opportunities to reduce nuclear construction costs

The previous chapter identified lessons learnt from recent and historical nuclear construction projects. Without these lessons, nuclear cost reductions could hardly be achieved. The concept itself is straightforward but fundamental: take a mature and frozen design with a capable supply chain and replicate it as many times as possible in a stable and predictable regulatory framework. Under these conditions, nuclear construction costs *should* decrease steadily, as in the past. Recent projects have contributed to design maturity and to the rebuilding of lost supply chain capabilities. By simply committing to a nuclear programme and taking advantage of the core lessons learnt, many countries will not only activate cost reductions but trigger a new range of cost-saving opportunities that can be exploited by the industry in the short term (i.e. before 2030) (see Figure 17).

These opportunities are the result of continuous design (or product) and associated process [33] improvements, similar to other industries, and are possible only with serial construction. The complementarity of this new set of cost reduction drivers with the lessons identified in Chapter 3 is illustrated in Table 4. In fact, these drivers are not sequential and could also be mobilised in the early stages of development to accelerate nuclear learning while mitigating technical, organisational and regulatory risks. The evidence gathered in this chapter shows that countries in more advanced stages of learning are already benefitting from these opportunities, suggesting that nuclear costs and risks *could* be further reduced. In the next sections, the cost reduction potential of each of these drivers is analysed in detail.

Table 4: **Complementarity of cost reduction drivers at different learning stages**

Risk dimension	Lessons learnt (core) (Chapter 3)	Short-term cost reduction opportunities (Chapter 4)
Technology	Design maturity	Design optimisation
Organisational	Effective project management	Innovative technologies and processes
Regulatory	Stability and predictability of the regulatory framework	Revised regulatory interactions

4.1 Design optimisation of Gen-III reactors

Learning by doing is not static. Learning rates differ among designs, depending on the efficiencies generated during their execution thanks to the optimisation that, for instance, takes requirements to improve delivery and constructability into account. Additional design optimisations may also maximise the power outputs of the existing design. This section covers four main design optimisation approaches: simplification; standardisation; reclassification of safety-related components; and power uprates.

33. The distinction between products and processes is at the core of the different cost reduction strategies analysed in this part of the report. In fact, some of the drivers apply directly to the design, another subset to the processes, and others influence both at the same time. This approach facilitates the adequate assessment of cost reductions, particularly those associated with indirect costs or "support processes", which have considerable potential. The interplay between a product and its delivery processes is further explored in Section 5.3.

It is important to remember that most of these design optimisation approaches can be considered when developing a new design from scratch; this section pays special attention to design optimisation opportunities that arise after the first-of-a-kind (FOAK) phase. In the post-FOAK phase, designers may prioritise marginal modifications and seek the best compromise between simplification and design replication to preserve learning from previous constructions as much as possible. The attractiveness of major design optimisations tends to increase with the number of units to be built, allowing for amortisation of the engineering investment.

4.1.1 Simplification

Design simplification is not a new issue for nuclear technology. Combining larger cores with higher regulatory stringency rapidly produced a complex technical and organisational layering still found in most contemporary designs. Vendors and designers have been pursuing greater design simplification since the early 1980s to limit the negative spillovers of complexity and nuclear costs.

Manno and Golay (1985) illustrate how design simplification is not a straightforward process, however. The main difficulty in developing a simplified design is to find a starting point, given the physical connections and interdependencies of plant systems. Vendors may adopt different methodologies, but all require sound engineering knowledge of the system and a comprehensive assessment of all possible impacts of design changes on the system's overall architecture and on plant reliability.

Some key lessons of past construction projects remain completely applicable today (NEA, 2000). The main simplification guidelines include:

- Streamlining overall plant architecture to reduce the number and volume of buildings while ensuring a compact, accessible layout.
- Exploring the potential of reactor systems sharing infrastructure when possible.
- Simplifying component, system and structure drawings, technical specifications and quality assurance requirements.
- Rationalising civil works, reducing the quantity and complexity of rebar, piping and cable by using new technologies when available.
- Reducing the number of system components when possible.

Some Gen-III designs are the result of significant simplification efforts (Box 10). Nevertheless, these efforts did not yield the expected benefits, as they were largely offset by the absence of the conditions and learning described in Chapter 3.

In addition, new opportunities arise from the adoption of product-oriented design processes commonly used in other industries. This is the case, for instance, with value engineering.

Value engineering aims to maximise the value of a product or service by meeting customer expectations at the lowest possible cost. When applied to nuclear designs, this approach assesses the functionalities of each component and systematically compares their costs with stakeholder expectations in terms of safety and performance requirements, which could result in major design simplifications.[34] At the same time, these principles help set priorities and refocus engineering efforts to reduce the risks of over-engineering[35] already reported for recent Gen-III FOAK projects. Box 11 presents an example of application, using design-to-cost methodology.

34. Simply put, if the functionality of component A is already provided by component B and the overall system complies with all requirements, component A can be discarded.

35. Engineering efforts that do not add value to the project.

Box 10: **Design simplification in large contemporary reactors**

AP1000 experience

The AP1000 design developed by Westinghouse received design approval from the US Nuclear Regulatory Commission (NRC) using approximately 60% fewer valves, 75% less piping, 80% less control cable, 35% fewer pumps and 50% less seismic building volume than usual reactor designs (Sutharshan et al., 2011). It also took advantage of the design simplification associated with passive safety systems, which rely on a gravity-driven mechanism and natural circulation. They have one-third of the remote valves needed in typical active systems and they contain no pumps. In most cases, these types of systems are also considered easier to inspect and maintain.[36] Equally important is the limited departure of passive systems from previous designs, which minimises the impact on neighbouring systems.

In addition, the implementation of passive safety systems enables the reclassification of some active safety support systems. This simplification applies, for instance, to the emergency diesel generators and their network support systems, which are no longer safety-class and can benefit from lower standards and higher competition in the supply chain. In some cases, the systems can be eliminated completely.

Another aspect reported by AP1000 designers is the higher degree of modularisation used in this design. The benefits and challenges of modularisation are explored in more detail in Section 4.2.2.

Advanced boiling water reactor (ABWR) and economic simplified boiling water reactor (ESBWR) experience

The ABWR developed by General Electric with Toshiba and Hitachi includes simplifications that have an impact on both the safety and overall economics of the plant. This design uses internal recirculation pumps that obviate the need for major piping found in earlier boiling water reactor designs. Build on ABWR experience, the ESBWR achieves greater simplicity by using natural circulation, leading to 25% fewer pumps and active drives than other designs relying on active safety systems.

The benefits of design simplification and value engineering are evident in both direct and indirect engineering, procurement and construction (EPC) costs as a result of the lower quantity and number of components as well as streamlined design processes. Furthermore, project management and productivity savings may arise from the reduced complexity of simplified designs and the lower risk of reworking.

It is important that any additional regulatory interactions required for design simplification not be neglected. As indicated in Chapter 2, licensing and certification are nonrecurring costs. If reproduced in subsequent constructions, they could hamper normal learning dynamics.

36. However, there may be challenges in periodic testing, as heat exchangers (HEs) tend to be larger. Furthermore, the cleaning of water-air HEs can also be problematic.

Box 11: **Product-oriented approaches for post-FOAK design simplification: The EPR2 project and design-to-cost methodology**

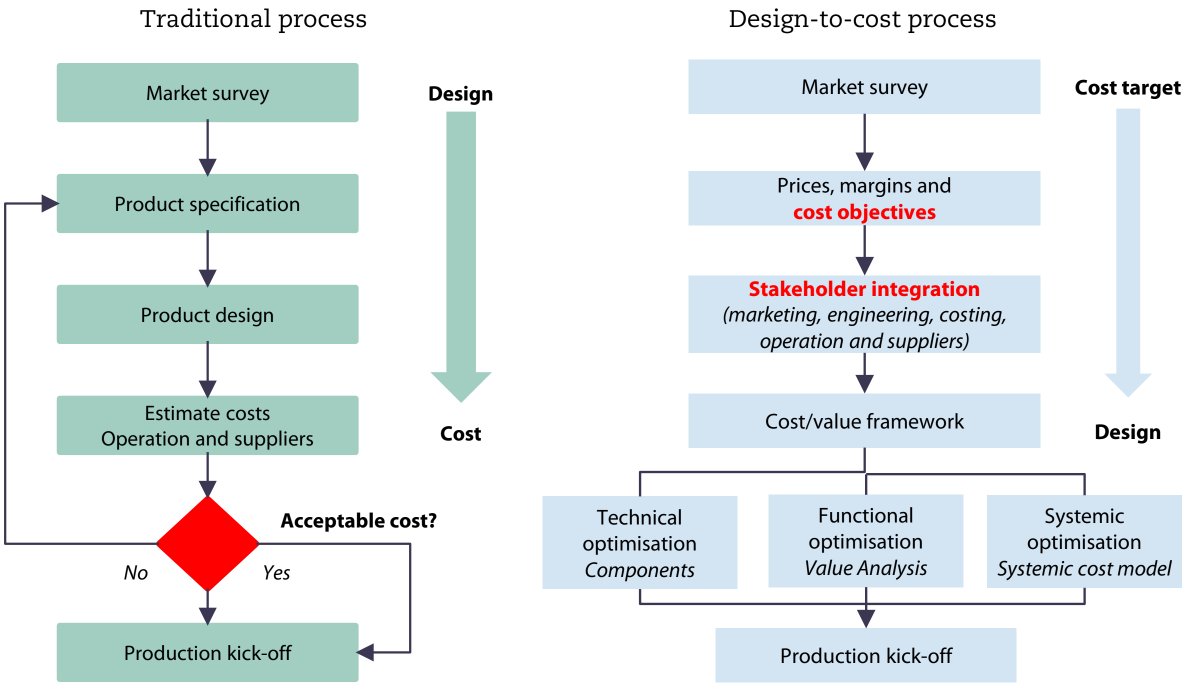
The EPR2 project is an evolutionary EPR design co-developed by the EDF and Framatome. It is a joint effort to optimise and simplify the previous design, taking lessons learnt from recent EPR projects into account.

Contrary to traditional processes that check cost acceptability once a design is completed, the design-to-cost approach sets a cost target at the early design stages (see Figure 27). The resulting design meets the cost objective while producing a final product of the highest value because value-engineering techniques are used to question the technical choices at each stage and identify the configurations that meet stakeholder expectations at the given cost target.

As a result, the new EPR2 has only three safety injection trains instead of four, a single containment with metallic liner, a reduced number of rooms, less rebar and materials, and fewer welds performed on-site. The French safety authority, following the recommendations from IRSN (2018), announced in July 2019 that the new design configuration meets current safety standards (ASN, 2019). This example illustrates how safety requirements can be met at a lower cost using the appropriate design techniques.

More importantly, this process also involves suppliers throughout all design phases to get immediate cost feedback and to verify that the solutions adopted are aligned with supply chain capabilities. Consequently, design-to-cost also provides an effective framework that enables collaboration as well as supply chain integration (Jorgensen, 2005). With the necessary adjustments, this methodology could also integrate some regulatory involvement in the future, which could lead to further cost savings (see Box 16).

Figure 27: **Traditional design vs. design-to-cost process**



4.1.2 *Standardisation*

Similar to other products and services in several industries, nuclear design could take advantage of standardisation to maintain design uniformity and homogenisation over several product iterations. Standardisation reduces the indirect costs associated with a new construction primarily by minimising recurring upfront design activities and enabling supply chain efficiency to foster series construction. Industrial code standardisation is addressed in more detail in Chapter 5.

In practice, the full uniformity sought by standardisation encounters some physical constraints. Due to the specific conditions of every site, some adjustments to the standardised design may need to be implemented. Experience shows that these design modifications are limited to:

- The foundations, as each site has specific conditions in terms of geology and seismicity.
- The heat sink, depending on the cooling capabilities, environmental rules and water chemistry, and whether the cooling circuit is open or closed.
- The power transmission network.
- The local industrial environment.

As indicated by the World Nuclear Association (WNA),

> the concept of standardised reactor designs does not require units to be completely identical. Rather all units that use the standardised design technology should at least share the same global architecture and the same specifications for the nuclear steam supply system design and components, and associated safety systems. (WNA, 2015)

France's case illustrates the economic benefits of defining a generic standard design that can be adapted to each site while keeping design modifications to a minimum (Roche, n.d.). Today, thanks to advances in seismic isolation, it could be possible to achieve higher levels of standardisation (see Section 4.2.2 for more information).

Standardisation also requires strong industrial organisation. Supply chain interactions must be homogenised to speeds up transactions and increase manufacturing process productivity with the production of a greater number of identical components. Volume production, and the associated allotment process, also improves overall quality (i.e. specialisation leads to the rapid detection of flaws in the manufacturing processes and a skilled workforce), increases supply chain competition and enables long-term contracting. The latter provides visibility to suppliers so that they can mobilise their resources in more optimal conditions.

Similarly, interactions with regulators (i.e. through the licensing process) are expedited and improved. Once a standard design has been licensed, it can be applied to all identical units (with adaptations to site-specific conditions), thus reducing time spent on regulatory activities compared with a diversified fleet (Ramana and Saikawa, 2011). In addition, design standardisation enables the accumulation of experience, which increases the probability that design flaws will be detected early, improving overall safety levels.

Consequently, standardisation must be thought of as an industrial strategy involving the whole supply chain and regulators working together to ensure that the overall design, functionalities and interactions are maintained as much as possible, and that potential factors that could prevent this are minimised. Standardisation also has noteworthy advantages in terms of plant operations, but they are outside the scope of this report.

Nevertheless, standardisation also has some drawbacks. The one most often cited is that a standardised fleet is more vulnerable to common problems (Ramana and Saikawa, 2011).[37] This risk can, however, be minimised with the adoption and standardisation of a proven and mature technology.

37. The French fleet already experienced this issue in 2016 when a carbon segregation problem was detected in the lower plates of the steam generators. Around 20 reactors were shut down to perform the necessary verifications, tests and maintenance work (Les Échos, 2016).

Another disadvantage of standardisation is its inability to foster nuclear design learning and experimentation, limiting the selection of superior design variants available that could, ultimately, also lead to lower costs.

Despite these limitations, most authors agree that at some point in a nuclear programme, extensive standardisation will be desirable to reduce nuclear construction costs, especially indirect costs associated with recurring design activities. This is supported by empirical evidence from the French and Korean nuclear programmes, which effectively relied on standardisation to enhance nuclear learning (see Chapter 3).

The key question is when standardisation should be undertaken (David and Rothwell, 1996). Timing will be determined by a country's ability to commit to several nuclear constructions, depending on national demand. Those that do not have enough electricity demand to deploy a standardised programme may find it more convenient to take advantage of more developed foreign supply chains. However, as Chapter 5 explores in detail, the lack of international harmonisation is still a major hurdle preventing countries from benefitting from international standardisation processes.

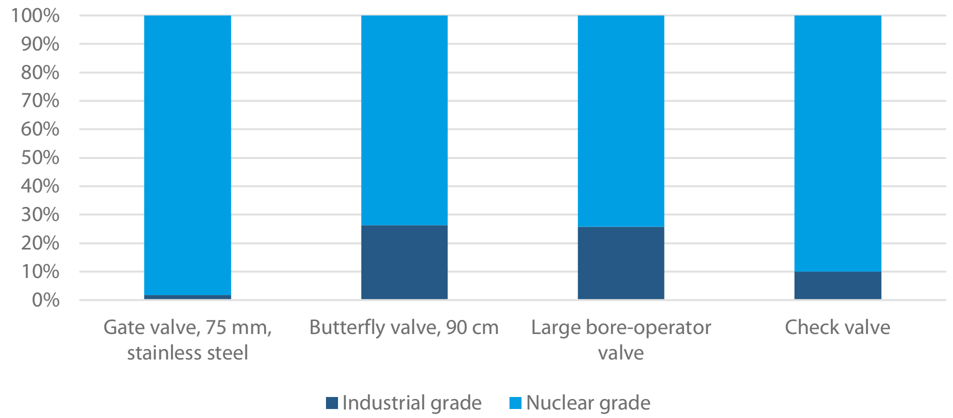
4.1.3 *Reclassification of safety components*

The high level of scrutiny to which nuclear design processes are subjected may have some undesirable spillover effects during the definition of technical specifications. Higher safety classes than required according to existing safety rules might be assigned to some components simply because they are going to be part of a nuclear facility.

The use of more refined risk-informed approaches during design stages may allow for better assessment of the boundary between nuclear and non-nuclear components. Reducing (or suppressing) the safety class in some systems enables the introduction of commercial off-the-shelf (COTS) components, especially for lower safety classes. As a result, substantial savings can be realised in the absence of nuclear-grade labels thanks to a greater supplier availability and keener competition.

Furthermore, using COTS components promotes higher levels of nuclear design simplification and standardisation, leading to additional cost cuts. Lastly, owing to manufacturers' extensive experience in a variety of industries, COTS components may be more reliable. As an example, a cost reduction of 98% could be obtained for valves, depending on the valve quality standards (Figure 28). The impact of quality assurance standards on the cost of nuclear components is further assessed in Chapter 5.

Figure 28: **Cost gap between nuclear- and industrial-grade valves**



Source: EPRI (2012), *Risk-Informed Strategies for the New Build Fleet: Risk-Informed Procurement and US NRC Rule 10CFR50.69.*

4.1.4 *Power uprates*

A power uprate is an increment of the net electrical power of a nuclear power plant (NPP). It takes advantage of economies of scale to reduce the overnight cost of a given design. The nuclear industry has accumulated extensive experience in performing power uprates in existing reactors, an approach that can be effective during the post-FOAK phase of nuclear design.

Higher power output can be achieved simply by employing enhanced techniques and sensors that reduce uncertainty in measurements of the flows necessary for calculating reactor power. More extensive power uprates may exploit the potential margins of current designs to accommodate higher outlet temperatures and steam flows, leading to higher power output. Achieving greater efficiency by minimising pressure drops on the secondary side and improved turbine blading could also be explored.

Power uprates must be performed with caution, however, as they may entail significant safety demonstrations (nonrecurring costs) that could be detrimental to learning, especially for reactors already operating at high power levels.[38] Developers also have to ensure that the size of the components and volumes remain unchanged so that established manufacturing processes are not altered, and they must keep commodity usage and civil work costs under control.

4.2 Innovative technologies and processes

Several innovations can be incorporated in the delivery processes of post-FOAK designs to accelerate their learning rates. Opportunities arise at several levels and include the introduction of new technologies as well as alternative organisational approaches and processes. The real value of these advances stems from their having already been proven in other industries, so that nuclear organisations could leverage this experience to reduce deployment time and potential risks.

It is important to highlight that these innovations represent incremental improvements rather than disruptive or revolutionary changes. The objective, similar to design optimisation, is to preserve the learning effect from previous constructions as much as possible.

Two domains deserve special attention when the adoption of innovative technologies and processes are being considered: organisation and management; and manufacturing and construction. (Opportunities and challenges associated with digital transformation are assessed separately in Box 12, as they are cross-cutting and have the potential to enhance multiple business processes at the same time.)

4.2.1 *Organisation and management*

As already highlighted several times in this report, the cost and risk issues affecting the nuclear industry today are not necessarily related to the technology itself, but rather to how the delivery infrastructure is being managed. NPPs remain one of the most complex capital projects, especially in organisational terms, as they involve numerous stakeholders, disciplines, systems and processes for which co-ordination and management can be difficult and time-consuming (Locatelli, 2018). Recent nuclear projects in western OECD countries provide evidence of these factors and how they have raised indirect costs in the last decade.

Nevertheless, the ways organisational and managerial issues contribute to nuclear construction costs are often overlooked. Box 6 explains the existence of significant *soft* costs resulting from organisational dysfunctions that are usually not properly accounted for in initial estimates. Inefficient project organisation, a lack of skills and competencies, and poor-quality control are the most common sources of soft costs in nuclear projects. All recent projects in Europe and the United States have suffered the consequences of problems in these areas, even though various organisational and management modes exist to overcome these issues during the design and construction of new nuclear projects. These techniques originate from (and have

38. High power levels tend to make safety demonstration more complex.

been successfully implemented in) the automotive and aviation manufacturing industries, which have levels of expertise and quality control similar to the nuclear industry.

However, in most cases these new management modes are a substantial shift from the more traditional approaches and mindsets that have classically governed the nuclear industry. To increase the chances of success, they must be accompanied by robust change-management practices, a dedicated budget and top management support.

Box 12: **Digital transformation in the nuclear industry: Opportunities and challenges**

Recent advances in computer power and information systems have introduced numerous digital applications that incite organisations to rethink the way they create value. Digital transformation is the organisational process of using digital solutions to enhance the performance of existing business processes,[39] and its adoption in the nuclear industry, particularly for design and construction,[40] could provide a range of benefits:

- Increased productivity: As labour represents approximately 60% of total EPC costs, the higher degrees of automation, simplification and streamlining that can be achieved with digital tools may offer significant cost savings.
- Detailed engineering: System engineering approaches can be digitally enabled to accommodate more simulations, analyses and verification in the early stages of design, thus reducing reworking risks.
- Supply chain integration: Digital platforms shared among suppliers based on extended enterprise frameworks enable greater alignment and co-ordination of the supply chain.
- Quick and well-informed decision-making: Digitalisation also allows for greater unification, synchronisation and traceability of information. Plus, information can be more easily retrieved, facilitating exchanges among stakeholders.
- New operational modes: Digital tools provide the opportunity to explore processes characterised by higher collaboration, reactivity, agility[41] and innovative thinking.

Based on experience gained in other industries, including the energy sector and aircraft manufacturing, several solutions are already available for the design, procurement and construction process of nuclear systems. These solutions are at a high level of maturity, and the nuclear industry is currently in the deployment phase while developing the standards and rules necessary to make them robust and their effects long-lasting.

Among the several digital tools being employed by nuclear vendors, product lifecycle management (PLM) systems are capturing most of the attention. A digital PLM platform enables the efficient management of data generated by a product (in this case an NPP) over its entire lifecycle. It provides a unified information system in which interaction with other applications and databases (i.e. document management systems, enterprise resource planning, etc.) is possible. With the appropriate access rights, the PLM platform can also be opened to external partners to increase supply chain integration. As a result, a PLM system acts as backbone, feeding all tools, activities and stakeholders involved in the lifecycle of an NPP with updated information. It codifies data exchanges and validation processes from systems to subsystems, and from design engineers to subcontractors throughout the entire lifecycle while assuring the accessibility and detailed traceability of all modifications and technical choices based on performance and regulatory requirements. The latter feature is particularly important in stringent and evolving regulatory frameworks.

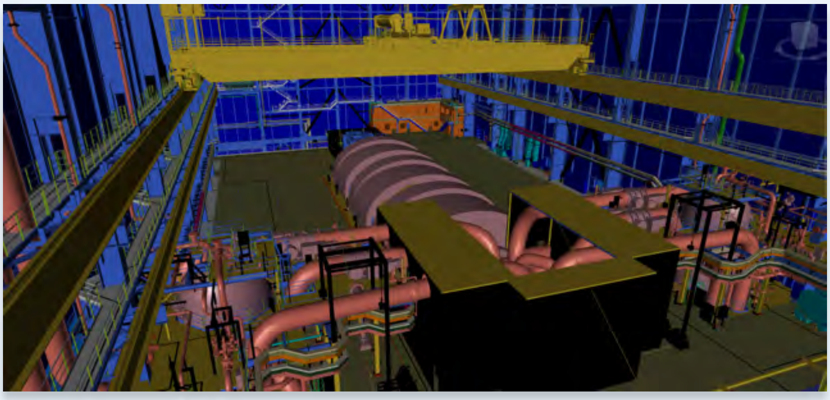
39. Generating new business and revenue streams is also possible with digital transformation.
40. Adopting digital tools would also positively impact plant operations and decommissioning, but these aspects fall outside the scope of this report.
41. Inherited from software companies, agile teams change protocols and silos by iterative and cross-functional interactions. In changing environments, this methodology has proven very effective in delivering high-quality products.

Box 12: Digital transformation in the nuclear industry: Opportunities and challenges *(cont'd)*

Other promising digital levers include building information management (BIM) systems, multi-dimensional (multi-D) tools and digital twins. A BIM tool is equivalent to a PLM system, but deals with the physical and functional characteristics of an NPP's various buildings and components. When used with a 3-D virtual environment, the digital mock-up provides a higher degree of integration and simulation capabilities (Figure 29). Most advanced versions couple the benefits of BIM with additional dimensions, such as a project's cost and schedule, to become multi-D tools.

Additional simulation capabilities can be used to optimise the installation sequences of critical components. Digital twins[42] make it possible to continuously update existing BIM and multi-D models, narrowing the gap between "as-planned" and "as-built" information, thus facilitating the detection and correction of deviations, and enabling quick and well-informed on-site decision-making. One interesting feature of digital twins is their potential to perform online resource planning, logistics and localisation. This facilitates the control of workforce densities[43] and avoids unnecessary movements and material handling, which is particularly relevant for nuclear projects in which the peak workforce can reach more than 4 000 people.[44]

Figure 29: **3-D virtual representation of the turbine hall with BIM tools**



Source: Courtesy of EDF.

Despite these opportunities, empirical evidence from other organisations shows that two-thirds of digital transformations fail. One of the reasons often cited by practitioners is the underestimation of organisational change. Like any other change management process, digital transformation may require strong leadership and a dedicated budget to absorb emergent risks and for employee training, communication and empowerment.

Most importantly, digital transformation should not be limited to one company only. Change management, IT infrastructure and harmonisation efforts have to extend to the whole industrial ecosystem, and this may take considerable time. All these aspects must be fully acknowledged and embedded in the digital strategy to overcome digital maturity differences among partners.

Finally, potential safety and security obstacles also need to be addressed in nuclear industry digitalisation. Regulator inertia and additional regulatory requirements (i.e. cybersecurity) are additional challenges the industry may face.

42. Digital twins are virtual and dynamic representations of physical assets and processes.
43. Number of workers within a unit working area.
44. A typical NPP construction project in Korea has 400 management staff and a workforce of 4 200 (Shin, 2018).

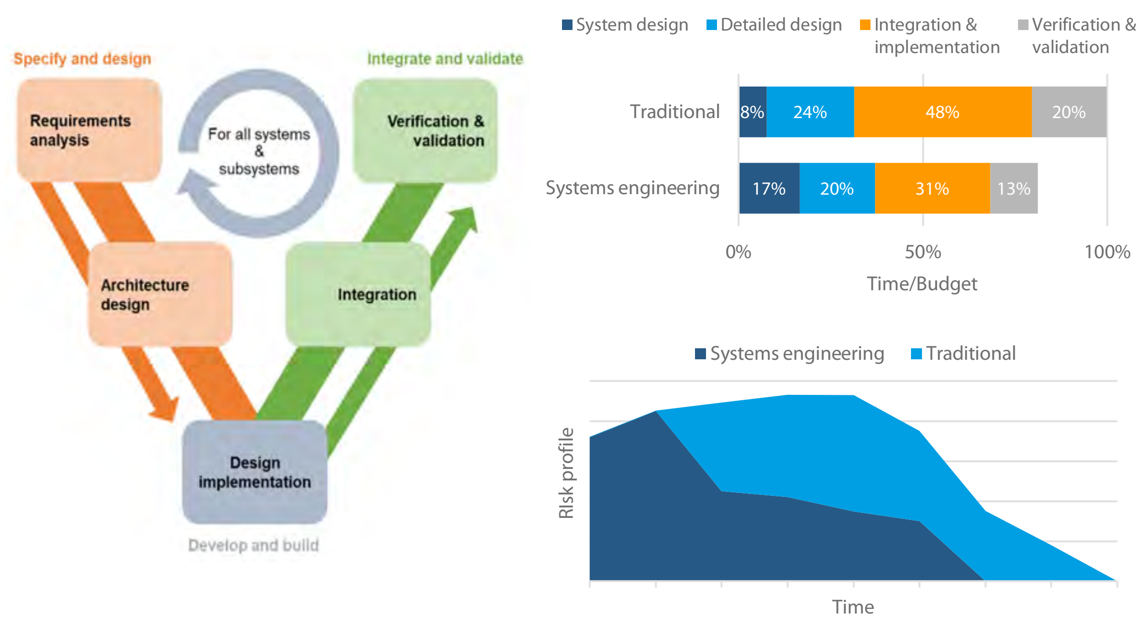
Systems engineering (project organisation)

The intricate architecture of nuclear designs, involving numerous systems and interfaces, makes managing projects particularly difficult. Systems engineering (SE) is a multidisciplinary approach to enable the successful delivery of systems and products in complex environments through comprehensive techniques and tools (Locatelli, Mancini and Romano, 2014).

One of the pillars of SE is the "V model" (Figure 30). Applied recursively to each system and subsystem, this tool enables detailed front-end engineering and early verification and validation of the different components of the system. This increases the chances of getting the design right the first time and avoiding very expensive construction delays (Figure 30 illustrates potential cost and time gains that can be achieved with SE design efforts).

One of the main outputs of the V model is an easily understandable reference system architecture that acts as a common language for all teams and stakeholders. If requirements evolve, this architecture also enables rapid impact analysis, smooth change management and rapid adaptation to complex environments. All these features and principles can be enhanced with digital tools and are currently at the core of most PLM systems (see Box 12).

Figure 30: **The SE "V model" and potential return on investment**



Knowledge management (skills and competences)

Nuclear energy is a knowledge-intensive domain that requires high technical skill, competence and excellence levels, which take a long time to be acquired and properly adopted across the entire supply chain. Of capital importance is knowledge acquired in a tacit[45] manner. Tacit knowledge is the result of experience, trial and error, human interactions and work practices. Most of the knowledge capital accumulated at the end of a project is tacit knowledge (Dudézert A. et al., 2012). The main issue with tacit knowledge is that it is "sticky" – i.e. inseparable from individuals and thus difficult to transfer. Consequently, once a project is finished, the learning tends to leak away as people move to other projects. Rising turnover rates of young professionals and uncertainty surrounding nuclear new-build orders in OECD countries aggravate this situation.

45. As compared with explicit knowledge, which is well documented and codified in books, archives, drawings, etc.

In this context, knowledge management (KM) is an emerging integrated, systematic approach to identify, manage and share an organisation's knowledge and enable people to create new knowledge collectively, and thereby help achieve the organisation's objectives (IAEA, 2012). The nuclear industry is already familiar with traditional KM approaches[46] but has been falling behind in embracing more bottom-up network-centric approaches that rely on communities of practice and digital platforms. These approaches consider knowledge as a resource that is built collectively and enriched through everyday interactions with peers, and they have proven to be an efficient way to sustain tacit knowledge, despite organisational turnover and activity downturns.

Digital transformation (see Box 12) therefore offers a prime opportunity to introduce these new KM techniques into business processes to raise the overall performance of nuclear organisations. For instance, bottom-up KM processes can be embedded within a PLM platform to incorporate new knowledge and valuable lessons learnt in the field, from recent and ongoing projects. As a result, the PLM system would become a virtual environment capable of ensuring the continuity of data, information and knowledge throughout the supply chain, accelerating learning effects in the nuclear industry. Lastly, as for other transformative processes, the introduction of new KM techniques may require corporate culture shifts and other organisational changes that have to be properly managed.

In spite of the potential of modern KM techniques, it must be underlined that the most effective way to create and sustain knowledge is to keep the same people doing the same activity for as long as possible (Mckinsey, 2018). Governments thus have a major responsibility to create favourable conditions by committing to a nuclear programme, which could be complemented by national-level strategic planning. To this end, government, industry and academics could work together to provide a functional framework for workforce development that includes attractive university programmes, rigorous professional training, research and development (R&D) investments, mobility, partnerships between utilities and universities, and international collaboration programmes.

Operational excellence (quality control)

If encountered once construction has begun, quality flaws could result in important delays and additional costs in terms of regulatory interactions, engineering efforts and reworking. As quality in execution is linked with skill and competence, it is important to underline that countries building several reactors will benefit from quality improvements and more effective quality management systems as supply chain capabilities develop.

At the same time, it is possible to mobilise a set of tools, techniques and principles to foster operational excellence and strengthen the quality control system continuously with every new construction. This is the aim of lean management (LM). Popularised by the Japanese car manufacturer Toyota in 1980, LM is a management philosophy that pursues the continuous improvement of processes by eliminating sources of waste and tasks that do not add value. It relies on workforce engagement as the best ally to identify operational flaws and propose potential improvements. Its application to the nuclear industry could help identify and remove redundant quality checks and engineering efforts while reducing the risk and number of non-quality issues at all levels: design, construction, component manufacturing and regulation.

4.2.2 Construction and manufacturing

In addition to organisational and managerial cost reduction opportunities, incremental innovations in construction and manufacturing could lead to additional cost savings in the short term. The most promising technologies and processes include advanced manufacturing; advanced concrete and rebar solutions; risk-informed inspection; improved seismic design; modularisation; and other advanced construction methods. These solutions essentially pursue greater labour productivity and more aggressive reductions in lead times and raw material

46. Including knowledge-mapping (the identification of knowledge-holders and flows), expert interviews and mentoring (IAEA, 2012). Practices are quite formal and adhere to top-down logic.

usage. As the following sections illustrate, the large size of components is the main technical barrier in implementing some of these solutions.

Advanced manufacturing

The manufacturing process can be particularly expensive, especially for large, heavy safety-related components such as the reactor pressure vessel (RPV). Particularly important is the thick section during the welding process. With traditional techniques based on tungsten inert gas (TIG) arc welding, around 100 runs are required for a 20-mm-thick section. Each run also requires heating, inter-pass temperature control and inter-stage non-destructive examination (NDE). As a result, the welding, inspection and completion of a RPV is an expensive and time-consuming process that can take several months, and accounts for a large proportion of fabrication costs and component lead time (Nuclear Engineering International, 2019).

Significant progress has been made in recent years in the development of manufacturing techniques and processes (joining, welding, machining, forming, etc.) in various industries, especially automotive and aerospace. Some of these techniques are electron beam welding, powder-metallurgy hot isostatic pressing, diode laser cladding and additive manufacturing (EY, 2016; Nuclear AMRC, n.d.). The cost and lead-time reductions these solutions may offer are also remarkable.

However, their large-scale application in the nuclear industry still needs additional development and the physical size of nuclear components does not facilitate their implementation. According to EY (2016), of 14 potential advanced manufacturing techniques, only 2 are applicable to large reactors and could be ready for production in 2022: rapid, large-body and in-process metrology; and automated welding and rebar assembly. The latter has been successfully used to weld the reactor coolant pumps of the Korean APR-1400 design and in the Japanese ABWR Kashiwazaki-Kariwa 6&7 project (IAEA, 2004).

Advanced concrete and rebar solutions

Activities involving concrete and rebar are labour-intensive. In some cases, steel congestion can be a serious problem as it stunts constructability by limiting access, increasing workforce densities and thus undermining the overall productivity of civil works. Considerable rebar congestion may also result in particular defects in concrete such as voids. Some advanced concrete and rebar solutions include high-strength reinforcing steel (EPRI, 2016), ultra-high-performance concrete and self-consolidating concrete (EPRI, 2019). The latter flows into place using gravity alone, reducing defects and labour requirements during placement. Its use in the nuclear industry has already been reported for AP1000 projects (MIT, 2018).

Another technique that is being increasingly adopted for nuclear civil works is the use of steel-plate composites (SPCs), which consist of two parallel steel plates connected by ties. The additional mechanical strength provided by the plates allows for the replacement of rebar and also facilities concrete-pouring without temporary supports during fabrication, resulting in a 50% reduction in installation time (MIT, 2018) (Figure 31). This technique has already been certified for nuclear applications in Japan, Korea (Lloyd, 2019) and the United States (MIT, 2018). For instance, it has been successfully implemented as a part of a global modularisation approach in the APR-1400 design (see Box 13).

These different techniques can all be combined as a part of a comprehensive advanced construction approach involving modularisation and more advanced construction methods, as described later in this chapter.

Risk-informed inspection

Risk-informed approaches used to redefine safety boundaries and enable the adoption of COTS components can also be extended to inspection, particularly to NDE. NDE is mandatory to comply with nuclear industry licensing requirements. It may involve significant resources during the manufacturing of critical components, especially those associated with reactor plant equipment subject to stringent safety standards. Requirements are usually generated using deterministic design analyses that quantify the necessary safety factors. This may produce conservative inspection schemes that do not always take the probability of damage occurrence into account. Risk-informed methods rely on probabilistic techniques that lead to a more efficient inspection regimen by identifying appropriate inspection locations and frequencies.

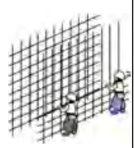
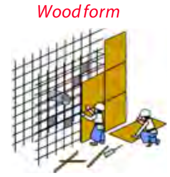
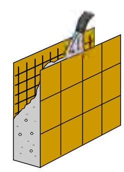
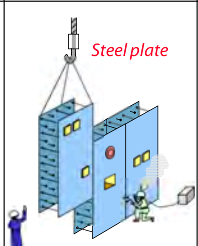
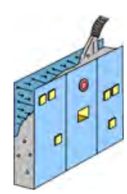
Modelling and simulation techniques are also an effective way to enhance risk-informed NDE processes. New configurations and sensors can be tested, and optimised accordingly, to increase the probability of success. The extension of existing risk-information NDE approaches to other components can be accelerated using simulations to generate the required scientific-based evidence for the regulatory bodies (EPRI, 2014).

Improved seismic design

Due to the lack of advanced models for dynamic load analysis during the 1970s-1980s, especially for seismic-related design activities, Gen-II reactor structural designs contained significantly conservative estimates. Current Gen-III designs, based on the legacy of the previous generation of reactors, may have inherited some of these conservative assumptions in their licensing approaches. More accurate estimates of the seismic response of current nuclear designs with more refined models may result in lower structural load requirements and thus major savings owing to downgrades in reinforcing-steel needs, concrete wall thickness, the number of structural steel connections, and anchorage between structural elements and components.

In addition to increasing the accuracy of ground-motion estimates, technologies such as seismic isolation systems can be implemented to reduce the overall effect of a seismic-related event.[47] As dependency on site-specific seismic conditions is significantly reduced, this type of technology enables greater design standardisation. Seismic isolation devices have already been successfully installed in the Cruas NPP, the ITER facility, the Jules Horowitz research reactor (France) and the Koeberg NPP (South Africa). In terms of cost, installing these devices is expensive. Investment attractiveness increases for ground acceleration peaks exceeding 0.2 g.

Figure 31: **Advantages of SPC vs. rebar-based structures, ABWR study**

Work / Structure	*Rebar arrangement*	*Formwork (assembling)*	*Placing concrete*	*Formwork (removal)*
RC		*Wood form* 		
Total 28 days	*13 days*	*7 days*	*4 days*	*4 days*
SC	———			———
Total 14 days		*10 days*	*4 days*	

Source: IAEA (2004), *Construction and Commissioning Experience of Evolutionary Water Cooled Nuclear Power Plants.*

47. Seismic isolation systems consist of devices (elastomeric [rubber] bearings or low-friction sliders) that "isolate" a structure from the ground by absorbing shock for the buildings. Compared with a fixed-based structure, seismic isolation effectively dampens horizontal acceleration from an earthquake, although vertical displacements must still be considered.

Modularisation and other advanced construction methods

Modularisation is the process of breaking a large and complicated product down into smaller building blocks, or modules, according to a set of limited constraints. The objective is to maximise the amount of work that can be transferred to a shop or factory, as this type of environment offers greater predictability and control, greatly improving overall productivity (and often quality) while making parallel construction possible. Constructability is also enhanced as the number of components, interfaces and workers (i.e. site congestion) is reduced.

A more controlled environment could be also more convenient for critical processes such as concrete-pouring, welding, steel-cutting and testing. Modularisation has already provided benefits in other industries such as shipbuilding, aviation, chemical processing, and oil and gas. General observations of modularisation in the power sector indicate lead-time reductions of 40% and 20% lower costs (Lloyd, 2019).

Large stick-built Gen-III reactors already accommodate a certain amount of factory construction, approximately 30% of construction costs[48] (EY, 2016). According to recent results from the University of Cambridge, for reactors with a power output greater than 750 megawatts of electrical capacity (MW_e), this number could be increased up to 40% through modularisation (Lloyd, 2019). The nuclear industry has already accumulated some experience in implementing modularisation techniques for large reactors (Box 13), but evidence indicates that larger projects could be delivered faster with more extensive modularisation. However, if the supply chain's ability to deal with the modules is limited, this could rapidly offset expected benefits.[49] Also, additional upfront engineering efforts and funds are required to assess the feasibility of the different modules and secure their procurement before construction begins.

As with advanced manufacturing techniques, component size, weight and geometry are the main physical constraints on modularisation. These parameters directly dictate how easily the various components can be transported, lifted and installed. The infrastructure to access the site and national transportation standards may present additional restrictions.

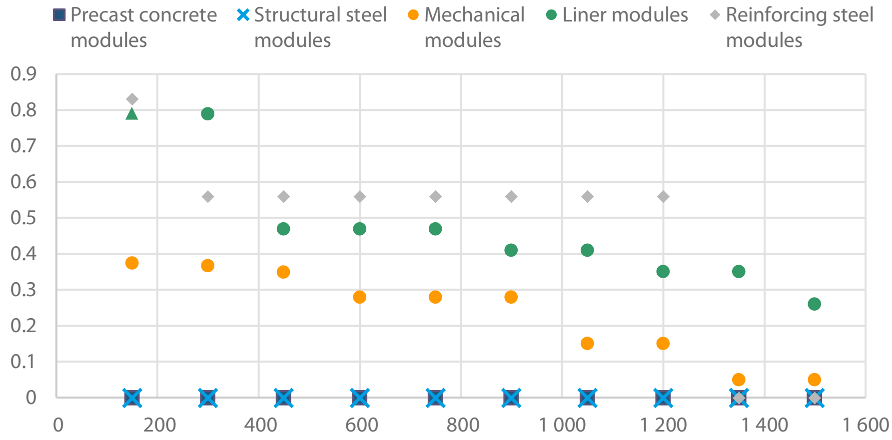
Figure 32 illustrates a more granular analysis of the degree of modularisation of different types of components: as the size of the component tends to increase with power output, the degree of modularisation falls. While concrete and structural steel components cannot be easily modularised for all ranges of power, reinforcing steel, liner and, to some extent, mechanical components offer higher potential for modularisation. To counteract these constraints, designers may adopt more aggressive modularisation strategies, further subdividing modules to make them transportable.[50] Furthermore, a net improvement in the degree of modularisation for reduced power outputs presents opportunities for factory-based construction for smaller reactor concepts. This is one of the main factors that makes small modular reactors (SMRs) and micro-reactors attractive, as Chapter 5 will discuss in more detail.

Other advanced construction techniques include open-top construction; parallel construction; layout and crane optimisation; and all-weather conditions. These construction approaches and their associated benefits have been well documented in past in publications (NEA, 2000; IAEA, 2004 and 2011; EY, 2016), but they are still applicable and could produce additional savings for post-FOAK nuclear projects.

The design phase is critical, because it is in this stage that all the construction techniques must be assessed and combined into an overarching construction plan to reduce construction risks and improve constructability. Digital solutions such as BIM and multi-D tools (see Box 12) enable higher degrees of testing and experimentation, and therefore a more optimal construction plan. Modularisation is a clear example of how construction techniques have to be incorporated into the design as soon as possible, with the early involvement of the supply chain.

48. This essentially involves fabrication of the reactor and turbine plant components and control systems.
49. This issue has been observed in the delivery of first AP1000 units.
50. Lloyd et al. (2018) explore the relationship between the module division factor and the number of modules possible in an NPP design. While the S&W scheme results in 1 417 modules, when the dimension of the modules is halved the total rises to 6 324, potentially increasing the degree of modularisation.

Figure 32: **Maximum degree of modularisation for different components attainable with S&W scheme**



Source: Lloyd, Roulstone and Middleton (2018), "The impact of modularisation strategies on Small Modular Reactors."

Box 13: **Modularisation schemes for large reactors**

Modularisation efforts are not recent in the history of nuclear power. The Stone & Webster (S&W) modularisation scheme developed for a generic 950-MW$_e$ Westinghouse PWR in 1977 was supposed to be used in the Sundesert NPP in California. The project was halted and the S&W scheme was never implemented, but it certainly inspired subsequent modularisation efforts for the AP1000 design.

The S&W scheme uses time and cost savings to determine final modules selection. Feasible modules must create cost savings of at least 5% (either on materials, labour or both). The strategy involves the use of on-site shops for the fabrication of modules, limiting the remaining constraints to heavy lifting only. Nevertheless, transportation is cited as one of the primary limitations. The S&W report identifies roughly 1 400 modules, most of them structural (approximately 1 300) and the remainder mechanical.

More aggressive modularisation approaches show that is possible to design combined modules, incorporating structural elements with other components such as piping, cable trays or ducting. These types of modules are typically selected if the equipment layout in the given area is very compact. The density of bulk commodities inside combined modules is therefore a key parameter for its selection and design. Consequently, procurement may become an issue in combined modules as the build sequence is altered from that of conventional construction (Lloyd, 2019).

AP1000 experience

The AP1000 modularisation approach is the materialisation of efforts initiated with the S&W scheme. It consists of 160 structural and 56 mechanical modules that target essentially three areas: the containment building, the auxiliary building and the turbine building (Niemer, 2011).

One of the main structural modules (known as CA-01) is a multi-compartment structure comprising the central walls of the containment's internal structure. The vertical walls of the module house the refuelling cavity, the reactor vessel compartment, and the two steam generator compartments. The CA-01 consists of 40 prefabricated walls, or steel plates, call submodules. These submodules can be transported by rail to the site, and they weigh between 10 tonnes and 73 tonnes; if barge access is available at the site, larger subassemblies can be envisaged. The various modules are assembled in an on-site shop, and the completed CA-01 is then lifted to its final location within the containment vessel with a very-heavy-lift crane (Sutharshan et al., 2011). After erection, concrete is finally poured between the steel plates. The level of standardisation of the modules or super-modules of the AP1000 is reportedly low (Lloyd, 2019).

Box 13: **Modularisation schemes for large reactors** *(cont'd)*

ABWR experience

Unit 7 of the ABWR Kashiwazaki-Kariwa project used the "large modularising construction method." The seven floors of the ABWR building were divided into three levels and constructed in three steps in a preassembly yard before the pieces were successfully lifted and installed. The heaviest and most complicated module was the "upper drywell super large-scale module". It was a combined module consisting of walls and support structures, pipes, valves, cable trays and air ducts weighting around 650 tonnes[51] (IAEA, 2004).

Hitachi-GE Nuclear Energy has made significant improvements in its modularisation strategy since the Kashiwazaki-Kariwa 6&7 project in the late 1990s. In 2009, 193 modules were used, compared with only 18 in 1985. These modules involve piping, platform equipment, cable trays and civil modules. Module weights vary between 5 tonnes and 650 tonnes and they are shipped using trucks, trailers or barges, depending on their weight, size and site location (Lloyd, 2019). The Hitachi-GE design and modularisation approach is 90% complete before construction starts, reducing the chance that reworking will be needed by about 20 times (Choi and Song, 2014)

OPR-1000 and APR-1400 experience

OPR-1000 Unit 2 at the Shin-Wolsong project provides insights into the modularisation of containment liner plates. The limiting factors of the liner modules are dimensions and constructability, not weight. The strategy that was retained combined smaller ring modules into a larger super-module before lifting it into place. As a result, the number of construction steps was reduced from 11 to 8 and the building schedule was shortened by 30 days. Furthermore, the total number of lifts was also reduced, allowing 54% of the welding jobs to be performed at ground level instead, improving both worker safety and weld quality (Lloyd, 2019). The APR-1400 design includes SPC structural modules and several combined modules.

4.3 Revisiting regulatory interactions

Regulation, alongside safety culture, is at the core of all nuclear activities. Its objective is not only to ensure that nuclear installations are safely operated and meet all standards, but also to create stakeholder and public confidence. An efficient, independent and transparent nuclear regulatory body is paramount to establish the social licence[52] needed for nuclear power to have a stable and durable foundation in any society.

The regulation of nuclear power involves several dimensions and stakeholders. First, given the complexity of nuclear systems, regulation is dominated by high levels of expertise. Second, to build and maintain a social licence, regulators must be able to interpret what society expects in terms of requirements imposed on licensees. How this interpretation is accomplished may vary from one country to another, depending on, among other elements, public attitude and regulatory practices. Conversely, the economic dimension of regulation is rarely discussed.

The first economic impact of regulation, as indicated in Chapter 3, is on nuclear project costs in the absence of regulatory predictability and stability. While regulatory decisions may delay the initial design and construction schedule, delays are more detrimental once construction has begun. Longer lead times may trigger not only an IDC increase but productivity

51. For comparison, the largest crane in the world (the SGC-250, also called "Big Carl"), developed by Sarens especially for the EPR Hinkley Point C project, has a maximum lifting capacity of 3 000 tonnes.

52. The concept of social licence to operate (SLO) covers three key ideas: i) a SLO is granted by the local community hosting a project; ii) it entails processes of acceptance and approval of industry activities; and iii) it is constructed through dynamic interactions among the community, stakeholders and companies (Lehtonen et al., 2020).

downturns. Regulatory decisions may impose changes on the design that, again, would be particularly damaging in the construction phase. US experience provides empirical evidence of this type of impact: during the 1970s, especially after the Three Mile Island (TMI) accident, many regulatory-driven design changes affected both existing plants and those under construction. As suggested by Lovering, Yip and Nordhaus (2016), the NPPs that were under construction during the TMI accident and were eventually completed afterwards had higher median costs and durations compared with pre-TMI trends.

Regulatory requirements may also impose base design changes, particularly for reactor designs that have already been licensed under the regulations of the country of origin but require design modifications to comply with the import country's regulatory framework.[53] The case study presented in Box 14 suggests that adaptation of a base design to a foreign regulatory regime might induce an EPC cost increase of around 30%. As will be explored in Chapter 5, the harmonisation of regulatory regimes may help limit the impact of adaptation costs.

Box 14: **Case study: Estimating the costs of adapting to national regulatory frameworks**

The lack of nuclear regulatory regime harmonisation implies that for nuclear designs to be exported, some modifications may be required for them to comply with the other county's safety requirements. This case study offers a macro-level estimate of potential costs incurred to adapt a base design to a country-specific regulatory framework. The results were recognised by the REDCOST expert group.

The four main potential sources of adaptation costs are:

- An increase in the bill of quantities (BoQ) due to anticipated increases in the volumes of buildings.
- An increase in the number of systems and equipment.
- An increase in the number of work hours based on these modifications.
- An increase in the number of work hours for licensing-related tasks.

In line with the cost structure presented in Chapter 2, EPC expenses were assumed to be made up of 39% material costs and 61% labour costs. Another important assumption is that most of the adaptation costs induced by various regulatory requirements are captured by safety-related systems, components and structures such as the reactor plant and instrumentation and control (I&C) equipment, and construction works. The turbine and main heat rejection systems, however, were assumed to be outside the scope of adaptation costs.

Using expert and engineering judgement, sets of multipliers were determined for the material and labour costs of each component; it was considered fair to assume a 30% increase in the BoQ and in the number of systems and equipment needed to meet more stringent safety requirements. This resulted in a general multiplier of 1.3 for the BoQ for construction works and concerned equipment.

The correlation between the BoQ and construction work hours is almost linear, so a similar multiplier was used for work hours related to the various modifications. However, depending on the national licensing process, significant additional work might be needed for the licensing activities associated with safety-related components (i.e. reactor and electric plant equipment). This explains why different labour multipliers were used depending on component type, as well as the rise in indirect costs. The table below presents the cost breakdown and estimated multipliers of the selected safety-related components.

53. Safety requirements may vary from one country to another in areas such as defence-in-depth concept; diversity and redundancy; and physical separation. These aspects are further investigated in Chapter 5.

Box 14: **Case study: Estimating the costs of adapting to national regulatory frameworks** *(cont'd)*

	Materials and components	Labour	Materials and components	Labour	Materials and components	Labour
Civil structural works	5%	9%	**1.3**	**1.4**	6%	13%
Reactor plant equipment	11%	3%	**1.3**	**2.2**	14%	6%
Turbine plant equipment	8%	2%			8%	2%
Electric plant equipment	2%	2%	**1.3**	**2.0**	3%	3%
Main heat rejection system	2%	2%			2%	2%
Miscellaneous plant equipment	1%	2%			1%	2%
Indirect costs	11%	42%		**1.4**	11%	58%
Total	39%	61%			44%	86%
		100%				**130%**

Material costs rise from 39% to 44%, and labour costs from 61% to 86%, leading to an indicative cumulated cost increase of 30%. Based on this analysis and underlying assumptions, adapting a design to a different regulatory regime may raise EPC costs by around 30%.

It is important to note that these estimates are subject to significant uncertainties. Adaptation costs may also vary depending on the design and the extent of the regulatory gap between countries. Nevertheless, this exercise confirms that adaptation costs are not negligible and potential cost savings could be obtained by strengthening regulatory harmonisation.

From an economic perspective, the additional costs induced by regulatory activities are the price that must be paid to reduce the externalities associated with nuclear power, to ultimately maximise social benefits. Economic theory postulates that optimum nuclear power safety efforts are reached when the marginal social cost of protection equates the marginal social benefit in terms of potential harm avoided. Beyond this optimum, any additional regulatory effort is more costly than the potential benefits to the society. In practice, however, finding this optimal level is not a simple task. One of the main hurdles is the incompleteness of information. In fact, the marginal costs of regulatory efforts are not well known and uncertainties surrounding the marginal costs of risks avoided are high.

Since establishment of the first regulatory bodies, rules and approaches for safety demonstration have not ceased to evolve. Various adjustments have been made to integrate increasing knowledge of the physical phenomena involved, as well as to improve regulatory efficiency and find a better balance between the costs and benefits of safety regulation. Traditional regulatory processes were characterised by high levels of prescription. This type of approach makes sense only when knowledge of nuclear safety is limited in order to reduce levels of uncertainty, ambiguity and misinterpretation (Sainati, Locatelli and Brookes, 2015). At the same time, safety demonstration relied heavily on deterministic approaches.[54]

54. Build upon defence-in-depth principles (prevent, protect and mitigate), deterministic safety assessment postulates a series of incidents and accidents that may occur for a given design, and evaluates, by means of codes and analytical methods, the capability of the design to withstand these transient conditions. If the safety requirements are not satisfied, design modifications (e.g. the introduction of additional safety systems) are implemented. It is the ability of defence-in-depth principles to meet safety criteria – and not necessarily their effectiveness to reduce overall risks – that prompt design modifications.

With the emergence of probabilistic safety assessment (PSA),[55] the introduction risk-informed, performance-based regulation (RIPBR) was facilitated. Instead of defining technical rules and then verifying their proper application, under RIPBR the regulator establishes basic requirements and sets overall performance goals, and the plant's management then decides how to best meet the stated goals. Using risk metrics obtained through PSAs allows resources to be allocated to plant equipment and systems according to their safety relevancy. As a result, regulatory processes can be streamlined to remove unnecessary rules (as their contribution to safety is judged negligible) and focus efforts on critical stages and components.

To reduce costs related to regulation, economic analysis suggests that RIPBR is more convenient for several reasons. As the choice of how to meet performance criteria is left to licensees, they have an economic incentive to select the least-costly solutions (Lévêque, 2014). Freedom of choice also implies greater innovation opportunities to further reduce costs and improve overall industry performance, and regulators also save the costs associated with gathering expert knowledge.

However, the weakness of RIPBR is that it is difficult to measure performance itself, as performance can normally be observed only indirectly or during the operating period. Plus, PSA metrics are also subject to uncertainties, particularly those related to human factors and behaviours. Lastly, deterministic safety assessment is the only way to identify factors that may still be unknown and, under accident conditions, it provides the right tools to mitigate the most severe consequences.

All these circumstances mean that, in practice, regulatory bodies adopt a more dual approach that combines the right level of prescription with goal-setting initiatives. Deterministic approaches are usually used for design-basis transient analysis, while probabilistic methods are more suited to beyond-design-basis assessment of accidents (i.e. external hazards, such as for the Fukushima Daiichi accident). The guiding principle of ALARA/P – as low as reasonably achievable/practicable – is widely accepted by all countries to ensure the proportionality and effectiveness of regulatory efforts in the interests of society.

The ALARA/P principle is essentially based on the philosophy that operators and regulators should constantly be asking themselves, "How safe is safe enough?". In the end, it is up to society to decide, on the basis that all the technical information is available. Regulators must therefore frame technical safety requirements in a way that reflects the expectations of society as a whole, considering the overall risks of nuclear activities. Consequently, in addition to potential interpretations of the ALARA/P concept, it is also important to understand the different strategies envisioned by regulators to translate the social perception of nuclear power into technical requirements and how this process may impact the cost of the technology.

In practice, it is extremely difficult for a regulatory body to accurately assess the level of risk deemed acceptable by the society it represents. The public inquiries, parliamentary questions and media coverage that follow any untoward nuclear event may provide the most reliable indication (NEA, 2000). Regardless, regulators have to ensure that the ALARA/P principles are clearly understood and properly applied at all stages of the safety assessment. Some studies suggest that ALARA/P guidelines are often misinterpreted in regulatory interactions, which may result in nuclear safety standards being applied uniformly to the entire plant rather than being adjusted, at the component level, according to its safety relevance (NIRAB, 2019). The adoption of risk-informed frameworks may provide a set of rules adequate to avoid this type of situation (Box 15).

55. PSAs seek to quantify the probability of cascading failure occurrence that, combined with potential consequences, yields the associated risks.

Box 15: **ONR's risk-informed decision-making process**

The United Kingdom's Office for Nuclear Regulation (ONR) deserves attention for its significant efforts to ensure proportionate and adequate application of the ALARA/P principle, using risk-based approaches to inform regulatory decision-making.

In *Risk Informed Regulatory Decision Making* (ONR, 2017), the ONR details the main principles and criteria guiding its regulatory decision-making process. Its philosophy is based on "tolerability of risks", which does not mean acceptance of risk but rather the willingness to live with it to secure certain benefits for society, in the confidence that risks are being technically and properly controlled. Risks are not therefore ignored, but kept under review and reduced as much as is reasonably practicable. For a risk to be acceptable, however, the society must be prepared to accept it. Consequently, the ONR's regulatory framework includes a set of criteria to decide whether risks are unacceptable, tolerable or broadly acceptable. ALARA/P guidelines are used to proceed though the risk tolerability continuum, underpinned by risk-informed approaches and metrics.

When it is considering whether licensees need to implement further measures, the ONR compares the degree of risk reduction with "the sacrifice, whether in money, time or trouble involved in the measures necessary to avert the risks." Unless the licensee can demonstrate a gross disproportion between these two factors and prove that the averted risk would be insignificant, additional measures to reduce risks have to be considered.

The ONR also indicates that "there is no precise legal factor or algorithm able to define gross disproportion between the costs associated with the measures to reduce risk and the benefits in terms of risk reduction." Numerical calculations are also rare, so in its decision-making the ONR recognises a disproportion factor (the cost-benefit ratio of a given solution) of up to approximately ten (this value is based on evidence from the Sizewell B public inquiry). Also, when the disproportionality of regulatory decisions is being assessed, the initial position of the risk on the tolerability continuum must be considered. Applying a costly solution to move risk from the "unacceptable" to the "tolerable" zone is not the same as using expensive means to shift it from "tolerable" to "broadly acceptable."

Consequently, in addition to the stability and predictability conditions highlighted in Chapter 3, regulatory frameworks can support cost reductions by revisiting regulatory interactions and approaches through:

- Increasing awareness among regulators that their activities increase the cost of the technology (by an amount that is necessary for the benefit of society but that should be proportionate to the risk avoided), and engendering among regulators a willingness to understand how their decisions may impact the final performance of the technology. For instance, in its 2019-2020 corporate plan the ONR expressed its commitment to develop greater understanding of the costs imposed by regulatory decisions, to use economic advice in framing and assessing its regulatory decisions, and to refine its current guidance on ALARA/P and gross disproportion (ONR, 2019).
- Identifying mutually beneficial situations, in which regulators and licensees can co-operate while maintaining regulatory independence and the highest level of safety. For instance, Box 16 presents success story of revisited regulatory interactions for cost optimisation on the Horizon project, and the design simplifications approved for the EPR2 design are also a good illustration (see Box 11). These examples show that stringent regulation does not necessarily imply higher costs when safety efforts are more focused and regulatory interactions permit some flexibility while satisfying the interests of both parties. Early engagement with regulators is essential.
- Avoiding misinterpretation and fostering the clear and transparent communication of requirements. Poorly interpreted requirements may lead to a lack of focus and additional efforts with limited added safety. This is even more important if the requirements are new and are imposed once construction has begun.

- Aligning regulator and licensee objectives and outcomes. Gaining design acceptability is an important objective, but so is the construction of a safe, secure, environmentally acceptable and affordable reactor. Regulators can establish these conditions, but licensees should also be proactive and work closely with regulators in developing clear safety cases and fixing potential shortfalls.

Governments also have a key role in establishing such a regulatory framework. They are responsible for setting regulator missions and objectives, while at the same time providing the means necessary to guarantee the independence and transparency of regulatory decisions (NEA, 2011). In the United Kingdom, the ONR's quest to better understand the economic costs of regulation is framed by the national Better Regulation initiative (ONR, 2019). This initiative requires the evaluation of business impact targets (BITs) to determine the financial impact that qualifying regulatory provisions have on business (in this case, the nuclear industry). National missions may also seek to limit potential distortions of the ALARA/P principle towards "zero-risk" approaches that may not maximise benefits for the whole society.

Finally, the innovative organisational modes described in this chapter (digital transformation, knowledge management, lean management, etc.) could also be adopted by regulatory bodies. The quality and efficiency of regulatory activities could thus be improved, resulting in lower costs as well as greater safety. An interesting example is the NRC's transformation plan (see NRC, 2019).

Box 16: **Cost optimisation with regulator involvement: The Horizon project**

This case study illustrates the value of securing a design that is ready for construction and has undergone design optimisation prior to the beginning of construction.

From 2012 until January 2019, Hitachi invested in potential UK nuclear new-build projects to deploy twin Advanced Boiling Water Reactor projects at Wylfa in North Wales and at Oldbury on the Severn river. In January 2019, Hitachi decided to "pause" these projects due to the suspension of further investment. The lead project at Wylfa was in an advanced stage of development, with the reactor design having passed the UK Generic Design Assessment (GDA). Ongoing activities at the time of suspension were focused on informing a final investment decision, with the anticipated subsequent construction expected to support commercial operations of the first reactor in the mid-2020s. (The decision to pause this investment is a separate matter outside the scope of this report.)

The 2016 estimate of construction costs for the Wylfa NPP deploying the UK GDA design was evaluated as unaffordable within the project's business case (project economics were determined by revenue from a contract for difference with an expected strike price of around GBP 75 per megawatt hour [/MWh]). The project challenge addressed in this case study reflects the need to reduce construction costs through design optimisation to achieve acceptable construction and operational risks while delivering a viable project business case.

A wide range of potential cost reduction opportunities was identified, including:

- Avoiding unnecessary system and building duplication by deploying an integrated twin unit rather than two single units, as per the GDA evaluation.
- Optimising the plot plan to reduce costs, including by reducing the number and size of support buildings and associated service galleries.
- Modifying engineering solutions to accommodate the hazards and constraints of the specific proposed UK site rather than the generic UK site.
- Employing alternative engineering solutions to mitigate selected natural hazards identified as significant cost drivers by extreme value analysis (e.g. peak maximum ambient temperature).
- Using an alternative approach to characterise the seismic hazard and associated ground motion spectrum.
- Optimising the redundancy and diversity of significant safety systems as necessary to meet the requirements of the safety case.

Box 16: **Cost optimisation with regulator involvement: The Horizon project** *(cont'd)*

The approach for reviewing over 100 potential optimisation opportunities was designed to:

- Provide an understanding of the potential impact on the safety case.
- Describe a set of principles for how to explore these opportunities.
- Maintain the integrity of the GDA as much as possible.
- Minimise deviations from the GDA as much as possible.

This review was implemented from October 2016 in parallel with completion of the GDA, with constructive results:

- A set of "papers of principle" was developed describing how the design optimisation phase would be delivered and how the safety case would be achieved. These papers were to ensure the UK regulators' understanding of the process and approach.
- From the individual opportunities, associated individual engineering propositions to implement the papers of principle were developed and finalised by May 2017.
- A regulatory review of Horizon's proposals was completed by the end of 2017.

Horizon's design optimisation process produced numerous outcomes:

- Regulators were engaged and motivated to support this process at the executive level.
- Regulatory knowledge and experience in general were enhanced by the GDA evaluation of two reactor designs already evaluated for potential UK deployment.
- The process benefitted from the capabilities and experience of both the project team and the regulators.
- Benefits were realised from challenging the initial design assumptions associated with co-locating units on the same site.
- It was discovered that design and regulatory efforts can be reduced by focusing on a specific rather than generic deployment site earlier in the project development process.
- The approach of designing a project to mitigate the impact of natural hazards may often use data from extreme value analysis, but using other approaches may be beneficial when they can be justified.
- Significant savings were successfully realised in the estimated construction cost of a twin-unit ABWR at Wylfa.
- There were indications that further significant cost reductions could be realised if there were a commitment at the outset to four units at the same site – greater savings than for an initial commitment to a twin unit with potential for a second twin unit at the same location.

The design optimisation phase pursued by Horizon realised expected overnight capital cost reductions exceeding 20% for twin-unit ABWR deployment at Wylfa, compared with deploying two units as per the GDA design of the UK ABWR. Horizon's design optimisation phase benefitted from a regulatory engagement process that gave Horizon and its stakeholders confidence that the optimised design for construction was acceptable to safety and environmental regulators. This case study confirms that a period of design optimisation focused on constructability and cost reduction is an important step in the project development process prior to construction commitment. With appropriate regulatory engagement, significant cost savings can be demonstrated through improved engineering without compromising safety and environmental standards.

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5. Long-term opportunities to reduce nuclear construction costs

As described in Chapter 4, countries adopting serial construction in the decade ahead could benefit from lower costs and risks thanks to implementation of a set of incremental improvements such as design optimisation, the adoption of new technologies and better organisational and construction approaches, as well as revisited regulatory interactions. These cost-saving strategies would also help mitigate nuclear risks in several dimensions as will be further detailed in Chapter 6.

In the longer term (beyond 2030), further cost reductions could be unlocked through greater harmonisation and materialisation of the economic case for more disruptive technologies such as small modular reactors (SMRs).[56]

These new opportunities are part of a long-term industrial performance strategy that envisions sustained efforts to activate the various cost reductions drivers and continuously raise the sophistication of products and processes by capitalising on learning acquired in each successive construction. The interplay between the product and the processes enables complementarities and synergies among different technology families. Evidence gathered for this study suggests that long-term cost reductions are achievable and that countries in the most advanced stages of learning are moving towards this direction.

5.1 The role of harmonisation at the industrial and regulatory levels

The concept of harmonisation is intimately related to the standardisation process detailed in Section 4.1.2. In fact, the uniformity sought by standardisation practices is not only limited to design but can be extended to the governance of nuclear activities. Current governing frameworks are essentially country-specific, creating a regulatory heterogeneity that may impact the overall cost of nuclear technology.

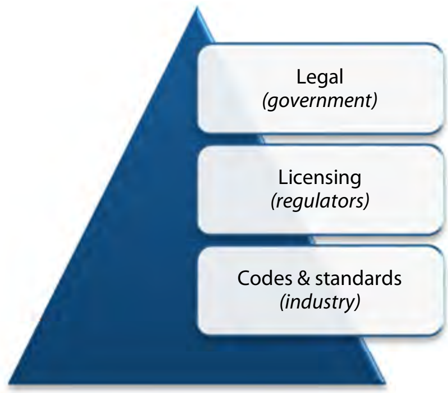
This report considers that harmonisation encompasses all activities and processes that seek to increase the homogenisation and convergence of nuclear rules among countries at three different levels (Figure 33):

- legal (governments);
- licensing and regulatory guidelines (nuclear regulators);
- codes and standards of practices (industry).

Each level is characterised by its own specific challenges and developmental pace, and even though complete harmonisation is unlikely, experience has shown that is possible to achieve consensus in some specific areas, particularly at the regulatory and industrial levels.

56. SMR progress has been significant in recent years, with some developers announcing the first prototypes for before the end of the decade. Nevertheless, recent work suggests that for SMRs to fully yield their expected benefits, several challenges in terms of licensing, harmonisation, technology risks and supply chain development must first be overcome (NEA, 2019). The extent of these challenges could vary depending on the maturity of different concepts (i.e. light water-cooled versus alternative coolants). REDCOST experts recognise that these issues are not likely to be resolved until after 2030.

Figure 33: **Harmonisation levels**



5.1.1 *Licensing regimes*

Licensing regimes set the requirements, guidelines and processes that regulators use to assess safety and certify nuclear designs. At the international level, the International Atomic Energy Agency (IAEA) provides high-level safety standards and recommendations; although they are broadly accepted by most countries, they are not binding (WNA, 2013). Furthermore, their level of detail is low and they are often subjected to interpretation. More comprehensive design, engineering and licensing requirements are therefore needed, resulting in regulatory regimes that tend to vary from country to country.

Areas in which harmonisation is still lacking include the defence-in-depth concept, the principles of diversity and redundancy, physical separation, external hazards (e.g. air-crush protection) and severe accident management. Consequently, vendors must perform design modifications and undergo certification processes for every host country. This situation turns nonrecurring design and licensing efforts into recurring activities and thus hampers nuclear learning in reactor construction abroad. Extra costs incurred by the lack of harmonisation (i.e. adaptation costs) are estimated at approximately 30% of the engineering, procurement and construction (EPC) costs of a generic nuclear power plant (NPP) (see Box 14). This value may vary depending on the extent of the regulatory gap between countries.

Nevertheless, harmonisation at the regulatory level may encounter some obstacles:

- The protection of national sovereignty: While respecting the internationally shared fundamental principles of nuclear safety, some countries may be reluctant to accept certain requirements, as they may not be aligned with their national interests and regulatory practices. Protecting the sovereignty of national regulators is also important to preserve the nuclear industry's social licence to operate in a country and the public's acceptance of regulatory decisions. This aspect inevitably has a strong political dimension and explains why regulatory harmonisation may face greater inertia than similar initiatives at the industrial level.
- Increased stringency: There is also a risk that harmonised regulations, being the sum of the highest expectations in all fields for all countries, may become too stringent and thus more expensive and less practical.

International collaboration therefore remains essential to identify areas of regulatory convergence. Two initiatives lead harmonisation efforts internationally: the Multinational Design Evaluation Programme (MDEP) and Cooperation in Reactor Design Evaluation and Licensing (CORDEL). (The latter is actively building on aircraft industry experience.) As is further detailed in Section 5.2, harmonisation is central to the development of SMRs.

5.1.2 *Codes and standards*

Similar to licensing regimes, nuclear codes and standards may vary from one country to another. Typical national quality standards include the American ASME NQA-1 code,[57] the French RCC-M and RCC-E codes and German KTA standards. Even if a certain level of convergence has been achieved among codes, some differences persist, and different total quality management systems still prevail at the national level.

More importantly, the cost of adopting nuclear standards is quite significant: for instance, it can almost double the cost of an industrial-grade valve (see Figure 28). Most of the cost burden is associated with the establishment of a quality management system (i.e. qualification process). As a result, some companies may be reluctant to qualify their processes, especially if the number of orders is limited, reducing the pool of qualified suppliers available.

In 2010, Bureau Veritas and Framatome (formerly AREVA NP) founded a global initiative, the Nuclear Quality Standard Association (NSQA), to lead harmonisation efforts while strengthening the quality management processes of the nuclear industry. Their efforts resulted in publication of the ISO 19443 in 2018 (ISO, 2018). This standard internationally harmonises the minimum level of requirements, creating a common language that can accelerate the qualification of a global supply chain. To guarantee the success of the ISO 19443 standard, further efforts in the accreditation process and in overseeing implementation may be needed in the near future. It is essential that the nuclear industry manage this process, with the endorsement of the regulatory bodies.

Given the nuclear sector's long time frames, it is difficult to describe with certainty the equilibrium that could be achieved through the combination of modularisation, harmonisation and potential externalisation strategies covered in this report. While modularisation has some limits, improved standardisation and flexible co-operation among different vendors, regulators and suppliers are likely to play significant roles in the future. In some cases, this will require changes to leadership practices and the type of cultural shift that is only possible in the long term. Additionally, the digital transformation is advancing quickly and will certainly reshape the final situation thanks to greater information traceability.

5.2 Construction costs of small modular reactors

The difficulties encountered in large Gen-III nuclear projects in western OECD countries have undermined investor and decision-maker confidence in nuclear energy, particularly in Gen-III designs. Although this report explains how the costs and risks of large contemporary nuclear designs can be reduced, large Gen-III reactors will to some extent continue to be complex, capital-intensive projects with significant labour costs and on-site work. Interest is therefore growing in more evolutionary concepts – "beyond" large Gen-III designs – that incorporate all the learning and techniques of previous projects (largely covered in this study) to yield greater productivity and predictability per unit. This could be the case for the SMR delivery model, for instance.[58]

SMRs have unique key design features that allow them to capitalise more extensively on some of the cost reduction strategies described in this report (Box 17). However, the smaller size of SMRs has a major economic drawback: the inability to benefit from economies of scale. Instead, their economic performance can be improved through series production and higher learning rates thanks to (also see Figure 34):

- Simplification: Passive mechanism improvements and greater design integration would reduce the number of components and result in containment building savings.

57. This standard has been widely adopted as part of the technology transfer agreements signed by American companies with several countries.

58. In this report, the term SMR refers to both light water-cooled and advanced concepts (see Box 17).