Modular Manufacture and Construction of Small Nuclear Power Generation Systems

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It is not substantially the same as any that I have submitted, or, is being concurrently submitted for a degree or diploma or other qualification at the University of Cambridge or any other University or similar institution except as declared in the Preface and specified in the text.

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SUMMARY

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Nuclear power is a stable, secure, low-carbon energy source; however, recent nuclear power plant projects are challenged by long build times and high construction costs, making them difficult to finance. Small Modular Reactors (SMRs) are nuclear reactors smaller than 300 MWe and claim to leverage manufacturing principles and modular build to resolve these issues and help improve the competitiveness of nuclear power.

This project investigates modular build in a nuclear context, explores modularisation principles and best practises in other industries, identifies key constraints and optimisation criteria, and develops a new conceptual framework for modularising nuclear plants based on their size and subject to transport constraints. Transportation limits the type and amount of construction work that can be moved off-site. Due to their smaller size, up to 80% of a SMR plant can be modularised and transported by road, compared to only 20% for large reactors. Schedule and cost benefits are maximised when at least 60% of *in-situ* work is moved off-site, favouring fully modular units smaller than 600 MWe.

Stick-built SMRs are not competitive with large reactors on the basis of their construction cost. A fully modularised SMR, however, can move 50% of its overnight construction cost off-site, achieving costs of $5,470/kWe (300 MWe SMR), competitive with the reference $6,000/kWe cost for a stick-built large reactor. Build schedule indirectly impacts construction cost by affecting overheads and interest during construction. Modular SMRs have the greatest scope for schedule reduction, moving 30% of *in-situ* time off-site and reducing build time to 3.5 years (300 MWe SMR), compared to 6.5 years for stick-built large reactors. Production learning is also critical to SMR economics and, when coupled with shorter build schedules, significantly impacts SMR total capital investment costs. A standardised series of modular SMRs can reach total capital costs of $4,600/kWe (300 MWe SMR) and can compete with the $4,400/kWe benchmark for energy technologies. SMRs have a unique opportunity to utilise modularisation and this project shows how they can leverage modular build to improve the economic competitiveness of nuclear power.

To my sister, Julia
who challenges me to make the most of what I am given

The race is not to the swift
or the battle to the strong,
nor does food come to the wise
or wealth to the brilliant
or favour to the learned;
but time and chance happen to them all.

Ecclesiastes 9:11

In thee, O Lord, do I put my trust: let me never be put to confusion.

Psalm 71:1

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List of Acronyms & Symbols

ABWR	Advanced Boiling Water Reactor
A-E	Architect-Engineer
AIL	Abnormal Indivisible Load
ASTRID	Advanced Sodium Technological Reactor for Industrial Demonstration
BE	Better Experience (in reference to EEDB Phase IX Update Report dataset)
BEIS	Department for Business, Energy and Industrial Strategy (UK) (formerly DECC)
BIM	Building Information Modelling
BoP	Balance of Plant
C&U	The Road Vehicles (Construction & Use) Regulations 1986 (UK)
CCS	Carbon Capture & Storage
CEA	Atomic Energy Commission (France)
COA	Code of Accounts
CRDM	Control Rod Drive Mechanism
DECC	Department of Energy and Climate Change (UK) (now BEIS)
DfMA	Design for Manufacture and Assembly
DOE	Department of Energy (USA)
DoM	Degree of Modularisation
EEDB	Energy Economics DataBase (USA)
EMWG	Economic Modelling Working Group
EPR	European Pressurised Water Reactor
ETI	Energy Technologies Institute (UK)
FOAK	First-of-a-Kind
FPSC	First Pour of Structural Concrete
GDA	Generic Design Assessment (UK)
GDEB	General Dynamics Electric Boat
HE	Highways England (UK)
HGNE	Hitachi-GE Nuclear Energy
I&C	Instrumentation & Control
IAEA	International Atomic Energy Agency
IDC	Interest During Construction

IRV	Integrated Reactor Vessel
LCOE	Levelised Cost of Electricity
LR	Large Reactor
LWR	Light Water Reactor
M&E	Mechanical & Electrical
ME	Median Experience (in reference to EEDB Phase IX Update Report)
M_{eff}	Effective Modularisation
MHI	Mitsubishi Heavy Industries
MIT	Massachusetts Institute of Technology
NEA	Nuclear Energy Agency
NEDB	Nuclear Energy DataBase (USA)
NI	Nuclear Island
NOAK	N^{th}-of-a-Kind
NPP	Nuclear Power Plant
OCC	Overnight Capital Cost
OECD	Organisation for Economic Co-operation and Development
O&M	Operating & Maintenance
PWR	Pressurised Water Reactor
QA	Quality Assurance
RBA	Road and Bridges Authority (UK)
RC	Reinforced Concrete
RPV	Reactor Pressure Vessel
S&W	Stone & Webster
SC	Steel-Plate Concrete
SMART	System-integrated Modular Advanced ReacTor
SMR	Small Modular Reactor
STGO	The Road Vehicles (Authorisation of Special Types) (General) Order 2003 (UK)
TCIC	Total Capital Investment Cost
USD	United States Dollars

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CHAPTER I
INTRODUCTION

I.1. Nuclear Power Plant Construction: Problems

The desire to reduce the carbon footprint of electricity generation technologies coupled with an increasing energy demand and ageing nuclear fleet creates an acute need for new nuclear projects – a trend that is observed in the UK and worldwide [1]. Installing indigenous nuclear power capabilities allows countries such as the UK to decrease their dependence on imported energy and maintain the diversity and security of the national electricity supply. Nuclear power is a promising candidate for the provision of large and stable supplies of low-carbon energy in the UK, but the future deployment of nuclear power plant (NPP) projects for civil power generation is challenged by high construction costs, long build schedules, and funding problems [2].

I.1.1. Large Reactor Construction

New NPP projects in the UK face some imposing cost and experience barriers. Sizewell B power station, an 1198 MWe pressurised water reactor (PWR), is the most recently constructed NPP in the UK, but it was commissioned over 20 years ago [3]. Nuclear construction knowledge and skills have been lost during the intervening time and new NPP projects now face an expensive learning curve. The tendency in the US and UK is for each new nuclear project to adopt bespoke design features tailored to the local situation. High construction costs and long build times are the main reasons why current large nuclear reactor options are not cost-competitive in the energy market.

i. Long Construction Schedules

LRs are difficult to build both physically and logistically. The current European Pressurised Water Reactor (EPR) reactor is the biggest LR built to date, at 1650 MWe per unit. The EPR size and design requirements are pushing the limit of what is possible with current construction technologies. EPR projects in France (Flamanville), and Finland (Okiluoto) have experienced severe scheduling and budget overruns.

Appendix I.1 shows how the construction duration for light water reactors (LWRs) in the West increases with size.

ii. Extensive Construction Rework

Nuclear construction tasks, which are often complex and conducted in a variable *in-situ* environment, need to be compliant with stringent safety standards and to adhere to strict quality assurance (QA) requirements. A significant amount of rework is often necessary, either because the NPP design details are not physically buildable or because *in-situ* work does not meet the regulatory standards [4] [5].

iii. Lack of Learning

Project-to-project learning is rarely observed in the nuclear industry in cases where the time between new nuclear projects is long [6]. Additionally, traditional construction practice is for contractors to produce their own detailed construction drawings based on a high-level design, meaning that no two NPPs are the same [1]. This is of particular relevance for countries such as the US and UK.

I.1.2. High Nuclear Construction Costs

Construction and project management issues are proving to be the systemic problem within the nuclear industry, characterised by the escalating costs observable in Western nuclear development (UK, US, and France) which are a sharp contrast with the more stable costs in Japan and the Republic of Korea, where nuclear construction projects were standardised [7] [8]. This is further complicated by funding issues where, in the West, the high upfront cost and scale of current projects means that they are too big to be funded by any nuclear vendor or power utility without Government backing [9] [6]. There is, therefore, a clear need for a nuclear construction programme that facilitates learning within the industry by standardising and centralising construction activities, improving build quality, and simplifying regulatory compliance.

Energy technologies commonly use Levelised Cost of Electricity (LCOE), a metric that spreads the entire lifetime costs of a power plant or other energy technology over its expected operational life, giving the energy cost per MWh generated. For a traditional

LR, the capital costs contribute about 70% of the total LCOE [10]. These costs occur during the initial project construction phase and include direct and indirect expenses, contingency, and owner's costs (these are explained below in Section I.3.1.5). The remaining 30% of the LCOE is discounted over an assumed NPP life of 60 years and includes operating & maintenance (O&M), insurance, fuel, and decommissioning costs. This dissertation focusses primarily on reducing *in-situ* construction work because this is the single greatest contributor to capital costs (see Figure I.1). This includes site material and site labour costs for construction of the primary loop system, civil structures and improvements, installation of mechanical & electrical (M&E), piping, and instrumentation & control (I&C) systems. Most of these activities occur on-site. A representative capital cost breakdown for a large PWR plant is shown in Figure I.1.

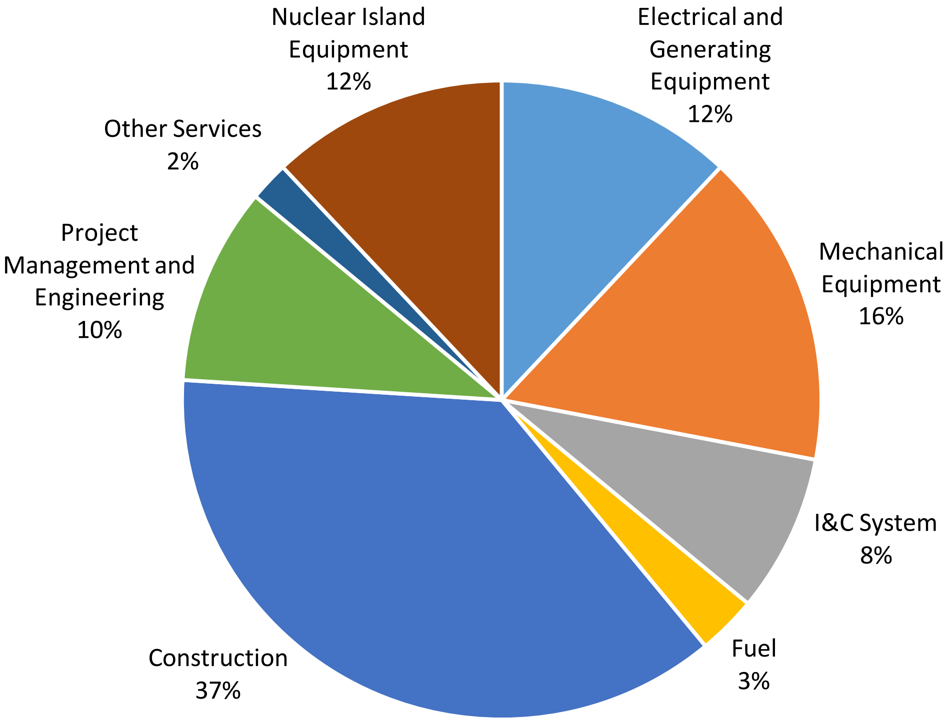
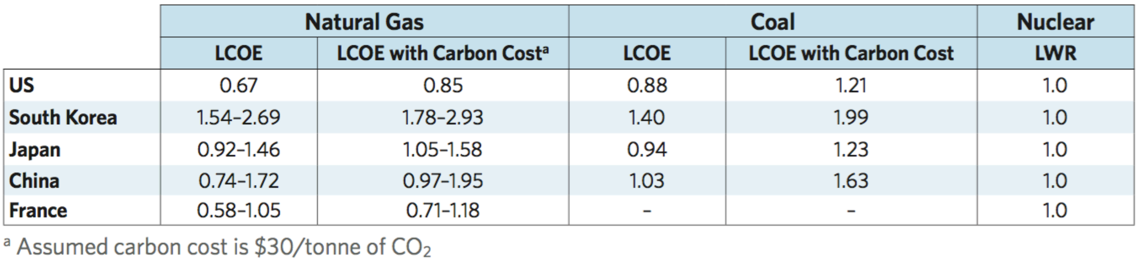


Figure I.1. Cost breakdown for a typical large PWR nuclear plant.
Values are % of overnight capital costs (excluding financing costs). Data from pp. 145-146 [6].

Although LCOE is a common metric used to compare the costs of different energy technologies, it is subject to variability in location, forecasted fuel prices, discount rate, whether a carbon tax is applied, and so on. Some relative LCOE figures are listed in

Figure I.2 and show how variable LCOE estimates can be. A benchmark large nuclear plant that is constructed following conventional methods in a Western country, such as the US or UK, can be expected to have a LCOE of \$110/MWh (at a 9% discount rate) [1]. This LCOE could be reduced to \$80/MWh if best-practices are used during construction, giving a specific capital cost of about \$4,385/kWe [1] and setting a competitive target for construction costs. Chapter VI will return to this topic in more detail.



	Natural Gas		Coal		Nuclear
	LCOE	LCOE with Carbon Cost[a]	LCOE	LCOE with Carbon Cost	LWR
US	0.67	0.85	0.88	1.21	1.0
South Korea	1.54-2.69	1.78-2.93	1.40	1.99	1.0
Japan	0.92-1.46	1.05-1.58	0.94	1.23	1.0
China	0.74-1.72	0.97-1.95	1.03	1.63	1.0
France	0.58-1.05	0.71-1.18	-	-	1.0

[a] Assumed carbon cost is \$30/tonne of CO_2

Figure I.2. Normalised LCOEs for natural gas (low-high range), coal, and nuclear in different countries, from Table 2.1 in [2].

I.1.3. Modularisation & SMRs

Modularisation, a design process by which *in-situ* work is organised into modules that can be fabricated off-site in a factory, allows a construction project to adopt a production-orientated mind-set to compress build times and reduce construction cost. Modularisation as a construction technique has already been implemented in a number of heavy industries, including shipbuilding and the oil & gas sector. The construction benefits achieved in these sectors has led to the development of the Small Modular Reactor (SMR) concept which, according to the International Atomic Energy Agency (IAEA), are ‘advanced nuclear reactors that produce electric power up to 300 MWe, designed to be built in factories and shipped to utilities for installation as demand arises’ [11].

In the West, constructing SMRs using the same case-by-case strategy that is currently employed by large reactor projects is economically infeasible, because SMRs experience diseconomies of scale relative to conventional GW-scale large reactors (LRs) [9]. Some estimates place the construction cost of SMRs at over 2.5 times that of large reactors for the same equivalent power output [12]. However, SMRs can offset their diseconomies of scale by leveraging some unique opportunities related to their reduced physical size, such as higher learning, more flexible siting, increased scope for modularisation, and a greater number of opportunities for using advanced construction techniques [9]. Modularisation in particular may bring a range of continuous cost and schedule reductions to an industry that has hitherto been based on large, one-of-a-kind projects. Modular build adopts a manufacturing approach in which the construction process makes the most of off-site manufacture and 'economies of numbers', using factory build and design standardisation, to achieve both consistent build quality and repeatable construction schedules.

The Organisation for Economic Co-Operation & Development (OECD) estimates that the global energy market can accommodate up to 300 GWe of additional nuclear power over the next 20 years; SMRs could provide up to 21 GWe of this [13]. In the UK, the Department for Business, Energy, and Industrial Strategy (BEIS) estimates that the UK alone could sustain SMR deployment at a rate of 0.4-0.8 GWe per year [14]; work by the Energy Technologies Institute (ETI) suggests that the UK has a potential 7 GWe market for SMRs [15]. These estimates, however, depend largely on local factors including energy policy, government support, nuclear site availability, production and manufacturing capabilities, in addition to energy markets and the competitiveness of SMRs with other energy technologies. Market scenarios are developed and discussed in literature; some sources include [13] [14] [16].

I.2. Construction Cost Reduction: Solutions

The OECD Nuclear Energy Agency (NEA) and the UK ETI both report on current best-practice strategies employed to reduce NPP capital cost [15] [17]. Over half the cost reduction strategies pertain to altering or improving the NPP construction process, shown in Table I.1.

Table I.1. Cost reduction strategies from [17], and their effect on SMR construction cost.

Cost Reduction Strategy	**Effect on SMR cost**
Increased plant size	Constructing larger plants achieves greater economies of scale
Improved construction methods	One-off material and labour efficiency improvements; achievable through off-site manufacture
Reduced construction schedule	One-off productivity improvements; achievable through off-site manufacture
Design improvement	Simplified designs require fewer components, less building materials, and reduced labour
Improved procurement, organisation, & contractual aspects	Continuous learning benefits; achievable through supply chain organisation
Standardisation & series construction	Continuous learning benefits; achievable through off-site manufacture
Multiple unit construction	Continuous learning benefits; achievable through off-site manufacture
Regulation & policy measures	Government reduces uncertainty in regulation & energy market

I.2.1. Plant Size & Economies of Scale

The rated power output of nuclear reactors has increased from about 400 MWe, in the early 1970's, to the present-day 1650 MWe LRs. This trend has been followed to take advantage of the so-called economies of scale or size, reducing the cost of electricity through lower specific capital costs [18]. While the benefits of scaling may hold true for individual items or components, they have not been observed at the aggregate whole-plant level because larger construction projects tend to be more complex, take more time to construct [19], and are not highly standardised, making it difficult to identify cost/schedule trends over time [20]. Economies of cost-power scaling are discussed and critiqued in Chapter III.

I.2.2. Modularisation & Standardisation

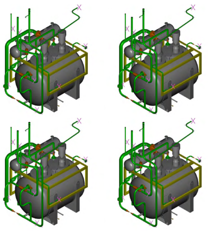
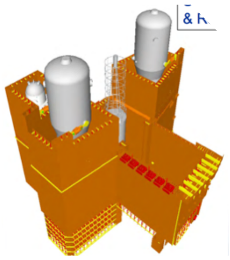
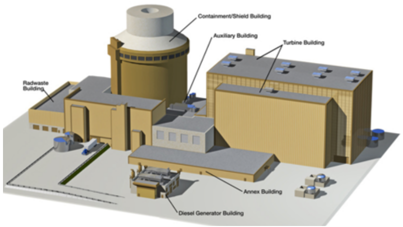
Modular construction seeks to transfer complicated, time-consuming work from the NPP construction site to a factory where better tools and conditions can be provided with improved productivity and higher learning rates [5]. Factory build is practical only if modules are readily transportable, standardised, highly repeatable, and produced in relatively large quantities [1]. Modular build is used in a number of different sectors including: civil construction; shipbuilding; chemical process and oil & gas; aerospace; automotive industries and to some extent the large nuclear sector.

Chapter II discusses the specifics of modular construction principles and best-practices.

Shifting construction work off-site can reduce both build time and cost through productivity improvements, as already evidenced in other modular industries. Material savings tend to be moderate but labour savings can be extensive, because site labour is more expensive and tasks are more time consuming than an equivalent amount of factory work [21]. The three options for construction location are shown in Table I.2. Construction can take place at the nuclear site (*in-situ*), in an on-site shop or assembly area, and/or in an off-site factory. This is analogous to modularisation experience from the shipbuilding industry, where construction activities can be performed in either a remote factory, at the dry-dock, or inside the ship's hull. The relative productivity for a task performed at one of these three locations, in terms of hours of construction, is often assumed to follow the 1-3-8 rule-of-thumb, where a task that takes 8 hours *in-situ* is expected to take 3 hours at the dry-dock (or in an on-site shop) and only 1 hour in an off-site factory [22].

Conventional construction provides the reference case for this project: where raw materials are shipped to the NPP site, construction work is completed *in-situ*, and only highly specialised components such as the reactor pressure vessel (RPV) and steam generators are brought complete to site. The modular construction strategy used throughout this dissertation employs a fully off-site factory or supplier that is located at some distance from the nuclear build site. Modules, components, and equipment items are assumed to arrive at the NPP site just-in-time, complete, and ready for installation and assembly. An off-site factory can be fully equipped to maximise productivity and to allow completion of highly complex, precision construction tasks. The off-site factory capabilities can vary from a relatively simple shed suitable for construction of basic structural elements (e.g. Forterra's Bison precast concrete facility [23]) to a fully outfitted module factory capable of manufacturing specialised components to high tolerances (e.g. Laing O'Rourke's Explore Industrial Park [24]).

Table I.2. Features of off-site factory, on-site shop, and *in-situ* construction locations.

Construction Location	**Off-Site Factory (or supplier)**	**On-Site Shop**	***In-situ***
Final Product	Modules, Components, Equipment 	Super-modules 	Final NPP 
Productivity (Relative Time)	High (1 hour)	Moderate (3 hours)	Low (8 hours)
Transport Options	Road and/or rail Maybe barge, air	Derrick crane Barge	N/A
Manufacturing Capabilities	Many	Limited	N/A

There is, however, an intermediate approach similar to that adopted by Westinghouse for their AP1000 and SMR designs, which does not adopt a full off-site modularisation strategy but instead uses largely on-site modularisation to enable parallel construction. A few difficult-to-transport super-modules are manufactured at an on-site module shop (Module Assembly Building) that is a large, simple shed that provides a protected work space for construction activities [25] [26]. Super-modules are too large for transport on public roads and are sized based on lifting limitations [27] and placed using an on-site heavy-lift derrick crane [28] [29]. In a set of comprehensive studies on the Westinghouse SMR construction methodology [27] [30] [31] [32], Maronati et al. applies the 1-3-8 rule from shipbuilding [22] to NPP construction to predict the TCIC of SMRs constructed under various scenarios.

I.2.3. Production Learning

Production learning cost reductions are observed in many manufacturing sectors. The Wright learning relationship [33], developed in the aeronautical industry, is based on the observation that a product's unit cost decreases as experience is gained by the manufacturer. Learning in this dissertation is represented as a percent reduction in unit cost relative to the number of times the production quantity doubles. While learning benefits are continuous, their returns are diminishing. The impact of learning on SMR cost is estimated and discussed further in Chapter VI Section VI.2.4.

Learning rates vary with local costs, the intensity of research and development during a given time period, and differences in performance measures. McDonald & Schrattenholzer [34] present a comprehensive study of learning rates observations for NPPs, coal-fired power stations, gas turbines, solar photovoltaic modules, and other energy-related technologies. They find that NPP unit construction costs decrease by only 6% per doubling of the production quantity; this is well below the 18%-25% learning rates in other industries [34] and supports the argument that LRs are too complex, too varied in design, and have been constructed too slowly to achieve significant learning.

Lovering et al. [7] investigate historical learning rates in large nuclear programmes over a very long period of time and from a global perspective, observing and comparing the total percentage change in nuclear OCC across various countries in the West (US, Canada, Germany, France) and in Asia (India, Japan, and the Republic of Korea). While mean nuclear OCC has increased in the West, the nuclear programmes in the Republic of Korea have realised a 25% decrease in average OCC. The success of the Korean programme can be attributed to a consistent commitment to new reactor build projects, a coordinated supply-chain, and explicit use of modularisation and DfMA [5]. The French nuclear build programme is another example of a large-scale, rapid deployment of nuclear reactors: 50 GWe of civil nuclear power were installed between 1980 and 1990. France did not achieve the full programmatic benefits of this large-scale programme due to labour management issues, increased regulatory activity and more stringent requirements, and increasing technological complexity [7].

Chen et al. [35] investigate learning in relation to the manufacture of 100 MWe PWR SMR Integrated Reactor Vessel (IRV) modules by using material, labour, tooling, and fabrication cost inputs to simulate the net cost of producing a series of IRV modules. Chen et al. identify two factors that can influence the learning process. Firstly, knowledge transfer from the nuclear and other, similar, energy industries can create initial learning-related cost reductions. Secondly, for components with low knowledge transfer, it is the lot size (the number of identical units that are produced before the factory is re-tooled) that governs the learning-related savings. Chen et al. estimate that producing the SMR IRV in lots of 5 will optimise learning cost reductions against the cost of retooling the factory and could achieve learning rates of 7% in the factory.

I.2.4. SMR Design

There are three ways SMR designs can specifically take advantage of their small size to reduce the capital cost of nuclear power.

i. Design Simplification

Passive safety systems and inherently safe design strategies are applied to proven LWR technologies, reducing the complexity of engineered safety systems and requiring a smaller, less expensive, containment (in total). The concept initiated with the International Reactor Innovative and Secure (IRIS) design; current examples include mPower, System Integrated Modular Advanced ReacTor (SMART), and NuScale.

A Westinghouse study compared the construction of four passive SMRs against one AP1000 but did not find that there was a compelling economic case for the SMRs; the pack of four SMRs had a capital cost that was 5% higher than the LR [36]. This has hindered the development of a number of passive SMRs and the only design that is currently being developed as a prototype is NuScale, in the US.

ii. New Construction Methods

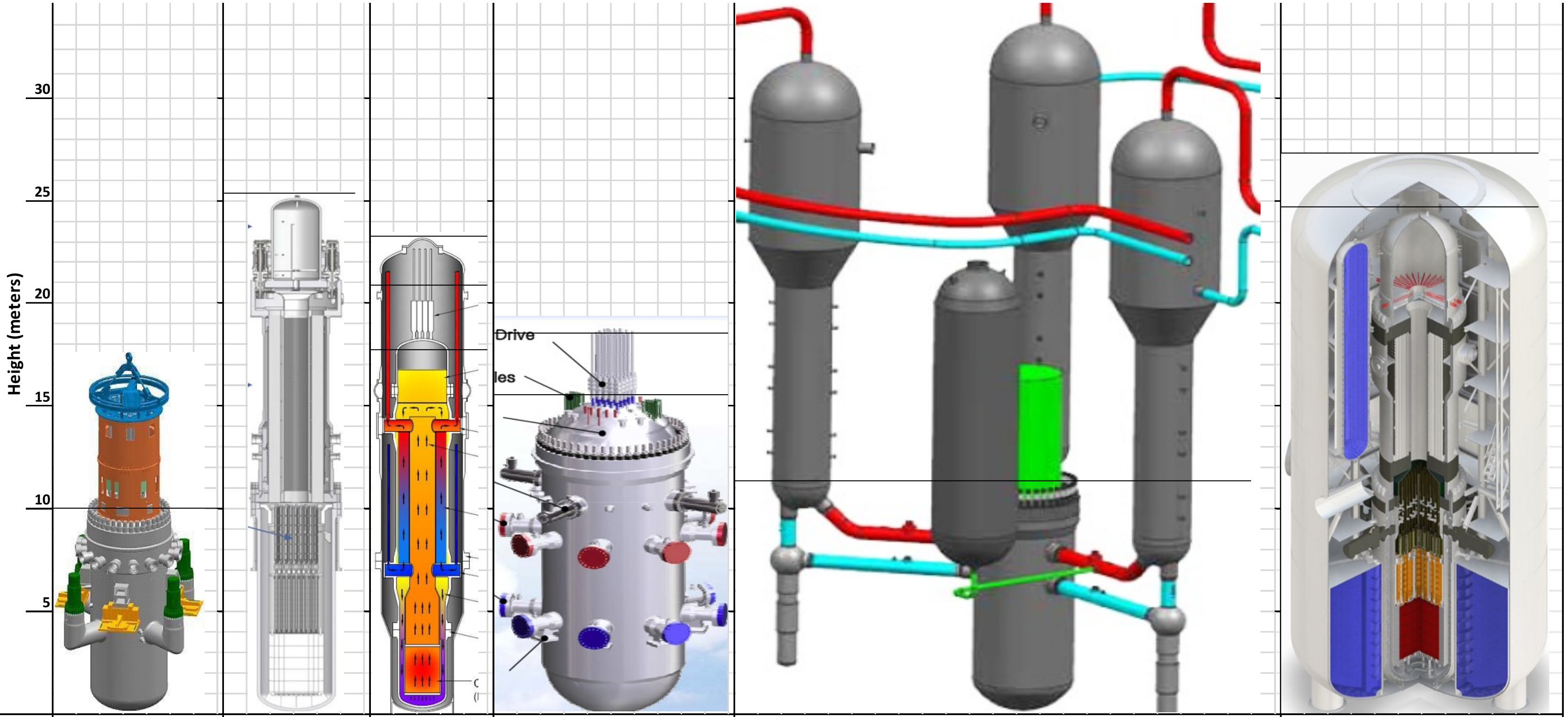
Production methods in the nuclear industry have not changed with methodological or technological advancements in the construction industry and new PWR NPP projects, such as the AP1000, still tend to adopt a one-off, stick-build approach to construction. This is particularly costly when many reactors are built on a case-by-case basis, as seen over the past decades in the US. SMRs attempt to cut the construction costs of nuclear by implementing new construction methods, including extensive modularisation, automated construction processes, and Building Information Modelling (BIM) technologies.

This project focusses on modularisation as a new construction method for LWR SMRs. LWRs are chosen for the focus of this work both because the majority of construction experience is with LWRs and also because the technology is mature enough for manufacturing and construction studies to be useful.

iii. Advanced Reactor Technology

Advanced reactors use higher temperature and different coolants to achieve higher thermal efficiencies and safety benefits. High temperature gas-cooled reactors, for example, have a ceramic fuel that can withstand higher temperatures in case of an accident and small gas-cooled reactors can in theory cool themselves after an incident. Alternative coolants, such as liquid metals, have high boiling points and operate at low pressure, eliminating the need for pressurised systems and vessels.

SMRs based on advanced reactor technology tend to be backed privately. Some prototypes may be developed in the US in the near future and, although the technology-readiness-levels of advanced reactors is currently low, they may be candidates for modular build when they reach a more mature stage of development. Small nuclear reactors have been used in niche applications for many years, either for research or to provide propulsion for submarines, aircraft carriers, and icebreakers. Using SMRs for civil power generation is, however, a relatively recent application of the technology and a full-scale, land-based, PWR SMR for civil use has yet to be constructed and commissioned. The IAEA lists 56 SMR design concepts [37] that are currently under development, all of which are based on existing or proposed large reactor technology and which include LWRs, high temperature gas-cooled reactors, liquid-metal cooled fast reactors, and molten salt reactors. 20 of these are land-based water-cooled SMR designs [37]. Six LWR SMRs, included based on the maturity of the SMR design concept and/or access to design information, are shown in Figure I.3 and described in Table I.3. Reference diagrams are in Appendix I.3.



Reactor	ACP100	Generation mPower	NuScale	SMART	UK SMR	Westinghouse SMR
Vendor	CNNC (China)	B&W (US)	NuScale Power (US)	KAERI (Republic of Korea)	Rolls-Royce (UK)	Westinghouse Electric Co (US)
Unit Power	100 MWe (310 MWth)	195 MWe (575 MWth)	45 MWe (160 MWth)	100 MWe (330 MWth)	400-450 Mwe (1200-1350 MWth)	>225 MWe (800 MWth)
Height						
RPV	10 m + CRDM	27.5 m	20.9 m	15.5 m + CRDM = 18.5 m	11.3 m + CRDM	24.7 m
Containment			23.2 m			27.1 m
Diameter						
RPV	3.2 m (inner diam)	4.1 m	2.8 m	6.5 m	4.5 m	3.7 m
Containment			4.6 m			9.7 m
Weight (RPV only)		688 tonnes	~ 635 tonnes			

Figure I.3. Summary of PWR SMR designs, with vendor and country of origin, rated power output, and weight/dimensions (as available). The relative sizes (height and width) of the SMR diagrams are to scale, assuming the dimensions within each vendor-generated diagram are to scale.

Table I.3. Summary of SMR designs listing vendor and country of origin, design status, and notes on SMR design features and philosophies specific to layout, configuration, construction. Development of the Generation mPower SMR is cancelled/on-hold (as of 2017) because of financial difficulty [38]. A 1/3rd scale prototype of the NuScale SMR has been constructed in Oregon, USA, and is currently undergoing testing and simulation [39].

SMR Design	**Vendor/Designer**	**Country**	**Design Status**	**Notes**
ACP100 [37]	China National Nuclear Corporation	China	Detailed design	Integral reactor pressure vessel (RPV) containing all primary loop components except the pressuriser Normal coolant flow is forced (active), emergency cooling is passive Multiple units can be placed at a single site but in separate containment buildings Underground containment philosophy
Generation mPower [40]	Babcock & Wilcox	US	Basic design (cancelled/on-hold)	Integral RPV containing all primary loop components Normal coolant flow is forced (active), emergency cooling is passive Multiple units can be placed at a single site but in separate containment buildings Underground containment philosophy
NuScale [41]	NuScale Power	US	Prototype construction & testing	Integral RPV containing all primary loop components Natural convection supplies normal and emergency cooling Multiple units are placed within a single large reactor pool and containment
SMART [37]	Korea Atomic Energy Research Institute	Republic of Korea	Licensed/certified	Integral RPV containing all primary loop components Normal coolant flow is forced (active), emergency cooling is passive Single or twin units can be placed on a site, with segregated containment
UK SMR [42] [43]	Rolls-Royce	UK	Concept	Dispersed RPV – all primary loop components are external to the reactor vessel Normal coolant flow is forced (active), emergency cooling is passive Design is for a single power unit per plant/site
Westinghouse SMR [28]	Westinghouse Electric Company	US	Preliminary design complete [11]	Integral RPV containing all primary loop components Normal coolant flow is forced (active), emergency cooling is passive Multiple units can share a site but are placed in separate containment buildings

I.3. Proposed Research Project

I.3.1. Research Question & Objectives

This dissertation establishes a framework that systematically investigates modularisation as a construction technique for NPPs, reducing their traditional long build times and high construction costs and showing that SMRs are uniquely able, because of their smaller size, to leverage the benefits of off-site fabrication. The purpose of this dissertation can be summarised by the project Research Question and Research Objectives.

Research Question

What are effective modularisation principles and practices, how can they be applied to SMR construction, and what are the implications for build time and capital cost?

Research Objectives

Identify means and constraints of reducing the long build times and high cost of NPP construction by using modularisation and taking advantage of SMR specific features and characteristics.

Highlight particular areas of focus and/or practices that need to change in nuclear construction programmes to make DfMA feasible for SMRs.

Identify any barriers to implementation of these modular principles and practices and, if possible, present strategies for overcoming these barriers.

I.3.2. Research Motivation

I.3.2.1. Academic Significance

The first main academic contribution of this project is to fill the knowledge gap on modularisation as a construction strategy for NPPs – something that is often proposed in industry and literature, but rarely studied – and identify the main and limiting constraints. A manufacturing (DfMA) framework is applied to NPP construction, based on an extensive literature study of current modularisation best-practices, both within the nuclear industry and in other industries where modularisation has already been adopted. This thesis finds that the primary constraint on module characteristics is module transportability. The relationship between reactor size and module transport directly affects the scope to which modularisation can be applied to the NPP and determines the magnitude of schedule and cost savings. This project makes this critical link between module transport and NPP size explicit, quantifying it in terms of a power plant's attainable modularity. This is a new concept for modular construction and one that is widely applicable and relevant to further work on build schedule and cost.

The second main academic contribution of this project is the scheduling work. While the long build time of NPPs is often regarded as the main driver of high cost and project difficulties, there is little academic work pertaining to NPP build schedule, and the studies that are available on NPP lead times lack detail. This project makes the link between NPP modularity and build time explicit, and develops a detailed model to estimate NPP schedule. The outputs of this model are useful in terms of quantifying task durations, the impact of modularisation, and the overall schedule critical path. Moreover, the logic that is used to develop this model is unique and is useful in filling the current existing knowledge gap as regards NPP schedule details. The project extends this work by applying modularisation to the build activities, coupling the detailed existing build schedule data with the constraints on modularity, to investigate how the build times and schedule critical path changes with both reactor size and scope of modularisation.

Additionally, this dissertation contributes to the general body of academic knowledge by linking the new knowledge from this project (transport constraints and scheduling) with existing knowledge (top-down cost estimating), placing the whole in the context of modularisation principles and best-practice. While NPP costs, and the associated issues, have been widely researched by existing literature, they have not been explicitly linked to modularisation and scheduling in the manner of this project. This project also relates the findings of this project to modularisation theory/principles as well as industry best-practices, thereby ensuring that the results from the main contributions are grounded in reality, useful, and achievable.

One drawback of this thesis project is that there is currently no way to explicitly validate and test the accuracy of the methodologies, models, and/or results developed in this thesis, since this would require construction data from a real, land-based PWR SMR project of the general type assumed in this dissertation. However, the findings in this thesis are implicitly validated where possible: through calibration of certain steps in the methodology with literature (e.g. using work by Berthélemy et al. [44] to select parameters for this dissertation's baseline scheduling model); through comparison of results with other literature sources, as appropriate and wherever possible (in charts, figures, or as marked in the text); and through soliciting expert opinion and advice on the results from the models (particular thanks to Nia Swann Bowden [45] for feedback on the transport model, Bill Carruthers for feedback on the scheduling model [46] [47], and Tony Roulstone for feedback on the cost model). Taken together, these means of implicit validation serve to increase confidence that the methods presented here provide reasonable estimates for construction cost and build time, and the uncertainty analysis performed for each model (Chapter VII) serves to demonstrate the robustness and resilience of these models to perturbations and uncertainty in the assumed parameters.

I.3.2.2. Relevance to Industry & Policy-Makers

This dissertation has not only academic value but is also relevant to the civil nuclear industry. The work presented in this project can guide SMR designers and/or vendors when applying DfMA principles to a specific SMR design, allowing them to determine the level of modularisation that should be incorporated into the design to achieve the desired reduction in construction cost and build time. It can also provide further information on how modularisation might be effectively integrated into an NPP construction strategy. This dissertation can help focus design efforts by identifying the areas in SMR design and manufacture that are critical and need extra design attention either because of their logistics (modularisation potential), schedule (critical path) and cost (high costs and/or low benefit).

This work also gives some context for what DfMA of SMRs would look like and identifies a few possible solutions for modules that are used in other applications or are proposed and being tested for application in nuclear. Finally, this work might be used to assist policy-makers define how a modular SMR programme could be rolled out, and what measures need to be taken to support the initiative, particularly from a logistic/transportation perspective, and can be used to build up the case – ‘selling point’ – for SMRs over LRs on a logistic, cost, and schedule basis.

I.3.3. Research Scope

I.3.3.1. Definitions & Terminology

These terms and concepts are key to fully understanding and developing the theory and models used throughout this project and are used frequently throughout this dissertation. The definitions included in this section are the author’s own in terms of both wording and interpretation, except in specific cases (as referenced). There is rarely a single, authoritative source that defines these terms; instead, the definitions listed below have been distilled from an extensive review of academic journals, industry reports, and papers on modularisation theory and practice. Some sources that were useful in developing this understanding of modular construction are in [48] [49] [50] [51] [52] [53].

Manufacturing & Construction Terms

Stick-Built Construction (interchangeable with conventional construction) refers to building a final product by assembling construction materials *in-situ* according to traditional construction methods.

Modular Construction, **Modular Build**, or **Prefabrication**, is a construction process by which various materials, prefabricated components, and/or equipment items are joined together in a specialised production facility for subsequent installation as a sub-unit or module. The production facility is located in a place other than the final point of installation and could be an on-site shop, a purpose-built SMR module factory, or a supplier’s production facilities.

Lean Manufacturing refers to a set of techniques by which the manufacturing sector can evaluate their construction processes and identify high-value streams, process inefficiencies, and areas of waste, with the overall objective of providing customers with the required product while minimising input effort [54].

Just-in-time Delivery, a concept that originated with Toyota in Japan, refers to minimising and eliminating waste by producing only "what is needed, when it is needed, at every stage of production" [55]. Components and parts are supplied to the construction process at the same rate at which they are used or installed.

Design for Manufacture and Assembly (also: Design for Manufacture) is used by the manufacturing industry to reduce total production time by focussing on the "ease of manufacture for the product's parts and the simplified assembly of those parts into the final product" [56].

Construction location refers to the physical and geographical location at which fabrication, assembly, testing, inspection, and/or commissioning tasks take place; this can be either:

- ***In-situ*** (interchangeable with on-site): the final operating location of the product.
    - **Nuclear Island** (NI), all nuclear-related equipment and processes.
    - **Balance of Plant** (BoP), remaining non-nuclear systems and processes.
- **Module Production Facility**
    - **On-Site Shop** (interchangeable with module assembly building, on-site preassembly area) is a production facility that is located a short distance from the final operating location. Transport of modules and/or super-modules is accomplished using cranes or special crawler trucks.
    - **Off-Site Factory** is a production facility that is located at some distance from the final operating location. Transport of components, modules, and/or super-modules is accomplished using rail, road, water, and/or air.

Modularisation Terms

Physical elements are the entities that are combined together to form a product and implement the product's functions. Physical elements can be raw materials, parts or components, equipment items, modules, or super-modules.

- **Module** refers to a major section of plant or structure, usually the largest readily transportable unit of a facility that is the result of a series of remote assembly operations. It may include portions of many systems and can be fabricated in an on-site shop or an off-site facility.
- **Super-Module** refers to a group of modules that are assembled in an on-site shop and significantly exceed normal road and rail transport limits.
- **Module Interface** (interchangeable with module joint) is the point at which modules connect with one another and the rest of the product.

Product refers to the overall item built out of physical elements; this could be a ship or an automobile, an electronic hardware item such as a smartphone, an oil and gas treatment plant, or a SMR.

Product Platform refers to the set of physical elements from which a number of customised products can be configured.

Product Architecture is how the product is broken down and organised into parts; this can focus on either functional and/or physical breakdown.

- **Integral Architecture** is when product functionality is implemented using multiple physical elements and/or modules. There is interaction between physical and functional elements and the product tends to have a less-structured layout.
  An example is a conventionally-built brick home.
- **Modular Architecture** is when product functionality is allocated to and implemented by separate modules which are brought together to form the final product. The product tends to be well-organised and highly structured.
  An example is a mass-produced automobile.

Modularisation is the design process by which *in-situ* work is organised into modules. These modules are essentially discrete packages of site time or cost that are moved off-site and are thereby introduced to a range of off-site build benefits.

Modularisation Scheme refers to the combination of objective design criteria, objectives, rules, and constraints that define a set of module characteristics (geometry, weight, material, etc.) dictating how physical elements can and cannot be grouped to form modules.

Degree of Modularisation (DoM) refers to the fraction of work, which can be taken on a weight, time, or cost basis, that is moved from the *in-situ* construction location into either an on-site shop or an off-site factory. DoM is usually calculated and applied at the 2-digit Economic Modelling Working Group (EMWG) Code of Accounts (COA) level.
The DoM for a NPP can, in theory, vary between 0.0 (no modularisation) and 1.0 (full modularisation); however, there is a practical upper limit on DoM, called DoM_{max}, for each reactor power. DoM_{max} is set by the the maximum fraction of transportable modules, by weight, according to the work presented in Chapter IV and is a function of the modularisation scheme and transport constraints.

Effective Modularisation ($\mathbf{M_{eff}}$) refers to the work content contained in modules divided by the total work content of a conventional stick-built NPP, and can be calculated on a time or cost basis, shown in Equation I.1 below. This gives the net fraction of time or cost that is moved from the NI and BoP and into a module production facility.

$$\mathrm{M_{eff}} = \frac{\text{Net Construction [Time | Cost]}_{\text{Modular NPP @ DoM}}}{\text{Net Construction [Time | Cost]}_{\text{Stick-Built NPP}}}$$

Equation I.1. $\mathrm{M_{eff}}$ calculation based on net reactor build times or construction cost.

Transportation Terms

Transportable weight fraction refers to the weight of modules that can be feasibly transported relative to the total weight of all modules, both transportable and non-

transportable. The granularity at which this fraction is determined can be changed based on whether modules are grouped by type, location, or both type + location. Note that 'feasibly transportable' is nominally taken to mean Transport Envelope 1 and Transport Envelope 2; however, an extended definition of this may include a percentage (by weight) of Transport Envelope 3 modules.
The transportable weight fraction of a modularisation scheme is very important because this equals the maximum DoM. It is used in subsequent calculations to as the maximum fraction of work that can be moved from the NPP site to an off-site factory.

Module Division Factor (MDF) refers to the maximum number of times the width, height, and/or length of a module can be divided. This allows further subdivision of a module to make it easier to transport. The characteristics of the net module (total weight, dimensions, and design) remain unchanged; MDF is simply used to determine the number and weight of sub-modules.
Note that the MDF is used to give an upper limit on the number of subdivisions that are permitted per dimension: if feasibly transportable modules can be formed with fewer subdivisions, this smaller number is used to avoid unnecessarily dividing modules and to attempt to balance the trade-off between module subdivision and transportability.

Build Schedule Terms

Project Duration, **Build Time**, or **Construction Duration** is the amount of time spent on-site constructing the NPP and is calculated as the difference (in months or years) between the first pour of structural concrete (FPSC) and the date on which the NPP begins commercial operation. This is consistent with the definition of construction duration, sometimes called lead time, established by the IAEA and used in literature [20] [44].

Construction Activities refers to the individual tasks that are required to build the NPP. Each construction activity is broken into **task time** and **wait time** components, inferred from the inter-dependency of activities based on task connectivity, as in Section V.2.2.1.

- **Task Time (T)** is the amount of on-site time that is spent performing a specific, added-value construction task; for example, building formwork, pouring concrete, fixing steel rebar, installing and assembling equipment items, or welding.
- **Wait Time (W)** is the amount of time spent on-site before a specific construction task begins. This time is non-added value and can be composed of one or more of the following types:
    - **Enforced wait time** is time spent waiting for a specific construction task to be at a certain stage of completion before the subsequent task can begin; for example, concrete curing, waiting for structures to be completed before installing equipment, or waiting for essential equipment and/or personnel to become available from a prior task.
    - **Inspection-based wait time** is required for testing and commissioning of systems and structures after their construction is complete. Only final plant commissioning activities are explicitly included in the original reference schedule data.
    - **Inefficient wait time** is non-value-added on-site time; for example, process inefficiencies or re-work.

Construction Cost Terms

Code of Accounts (COA) is a standardised cost-structuring system for nuclear power plant costs. This structuring system is explained in detail by the Energy Economics DataBase (EEDB) [57] and is used throughout this dissertation in order to maintain consistency with literature and academic work. The COA breakdown, by heading, is provided in Appendix III.1 to a 3-digit level of detail. Assigning NPP construction costs to the various COA headings can vary slightly, depending on the source that is used. The terms as defined and used in this thesis are consistent with the EEDB usage [57].

Direct Costs are the costs associated with constructing the NPP's physical elements either *in-situ* or off-site: structures; components; equipment items; mechanical, electrical, and piping systems; and so on. Direct costs are reported for each of the 3-digit account headings as follows:

- **Factory Equipment** refers to NPP elements that are already produced in a factory, even in stick built plants (e.g. the nuclear steam-supply system (NSSS) in Account 220a, or the turbine generators).
- **Site Material** refers to the materials that are used for *in-situ* construction of the NPP structures, systems, and/or components.
- **Site Labour** is all labour that is performed *in-situ* and is directly related to assembling site materials. This includes any *in-situ* labour involved with assembling and/or joining of prefabricated modules.
  Site labour does not include any indirect labour activities such as testing, supervision, design work, etc.

Indirect Costs are incurred within the indirect services (overheads) and indirect labour (engineering and design work, field supervisions, testing and inspection of systems, etc.) categories. They pertain to the cost of the work that is necessary to support and enable direct work activities.

Overnight Capital Cost (OCC) gives the cost of building a power plant as if the construction cost occurred at one time and there were no interest or inflation costs during the construction project. OCC is calculated as per Equation I.2.

Total Capital Investment Cost (TCIC) is also used to estimate and compare NPP construction costs and adds the interest costs incurred during construction period to the OCC to give the net present value of all funds that must be invested in the project.

Levelised Cost of Electricity (LCOE) captures the net present value of the construction, ongoing (operation, maintenance, fuel), and decommissioning costs of the plant and spreads them over the lifetime of the power plant.
LCOE is not widely reported in this project since it also depends on local factors relevant to the markets in which the NPPs operate. TCIC is a good indicator of the energy cost for a specific market since it correlates well with LCOE in cases where fuel and O&M costs are fixed. The target TCIC for SMRs is $4,400/kWe, which corresponds to an LCOE of about $80/MWh, and which would allow SMRs to compete with LRs and other low carbon energy technologies [1].

Direct Costs = Factory Equipment + Site Labour + Site Material
+ Indirect Costs = Indirect Labour + Indirect Services
Base Construction Costs
+ Owner's Costs = 10% Base Construction Costs (as per [58])
+ Contingency = 15% (Base Construction + Owner's) (as per [58])
Overnight Capital Cost

Equation I.2. Overnight Capital Cost (OCC) equation.

I.3.3.2. Assumptions & Hypotheses

This section presents the major assumptions on which the scope of this research and modelling in this thesis is based.

Establishing a Reference/Baseline SMR Case

i. PWR Nuclear Reactor Technology

Only pressurised light-water cooled, land-based, civil nuclear power generation technologies are considered in this project. The majority of operational civil nuclear reactors are large PWRs and, since LWR technology is well understood, they are the most feasible systems for near-term deployment. Additionally, the available construction, operational, and economic data can be extrapolated from large to small PWR systems.

ii. NPP Design & Constructability

This project assumes that any design differences between different sizes of NPP units are small and do not affect construction cost. The plant layout, reactor technology (PWR), safety philosophy and systems, number of major equipment items, and auxiliary building design, purposes, and contents are assumed to be substantially the same between large and small units. Units are equally constructible and use the same manufacturing and construction processes irrespective of their size.

iii. Nth-of-a-Kind (NOAK) & First-of-a-Kind (FOAK) Costs

NOAK costs are those costs incurred by the first of series of similar or identical reactors and NPPs. FOAK costs include some additional licensing, development, and supply chain costs and the associated uncertainty and, once incurred, do not need to be paid again by subsequent similar projects (NOAK). This project focusses on cost and schedule estimates of NOAK plants only, because baseline schedule and cost data are derived from NOAK plants, as in [57]. Additionally, production and modularisation estimates are concerned with series costs (NOAK) rather than initial development costs (FOAK).

Rosner & Goldberg [59] estimate that the Overnight Capital Cost (OCC) for a NOAK SMR will be 60% of the FOAK OCC because only the first project bears development and design costs, Generic Design Assessment (GDA) fees, and so on.

iv. Scope for Modularisation in SMRs

This dissertation assumes the scope for modularisation is the same in LRs and SMRs. In practice, SMRs may have greater scope for modularisation than large reactors because they have smaller components and may allow for more compact arrangements. The Stone & Webster (S&W) modularisation scheme, which is used as the reference module breakdown for a 950 MWe Westinghouse PWR (as per [60] and described in Section II.4.4) and is scaled to account for differences in reactor sizes, may underestimate the full modularisation potential of SMRs.

Modelling Modularisation, Build Time, & Construction Cost

i. Power Scaling Rule

Top-down power scaling estimation methods are used in this dissertation and, as a result, the scaling rule must be extended beyond its original cost-power application and applied to module weights, scaling LR module sizes to equivalent SMR sizes, and module build times, where LR tasks are scaled to SMR durations. This hypothesis is supported by literature studies (as referenced below) and assumes that scaling holds true at the individual module, task, or cost category level even though other factors might mask its effect on the aggregate cost of the NPP.

- **Weight-Power Scaling (Chapter IV):** assumes that the weight of input material scales in proportion to the NPP capacity. Materials are scaled by commodity type according to the exponents in Table III.1; this method assumes that a commodity's weight and cost are linked.

  Construction costing uses bills of quantities, such as volume or weight, and this method uses cost as an indicator of weight in a similar manner. This approach is also consistent with work by Parra & Bono [61] who state that module weight is directly proportional to module cost, and is also consistent with work by Peterson et al. [62] who use cost scaling exponents to estimate material input quantities for a study comparing the 1520 MWe S-PRISM reactor and the 760 MWe Advanced High-Temperature Reactor [63].

- **Schedule-Power Scaling (Chapter V):** assumes the time to construct a commodity at the NPP facility is proportional to NPP power. Tasks are scaled by type and work area using the exponents in Table III.1, assuming that commodity cost and task time are affected by scaling in the same manner. The model in Chapter V develops a modified scaling law to account for the fact that some construction time depends on the size of the item (e.g. fixing rebar or pouring concrete) while the remaining duration is independent of the reactor size (e.g. testing and commissioning activities). This approach compares the modified scaling model to historical NPP construction data and calibrates the results against the lead-time parametric model in Berthélemy et al. [44].
- **Cost-Power Scaling (Chapter VI):** applies the 2-digit cost scaling exponents in Table III.1 to the 3-digit cost data in the EEDB Phase IX report [57] across the factory equipment, site material, and site labour headings in each 3-digit category.

ii. Progressive NPP Modularisation

This thesis assumes that it is feasible to modularise different structures and components of the NPP independently of other systems and structures, the construction strategy, and the reactor power. This means it is possible to investigate the contribution of different commodities to an overall modularised schedule; to help visualise this, four progressive modularisation scenarios are established in Table I.4. Initially, none of the NPP systems, structures, equipment, or components are modularised; this case corresponds to construction of a stick-built reference reactor. Modularisation of the various NPP components is then considered sequentially, beginning with the M&E systems, piping runs, and equipment items, which are relatively easy to modularise (low modularisation), then adding in liner and structural element modularisation (medium modularisation), and finally modularising finishes and façade components (full modularisation), which is in line with best practice in the ship-building industry. Structural elements are relatively difficult to modularise, compared with M&E and piping systems, because their typically excessive size and/or weight require additional design effort in order to meet transport constraints (discussed further in Chapter IV).

Site preparation activities, including yardwork, excavation, and backfill, are not modularised in any scenario since these tasks are highly site-specific. Similarly, commissioning tasks are not modularised, since whole-plant testing will always be required once the NPP is complete, regardless of the amount of pre-testing that is performed in the module factory.

Table I.4. The four different progressive modularisation scenarios.

	M&E, Piping, Equipment	**Liners**	**Structures**	**Finishes**
NONE				
LOW	√			
MED	√	√	√	
FULL	√	√	√	√

iii. Testing & Commissioning

This project assumes that all inspection, testing, and commissioning activities for individual systems, equipment, and processes are included in the construction activities listed in the original schedule, are performed on-site, and are unaffected by modularisation. Final plant testing and commissioning is allocated its own task time. This is a conservative assumption: improved construction practices (in the case of a programme of identical SMRs) can be expected to extend to including some testing and commissioning work in the module factory, further reducing *in-situ* time.

iv. Working Week

For developing the project Gantt Charts included in Appendix V, work week hours are defined as 0800-1200 and 1300-1700, Monday through Sunday inclusive. Actual construction labour hours may differ from this, depending on the time of year, stage of construction, labour contracts, and so on; however, this definition is used throughout the project for simplicity and to provide consistent comparison between schedules.

In practice, the build programme at Sizewell B used a range of shift systems, depending on the stage of the project, to increase the available working hours. For example, M&E fabrication and installation occasionally used a a ‘double day shift’, giving up to 16 labour hours per day; alternatively, preparatory plant work used a night shift to increase work time [46].

v. Ignore Ongoing Costs

Ongoing costs are assumed to be unaffected by modularisation. This allows O&M, fuel, and decommissioning costs to be removed from the analysis and focusses the modelling work on construction costs alone.

Data Representativeness

i. Incomplete Module Data Set

Although the breakdown of a nuclear power plant into modules from Stone & Webster corporation [60] is the most extensive modularisation scheme available for a NPP to date, it still does not consider modularisation of all locations, structures, and components within the nuclear facility. The transportable fraction of modules is, therefore, based on a subset of the entire NPP. This work assumes that the S&W modules are representative of a modularisation scheme that could be extended and applied to the entire NPP and is illustrated diagrammatically in Figure I.4. This assumption is of particular importance when the Degree of Modularisation (DoM) which, by definition represents the modularisable proportion of the whole plant, is applied to the entire NPP.

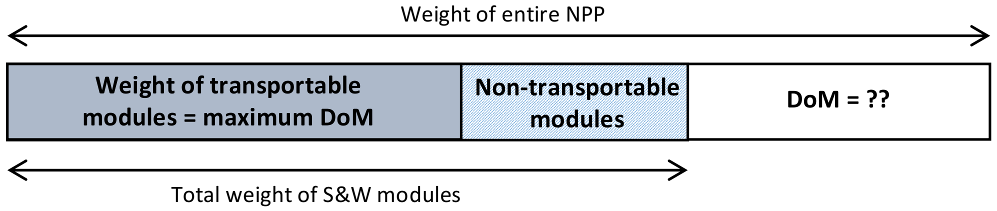


Figure I.4. Illustration of how DoM relates to net module weight and total NPP weight.

In addition, not all the modules are fully characterised in the S&W report; in particular, there is one set of fuel pit liner modules that does not have weights listed.

In these cases, the missing weights were inferred, using ‘worst case’ logic based on fully characterised modules that belong in the same location and are of the same type.

ii. Incomplete Scheduling Data Set

The schedule reference data from Sizewell B power station are not complete. Some buildings and components, most notably the electric plant and installation of cabling, wiring, safety systems, and so on, are excluded from the scheduling data. It is assumed that these structures and/or components have no significant influence on the critical path and will not limit either the stick-built construction schedule or the modularised schedule.

iii. No Location Factors

This project assumes that construction costs in the US are representative of UK construction costs. The ETI’s Nuclear Cost Drivers report indicates that conventional construction cost experience is similar in Europe and North America, and is significantly higher than the experience in the rest of the world [15]. A detailed analysis of location-related effects and the consequence for construction costs is outside the scope of this project, but it is possible to adjust for NPP location differences within a country as well as between countries using appropriate location-specific parameters (e.g. Berthélemy et al. [44]).

Module Factory & Transport to Site

i. Location of the Module Factory

This dissertation assumes that NPP module production occurs in off-site factories that are capable of producing sets of modules at the volumes and times required. Modules are therefore proposed based on functionality and transport constraints rather than production method constraints. This project assumes module production is fully off-site, employing a true manufacturing, series-production approach such as is used in other modular industries (automotive, aerospace, chemical process, shipbuilding).

Investigating an intermediate solution that uses a dedicated on-site shop, similar to the strategy adopted by Westinghouse for AP1000 or Hitachi for the Advanced Boiling Water Reactor (ABWR), falls outside the scope of this project. It also seems unlikely that, for a single design, modules will all be made in a single off-site factory. Some proponents of modular-build SMRs are considering three types of module factory: primary systems, structures, and BoP. The design of the supply chain will be driven by the manufacturing economics and the volume of SMRs to be produced. Finally, the type of factory, and the type of manufacturing work it can perform, will dictate what DoM_{max} a reactor can achieve. A more detailed investigation of these issues is better suited to a study of the module factory characteristics as they pertain to its location as well as capacity and capabilities, and as such are outside the scope of this project.

ii. Factory Lead Times

This dissertation assumes that off-site lead times do not affect the on-site construction and assembly duration and that it does not matter, from an on-site scheduling point of view, what type of module production facility is used. It is reasonable to believe, based on experience in other modular industries that, with careful planning and project management, just-in-time module delivery can be achieved and module fabrication will have little impact on the *in-situ* critical path [46].

iii. Limitations on Factory Construction & Operation Costs

This thesis assumes that the module factory is an off-site ‘black box’ facility that produces the set of required modules as needed for each construction site. The factory costs associated with producing modules for each specific site is estimated as 200% of the module’s construction cost, as per guidance from the EMWG [64]. Any other factory-related costs that are not directly linked to module production are not included in this analysis; therefore, the costs related to factory construction, overhead operation and/or maintenance costs, supervision and staffing costs, are not included in the cost modelling presented in this Chapter.

It is, however, worth noting that this parameter is subjected to an uncertainty analysis in Chapter VII, which varies the overheads associated with factory-produced modules by ± 25%. The results of this uncertainty analysis indicate that the overnight construction cost is not highly sensitive to variations in other modular cost factors (see Figure VII.6 in Section VII.2.3, which deals with cost model uncertainty). It can therefore be inferred that factory costs have a negligible effect on construction costs and, while the topic of factory construction and configuration has intrinsic interest and would be worth a separate study, the impact of these issues can be safely and reasonably omitted from this cost model.

The reason for limiting the scope to which factory costs are included in the cost analysis is primarily that these costs are highly dependant on the nature of the module factory – its capability, its capacity, the rate of module throughput, and the nature of the supply chain configuration. Hypothesising the different types of module factory and supply chain configurations would warrant a project in its own right and, since this thesis is not able to treat the range of factory-related configuration and cost issues comprehensively and rigorously, they are all placed outside the scope of this thesis in the above-described 'black box' model. A possible approach on future work pertaining to coupled factory and transport costs is presented in Section VI.4.2, point ii (off-site costs: factory and transport).

iv. Nominal Transport & Freight Costs

Transport distances and freight charges are assumed to be nominal. This is consistent with the use of road transport for the proposed modules and is according to the modularisation guidelines set out by the EMWG report [64].

Wider Nuclear Construction Programme & Energy Policy Issues

i. Standardisation in Design & Construction

This dissertation assumes that only one design of SMR is built in a given programme and that there are no or only minor changes to the manufacturing line. As a result, learning can be applied continuously to each modularised component. In practice, however, changes to the SMR design arising from regulation or technological developments could mean that the factory will need periodic reconfiguring over the construction life cycle.

ii. Exclusion of Co-Generation Products

SMRs can be used to generate, in addition to electricity, district heating, desalination, or hydrogen products. The use of SMRs for CHP (combined heat & power) applications in the UK, and the economic case for CHP SMR plants is presented in detail in a report by the ETI [65]. While CHP applications can act as a bridge for SMRs to become accepted and economic for power generation purposes, they require significant additional local and national infrastructure developments and are outside the scope of this work.

iii. Location & Siting Effects

This project ignores possible siting constraints and site-specific cost effects on SMRs. The ETI indicates that there are many more sites available to SMRs than LRs, without changing the siting rules, because of their lower heat rejection requirements [65] [66]. SMR siting issues in the UK, therefore, are not of prime concern and are ignored. Some different siting arrangements and location/siting effects include:

- Locating multiple power units at a single site
  Site development costs, as well as some construction costs (e.g. cranes, equipment, temporary services and infrastructure) can be shared if multiple units are located at the same site, improving the installation and financing arrangements [9] [12]. The NuScale SMR design, for example, houses up to 12 power modules in a very large single building [41].
- Development of marine-based sites
  Russia and China are developing floating barges that carry SMRs to provide a transportable power source and increase the number of feasible SMR sites [67] [68].

Variability in geography and location, both between countries and within countries, may have socio-economic and/or political effects that impact labour rates, availability of materials and skilled labour, cost/time of site preparation work, transport logistics, procurement and supply chain organisation, and regulations and regulatory activity. Investigating these topics in detail is outside the scope of this project but discussion of these issues and their impact on NPP cost and build times is covered in more detail in literature (see Carelli et al. [12] and Berthélemy et al. [44]).

iv. Wider Energy Policy Conditions

These assumptions about energy policy and the full life-cycle of the NPP project help to focus the study on NPP construction issues only.

- Infrastructure and pre-development costs are neglected
  These costs could include SMR design licensing, building the off-site module factory, preparing sites so they are suitable for nuclear new build, etc.
- Modularisation does not affect ongoing operating costs
  In reality, maintenance tasks may be more difficult because of extra module supporting structure; conversely, replacing worn-out components may be simplified, because a whole module can be removed/inserted at a time. The impact of modularisation on systems upgrade is a key component of flexible warship design [69] and is discussed in Chapter II.
- Regulatory approval is assumed
  SMRs are assumed to comply with all relevant UK regulatory requirements and standards, and modularisation is assumed to have no impact on regulation and/or GDA process.

I.4. Organisation

This thesis project is structured as follows: Chapter II discusses modularisation principles and practices, how modular build has been employed in other industries, and discusses how modular techniques could be adopted in SMR construction; Chapter III discusses the top-down modelling approach used by this dissertation; Chapter IV shows how transport logistics constrain the modules and their size/weight; Chapter V and VI develop the build schedule and construction cost models for NPP construction, demonstrating both how long SMRs can take to build and how much construction could cost; Chapter VII presents a Monte Carlo uncertainty analysis of the assumed parameters in this thesis; and Chapter VIII present the major conclusions and new findings that arise as a result from this dissertation.

LRs are used throughout this project as a source of reference data for the three key components of this work: the NPP modularisation scheme, build time, and construction costs. The lack of LR construction data in the public domain means that three different LRs must be used as reference NPPs for each of the models; each reference LR source is described in Table I.5.

- **Modularisation scheme:** reference module data are based on a conceptual scheme from Stone & Webster (S&W), developed for a Westinghouse 950 MWe PWR.
- **Build schedule:** reference build time data are from the as-built construction schedule for Sizewell B Power Station, an 1198 MWe PWR in Suffolk, UK.
- **Construction cost:** reference cost data are derived for a generic 1144 MWe PWR, labelled PWR-12, and is based on a 23-year span of studies summarised in a series of reports published by the EEDB. The most recent Phase IX Update Report from 1987 is used [57].

In general, the reference LR base case is a four-loop PWR based on Westinghouse technology. A single reactor is located at the NPP site and is not used for any other purpose than commercial power production. For a comprehensive description of the components of a large PWR, the reader is referred to report [70] which contains a thorough, non-technical but sufficiently detailed, description of the layout and components in the Sizewell B NPP.

Table I.5. Summary and comparison of the LR designs used to establish baseline data for the module scheme, build schedule, and construction cost models in this dissertation.

Reference LR Source	**Stone & Webster (concept)**	**Sizewell B (as-built)**	**PWR 12 Generic Design (concept & derived)**
Application	Used in the development of a detailed modularisation scheme Power plant details are taken from [71] [72]	Used to develop a detailed NPP construction schedule based on data from [47] Power station details are taken from [70]	Used to develop a detailed NPP cost breakdown based on the EEDB Phase IX Update Report [57] Details from EEDB Technical Reference [73]
Rated Power	950 MWe	1198 MWe	1144 MWe
Design Lifetime	No information	40 years (decommissioning planned for 2035)	30 years
Construction Date	Mid-1970's (proposed) but scrapped because of a moratorium on nuclear build in California	1988-1995	N/A; data are averaged over 23 years of studies summarised in 1987 EEDB report [57]
Location	Sundesert NPP project, Southern California, US	Suffolk coast, UK	Middletown site, US
Units on Site	Two	One (PWR) Built beside existing Sizewell A1 & A2 (Magnox)	One
Reactor Technology	Dispersed 4-loop Westinghouse PWR technology and S&W's Pressurised Water Reactor Reference Nuclear Power Plant Safety Analysis Report (SWESSAR-P1)	Dispersed 4-loop Westinghouse/Bechtel SNUPPS (Standardised Nuclear Power Plant System) concept	Dispersed 4-loop Westinghouse PWR Modified for each EEDB update to reflect industry practice, experience, regulation
Containment Design	Double-shell domed containment All necessary supporting buildings are located within protected plant perimeter	Large dry double-shell pre-stressed containment (free volume is about 90,000 m^3) Diaphragm wall encloses central part of plant	Reinforced concrete containment with steel plate liner (calculated free volume is about 85,000 m^3)
Cooling Towers	2 service water cooling towers 4 circulating water cooling towers	None (direct cooling)	2 hyperbolic natural draft wet cooling towers built from reinforced concrete
Site Features	Blythe site, Colorado Desert Barren ground, creosote scrub, arroyo vegetation Site land area is 655 acres	Shoreland site (Suffolk) Flat topography; surrounding land is marshland, farmland, some conifer plantations Seismically inactive region	Generic 'Middletown' site Gently rolling topography; site land area is 500 acres Seismically inactive region
Notes	Makeup water source is irrigation wastewater from Palo Verde Outfall Drain	Similar to contemporary SNUPPS plants and French NPPs with design modifications to meet UK regulation	Necessary utilities are readily available with year-round highway, rail, and river access Land transport in most cases; heavy equipment (RPV, generator stator) is barge transported
Plans & Diagrams	Not available	See Appendix I.2, Figures A.I.2 to A.I.4.	See Appendix I.2, Figures A.I.5 to A.I.6.

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CHAPTER II

MODULARISATION IN CONTEXT

II.1. Introduction

Modularisation is a design and construction philosophy whereby site work is packaged into discrete physical units in a way that enables these units to be fabricated in factory conditions and at some distance from the construction site. Modularisation was first developed in the manufacturing sector and enables simultaneous design and procurement, parallel construction activities, and increased control of the build schedule [74]. Modularisation also enables higher labour productivity from a factory workforce that has the right tools, jigs, and fixtures to manufacture or construct units more quickly. In order to fully exploit the range of benefits that modularisation offers, it is essential that the product is designed for modular build, that production volumes are high enough to establish a pipeline of work, and that the modules, components, and build processes are standardised and repeatable [75] [76]. In recent decades, many industries have made the transition from component or stick-built production (or construction) to modular methods and is now almost taken for granted in the electronics, automotive, aerospace, and shipbuilding sectors [77]. It is also adopted widely by the oil and gas and chemical plant industries [78] and is even being introduced into civil projects, specifically construction of off-site housing [79].

The motivation for a sector to employ modular construction depends on the industry, its design constraints (commonly imposed by function and/or regulation), and the nature of the final product [75]. One motivation for adopting modularisation comes from the need to improve a product's competitiveness by meeting as many unique customer requirements as possible, where designers prioritise module interchangeability in order to create a set of customisable products that are made by selecting modules and components from a standard set of parts [79]. In high-production rate industries (electronics and automobiles) this mass customisation is the most common reason for adopting modularisation; however, it has also been adopted, with success, in lower production-volume industries such as shipbuilding

[69]. The second modularisation strategy is a divide-and-conquer approach driven by the need to break a very large and/or heavy final product into smaller chunks that can fit within production facilities, crane and vehicle limits, or other production constraints [48] [51]. This is more often the reason for adopting modularisation in low production-volume industries that produce large items, such as off-site civil construction [23] and also shipbuilding [77].

II.2. Modularisation in Principle

Nuclear power plant modularisation is motivated by the desire to divide and conquer the construction of highly complex products that combine multiple structural, system, containment, and/or control functions in single structures or across single systems. Modular SMR construction must be consistent with the best practices that enable design for manufacture and assembly (DfMA), as described in Section II.2.3, while bearing in mind the end goal is not a customisable 'fleet' of options.

II.2.1. Benefits of Modularisation

This is a general list of benefits that have been reported from modular industries and is based on an extensive review of literature on modularisation and -modular industries, shown in Table II.1 and discussed in Sections II.3 and II.4. The extent to which modularisation benefits are realised as cost and build time reductions depends on the industry and the degree to which a product is modularised.

i. Shortened Construction Schedule

Modularisation reduces build time by allowing complex construction work to be completed off-site, improving work conditions and productivity, moving time-consuming tasks off the critical path, reducing installation time, and allowing concurrent construction and assembly at the site. A range of modular industries report *in-situ* build time reductions of 25%-50%, as per Table II.1.

ii. Reduced Construction Cost

The net effect of modularisation is to reduce construction cost, usually as a result of the higher productivity and lower labour rates at the off-site factory. Labour, material, and QA costs reduce with modularisation but the costs of design & engineering, as well as transport, tend to increase [80]. Cost reductions observed within different modular industries tend to be on the order of 10%-20%, as per Table II.1.

iii. Learning & Repeatability

Re-using components and modules within a design leads to repeatability and helps projects achieve greater continuous learning-related cost and time reductions, assuming the product is standardised and manufactured in sufficient quantities to realise economies of volume [74] [75].

iv. Improved Constructability

Choi & Song [81] show how modular build can outperform stick-build by reducing the number of components, simplifying piping geometry, minimising interfaces, and improving construction safety. Reducing the number of workers on site with a modular project also reduces site congestion and increases field safety [51] [76].

v. Improved Product Quality

Off-site manufacture means that construction activities are performed in a controlled environment which is particularly relevant to concrete pouring, welding, and steel cutting processes. *In-situ* testing may also be replaced with in-factory testing [52] resulting in better product quality and less *in-situ* rework.

vi. Ensure Labour Availability

Modular construction is often used in remote locations to resolve the issue of obtaining sufficiently skilled construction labour; since the bulk of the workforce remains at the factory, only a skeleton workforce is required to assemble modules *in-situ* (examples in [48] [61] [78]).

vii. Implementation of New Techniques & Technology

Factory production can use a higher degree of automation and employ other construction technologies in the fabrication process that would not be feasible *in-situ* [76] [52].

viii. Reduced Waste

Modularisation reduces the amount of temporary construction materials required and also reduces water consumption [51] [76]. One example in the civil sector [82] shows that modular build has reduced the project's landfill factor by 70% through more efficient material usage and recycling.

ix. Project Financing

Modularisation can improve project cash flow timings because payments can be better aligned with the manufacturing process and revenue can be generated earlier in the project cycle [76].

Table II.1. Modularisation across industries and its effect on reducing schedule and cost; extended from work by Mignacca *et al.* [80]

Study/Author	**Schedule Reduction**	**Cost Reduction**	**Project/Industry**
Murtaza *et al.* [83]	25%	22%	General modularisation theory: cost and schedule savings depend on how easy it is to modularise the facility and on the level of support available for modularisation
General Dynamics Electric Boat [80] [51]	28%		Shipbuilding: naval
Garver & Abbott [69]	25%	10%	Shipbuilding: Blohm & Voss MEKO flexible warship
Modular Building Institute [84]	30%-50%		Civil: general observations Modularisation removes about 80% of work from site
Eftimie [85]	25%-50%		Oil & gas: onshore
Gotlieb *et al.* [86]	20% reduction in net critical path (40% reduction in man-hours)	13%	Chemical process: 300 MWe solid fuel plants (a pulverised coal-fired facility and a circulating fluidised-bed boiler plant) Productivity improved by 15%
Jameson [87]		18%	Chemical process: gasoil hydrotreater in the US Great Lakes
Shelley [78]	50%	20%	Chemical process
Hesler [88]	40%	20%	Power plants: general observations
Choi & Song [81]	22%		Piping/equipment package: construction of an underground machine room for a high-rise residential building

II.2.2. Barriers to Modularisation

Many of the challenges modular construction faces are related to logistics and planning. Carriker & Langar [48] report that logistics-related delays are the most common reason that large-scale modular projects overrun on schedule and cost. Similarly, Mignacca *et al.* [80] highlight that poor planning during the design and construction process increases the risks associated with modularisation.

i. Module Transport

Transport imposes a major constraint on modular build, setting restrictions on module size and weight. There are a number of case studies where modules have been designed around transport logistics, including the chemical process industry (where plant location is the constraint [85] [87]), piping and equipment systems [81], the civil sector (maximising the surface area of façade per transport movement [89]), and the nuclear sector (transport is constrained by module weight, size, and power plant location [51]). Transport costs are an estimated 1%-2% of the module's cost [21] [78].

Carriker & Langar [48] address the importance of integrating module stowage, plans for transport, and module delivery schedule. Some of the transportation strategy and logistics may well be site or project-specific. Key elements of a transport strategy include:

- Developing transportation envelopes based on regulatory constraints
- Identifying transport mode availability and duration
- Ability to effectively manage in-transit variability and exceptions
- Identifying cost/service advantages between transport alternatives

ii. Module Lifting and Support

Extra structure is often required for modules so they can be self-supported and also to provide lift-specific bracings so the modules do not deform under the loading patterns experienced during transport, installation, and service. Barry [51] identifies module installation best-practice that develops lifting guidelines for each module to verify its centre of gravity and to ensure it can withstand the full range of lift load patterns. Work by Bedair [90] on modularised pipe racks shows that module design should take into account the loads encountered in-service, under impact, and during any reasonable beyond-design-basis loading conditions.

iii. Extra Cost of Modularisation

Modular projects will have increased structural material costs from additional support and bracing needs. Jameson [87] estimates that, for a gasoil hydrotreater, the structural requirements for a modular plant were increased by 17% over a stick-built plant. The Economic Modelling Working Group (EMWG) states that modularisation increases the site material costs by 5% for 'Structures and Improvements' elements [21]. Home office design and engineering costs may be higher for the FOAK plant since greater upfront design is required for modular projects [86].

iv. Series Production

Modules, components, and products should be repeatable and producible at the scale and volume required [91]. The production volumes that can be achieved depend on the demand for the product, production repetition and continuity, and the supply chain capacity and capabilities. In shipbuilding, for example, the efficiency improvements from modular construction and lean manufacture are realised to their fullest extent only over long-term series production [92].

v. Manufacturing Challenges & Product Complexity

More complex products require greater modularisation design effort. Product complexity depends on the number of physical elements and product variants, size differences between variants, the degree of coupling between different technologies, the mix between functional and physical elements, the level of integration in the design and/or product architecture, and the extent of interaction between subsystems [49] [50] [93].

II.2.3. Modularisation Best Practices

There are a set of core principles and best practices that are often implicitly accepted when modularisation is discussed and are common to all industries adopting modular-based designs.

i. Functional & Physical Integration

The functional elements and physical elements of a module must be fully compatible with one another, resulting in no interference with or loss of the overall product's functional performance and physical integrity [49].

ii. Interface Management & Minimisation

Module interfaces and joints need to be designed in a way that enables rapid assembly on-site following a standard process. Much design effort tends to be focussed on minimising the number of interfaces as well as reducing their impact on the assembly and functionality of the product [49].

iii. Standardisation

Standardisation refers to the level of commonality between designs, physical elements, construction processes, and so on. The module, its interfaces, and construction should be as standard as possible in order to improve the project's repeatability [49]. This is best-practice in both low- and high-volume sectors. Forg *et al.* [94] explain that component standardisation is often prioritised by optimising module positioning, interface compatibility, and functionality.

iv. Early Outfitting

In modular construction, each module passes through a series of fabrication stages which become progressively more difficult – and therefore costlier and time consuming – as the level of complexity increases. Best-practice is for modules to arrive on-site fully tested and commissioned, complete save for installation and final testing [51]. The shipbuilding industry demonstrates this practice by extensively outfitting modules rather than investing in hull section manufacture alone [50].

v. Design Management

In the shipbuilding [77], civil [91], and the South-Korean nuclear industries [95], fixing the design early in the project cycle is an essential component to maintaining project schedule. In the civil sector Bryden Wood *et al.* [91] attribute up to 8% of build time delays to incomplete designs prior to construction start. Managing the design change process is important in order to avoid copying errors from one project to another and to also avoid the need for re-licencing or gaining new licence approvals for the project, thereby increasing cost and uncertainty [50]. BIM systems should be employed to help develop design details before construction begins and supporting early module outfitting [49].

vi. Supply Chain & Project Management

Complete, thorough, and early planning of the project before it begins is essential, as is cooperation and communication between the different coordinating teams. The design, management, and site construction stages of the supply chain should be integrated to fully optimise the supply chain [96]. Suppliers of critical components should be reliable and available [91], and relying on a consistent subcontractor network helps to minimise the risk of project delays, maintaining production consistency [50].

II.2.4. Selecting and Developing a Modularisation Methodology

II.2.4.1. When to Use Modularisation

Designers are responsible for determining when it is appropriate to use modular construction on a project. This is usually a qualitative, multi-attribute problem depending on specific project requirements, social or regulatory considerations, the plant location, environmental conditions, and the availability of labour and/or special skills required for construction [50] [74]. Performing a feasibility study to see whether modularisation will have a positive impact is the best approach for power plants. Murtaza *et al.* [52] outline three steps that guide designers as to whether a plant design should be modularised or not, using five major decision factors (plant location, environmental & organisational, plant characteristics, labour considerations, project risks) to pre-screen whether the project is of the type that lends itself to modularisation. Each decision factor has 10+ sub-attributes which undergo a more detailed feasibility assessment if pre-screening suggests modularisation may be suitable. Finally, the designer must decide on a degree of modularity to incorporate into the plant design, and translate this into expected cost and/or schedule savings.

II.2.4.2. Understanding the Product

Whether the product is viewed from a functional, physical, and/or process systems perspective will affect how the product characteristics are organised into a product and module architecture [49]. The product architecture is a key component of understanding the product and dictates how difficult the modularisation of a given product will be. Four product architecture options are described in Table II.2. Highly complex products require more design and engineering effort to modularise and are characterised by [49]: a large number of product variants, many constituent parts, several technologies must integrate across module boundaries (physically or functionally), and/or there is more than one design solution for a functional requirement.

Table II.2. Types of modular product architecture, based on [49].

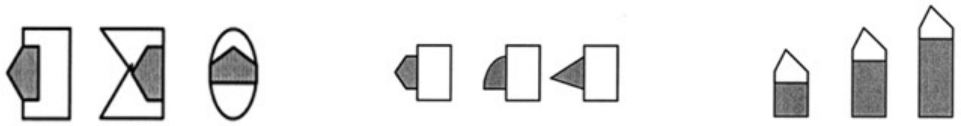
Design Strategy	Allocation of Functionality	Integration Between Modules	Example
Modular Design	One function → one module	None	Lego bricks
Function Distribution	One function → several modules	Low	Ikea furniture
Function Sharing	Several functions → one module	Moderate	Car chassis, ship hull
Integrated Design	Several functions → several modules	High	Flexible warship

II.2.4.3. Types of Modularity

There are six types of modularity illustrated diagrammatically in Figure II.1. The type of modularity that is used depends on how the modules interact functionally and/or physically within the product [97] [98] [99].

- **Component sharing modularity:** common components are configured in different ways to design unique products
- **Component-swapping modularity:** different modules can be interchanged on a base product
- **Cut-to-fit modularity:** a module's dimensions can be altered before combining with other modules to give products of different sizes

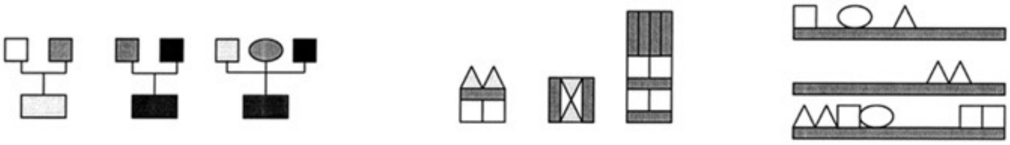
- **Mix modularity:** different modules are interchanged on a base product (similar to component swapping) but modules lose their unique identity
- **Sectional modularity:** arrange a set of standard modules in different configurations
- **Bus modularity:** modules are attached to a standard skeleton module (bus)



Component sharing modularity

Component swapping modularity

Cut to fit modularity



Mix modularity

Sectional modularity

Bus modularity

Figure II.1. Comparison between types of modular product architecture [98] [99].

II.2.4.4. Methods of Modular Design

The method by which a product is modularised consists of three general steps [49]. Firstly, product decomposition develops a set of parameters for breaking the product into smaller elements, resulting in a set of primitive design objectives. The second step is module integration, which is the process by which sub-problems are hierarchically integrated to form a final product. Finally, the modules or modular products are evaluated and compared with the original design. Three key modular design methodologies are listed below and are frequently used to guide the modular design process for existing and/or new-to-firm products.

i. Fractal Product Design

Kahmeyer, Warnecke, & Schneider; 1994 [100]

This method is used for products that need to be highly customisable, such as automobiles and domestic appliances. Modules have standard physical and/or functional interfaces but each has a precisely defined, distinct design. These different modules can be combined to form a range of products because they have the same material and information inputs/outputs. Each product is assessed in terms of its performance based on functionality, cost, safety, or other criteria.

ii. Modelling Product Modularity

Huang & Kusiak; 1998 [97]

This method uses matrix algebra to structure the interactions (material, force, thermal, electrical, geometrical, etc.) between the physical elements of the product. The suitability of the interactions is then assessed based on the module drivers or strategic rationale for desiring to modularise components. This strategy is often applied to mechanical, electrical, or electromechanical design.

iii. Integration Analysis of Product Decomposition

Pimmler & Eppinger; 1994 [101]

This method is commonly used in modular product design. The overall product is divided conceptually into functional and physical elements, and the interactions between elements (spatial, energy, information, and material) are documented. These interactions are then scored based on their relative importance. Finally, the elements are clustered, according to their score, and designed into modules. This method is used to support lightweight design in the aerospace industry [102].

II.2.4.5. Evaluating Modular Products

The feasibility of implementing a module scheme depends on the extent to which modularisation enhances the product's constructability. One way to evaluate the modularisation effort is to use a decision matrix to assess individual modules based on transport, design, and/or regulatory constraints (for example in Lee *et al.* [95]). This can generate a ranked shortlist of feasible modules which can be prioritised based on their contribution to schedule reduction, cost, product constructability, or other design criteria.

While improving a design's producibility results in lower costs, not all cost reductions are a result of improved producibility. Wilkins *et al.* [103] describe two methods, developed in the context of shipbuilding but more widely applicable to other industries, that can be used to evaluate the relative producibility of modular designs and their alternatives. The first method uses a direct evaluation and quantitatively compares design or sub-assembly construction on the basis of man-hours or total cost. This method is limited because the criteria traditionally used for evaluating producibility, such as module weight and performance factors, are not necessarily an accurate estimate of the magnitude of the construction effort. The second method is a relative evaluation and compares modular solutions using weighting factors (for example the Analytical Hierarchy Process (AHP) method; an example application of this approach in shipbuilding modularisation can be found in [103]).

II.3. Modularisation in Practice

This section presents modularisation practises that are adopted by other industries that have some relevance to modularisation of SMRs; either directly in terms of modular solutions and strategies that can be used (shipbuilding, civils, oil & gas and chemical process industries) and/or in terms of how the modular products are defined and modular design constraints and criteria are developed (shipbuilding, automotive and aerospace industries).

II.3.1. Shipbuilding Industry

Historically, the shipbuilding industry tended to utilise handicraft and stick-built construction, focussing on individual projects because the production run for a particular ship series is short compared with high-volume industries such as the automotive and aviation sectors [50]. In spite of these initial barriers, modular product platforms have nonetheless been extensively and successfully adopted in shipbuilding. German shipyards pioneered modular shipbuilding, establishing a foundational set of guidelines in the VDI 2222 document [104], which were subsequently updated with VDI 2221 guidelines [105]. These guidelines propose a general methodology that supports a methodical and systematic design for highly technical, complex systems. German shipyards continue to follow the VDI 2221 guidelines; however, Lehtonen *et al.* [106] argue that they do not encourage design reuse and could be challenging for serial ship production, where up to 70-90% of a ship design can be repeated.

Experience from the shipbuilding sector demonstrates that modularisation is feasible for an industry that produces tens of products per year, instead of the hundreds or thousands of modular products in automotive or electronics industries. A programme of SMRs which is expected to have a similar throughput as the shipbuilding sector, should therefore be able to realise production-line benefits from modular manufacturing, although these benefits may not hold for LRs, which are expected to have a lower production rate. One example is the manufacture of container vessels larger than 3,000 teu; shipyard production in Europe is on the order of up to 10 vessels per year [107], similar in magnitude to the hypothesised SMR production rates in the US [59] or UK [15]. The modules used for shipbuilding also have some similarities to nuclear modules: they are multi-function modules that often provide both structural and safety functions (the hull sections, for example) and they must be designed and manufactured to high tolerances to meet safety standards and pass stringent inspection and testing requirements [77].

Shipbuilding is, however, very dissimilar to SMR in terms of module materials, sizes, transportation flexibility, and also the well-established nature of supply chain and best practices that have had years to develop. It is reasonable to expect that SMR modularisation will take some years to develop modular manufacturing processes to the same high standard as those processes used in the shipbuilding industry. The first and most obvious difference is that ships are smaller products with very different structural requirements. Ships do not require traditional concrete civil elements; the fact that a ship is primarily fabricated from steel will make it easier to transport and join modules. The shipbuilding industry can also take advantage of the final product's smaller size to allow transport of fully completed ship sections between shipyards [51]; something that would be impossible in the nuclear industry because of the size and static nature of the final product. Additionally, ships have a much wider supply chain and network of players in the supply partnership [107] which can help incentivise standardisation and make it simpler to source standard parts, thereby facilitating greater learning through the supply chain. Finally, modularisation is a well established technique in the shipbuilding industry, meaning that manufacturing best-practices have had more time to develop in a way that is tailored to the shipbuilding industry than in the nuclear industry [77].

This section discusses two specific examples of modularisation used in the shipbuilding industry. First, the practice of hull-block construction shows that the main schedule reductions that shipbuilders have achieved are from minimising the amount of time spent in the bottleneck final assembly area (dry dock) [77]. Nuclear construction should aim to use modular build techniques to compress the schedule by reducing time *in-situ*. Second, the example of flexible warship design shows how modularisation and standardisation can actively decouple critical tasks in the construction schedule, with the net effect of shortening the critical path overall.

Experience from the shipbuilding industry provides some evidence for the expected productivity improvements from modularisation. The reduction in time of a construction task is estimated using the 1-3-8 rule of thumb [22], where the numbers 1, 3, and 8 refer to the relative number of hours spent performing a construction task in an off-site factory, in an on-site assembly area/shop, and *in-situ*, respectively. Both Barry [51] and Maronati *et al.* [32] argue that this rule of thumb can be extended to nuclear construction productivity.

II.3.1.1. Hull-Block Construction

The hull-block method for fabricating ships incorporates modular build with lean manufacturing and quality control techniques. This best-practice strategy was originally pioneered by South Korean and Japanese shipyards and has since been adopted in China and other countries [92] [108] [109]. Since the critical bottleneck of ship fabrication is the dry-dock availability, hull-block construction is adopted to minimise the time a ship spends in the final assembly area. Collins *et al.* [92] explain that ever-larger units are formed as modules follow a logical workflow pattern between work stations in the shipyard. The largest ‘blocks’ are ultimately moved to the dry dock for assembly into the final product. The shipyard layout and transport equipment is specific to the module fabrication process; shipyards are often built from scratch so they can take full advantage of the hull-block construction method.

South Korean shipyards are state-of-the-art in their fabrication capabilities and production capacity. South Korean shipyards adopted the hull-block construction technique to respond to a large shipbuilding boom in the early 2000's and to maintain a competitive advantage over Chinese shipyards [108]. Similarly, Japanese shipbuilders now operate as final assembly facilities in which 50%-70% of the added value comes from external subcontractors or suppliers in the form of smaller units, modules, or components [109]. Collins *et al.* [92] describe how China's military ship production capabilities have successfully expanded and been modernised as a direct result of incorporating a typical hull-block construction method employing an associated zone-based production system (on-block zone outfitting, painting, testing, etc.) The time to build a 175 deadweight tonne bulk-carrier in China's commercial shipyards, for example, was reduced from 369 days (conventional stick-built construction) to 35 days using hull-bock construction [92].

II.3.1.2. Flexible Warships

Modularisation was incorporated into warship design to keep pace with developments in combat technologies and to enable mission changes without incurring unnecessary expense [110]. Conventionally, warship designs are optimised along a design spiral that results in a custom-built ship which contains a specific set of combat systems: a time-consuming, iterative process in which the combat systems soon need to be replaced [69]. The primary design objective for a warship, therefore, is to reduce total ownership cost while maximising mission effectiveness by enabling combat systems to be easily installed and upgraded over the ship's lifecycle [110]. The modularisation and standardisation of the combat and ship systems on a flexible warship allows capabilities to be added and removed while minimising cost and/or downtime. Significant design effort is put into decoupling the module delivery schedule from the ship production schedule; ensuring that the combat system integration is independent of the critical path, consequently reducing the risk of equipment supply delays, allowing combat systems to be integrated later in the acquisition cycle, and ultimately minimising the disruption of system upgrades [69].

Warship modularisation began with the 1975 SEAMOD initiative in the US Navy and is emulated by the German navy (FLEXpatrol) and the Italian/French navies [110]. Figure

II.2 shows the MEKO modular design concept developed by German shipyard Blohm & Voss in the late 1970's, which is now the most widely-used design concept [111]. Garver & Abbott [69] identify a process for modularising warships based on division of the product into 'functional element zones'. Each zone provides space, structural support, and services for one major function or a collection of similar functions (e.g. weapons, exterior communications, habitability, etc.) The designer plans the equipment layout, how it will be moved in/out of place, and performs trade-off studies to determine the optimal zone arrangement [69].

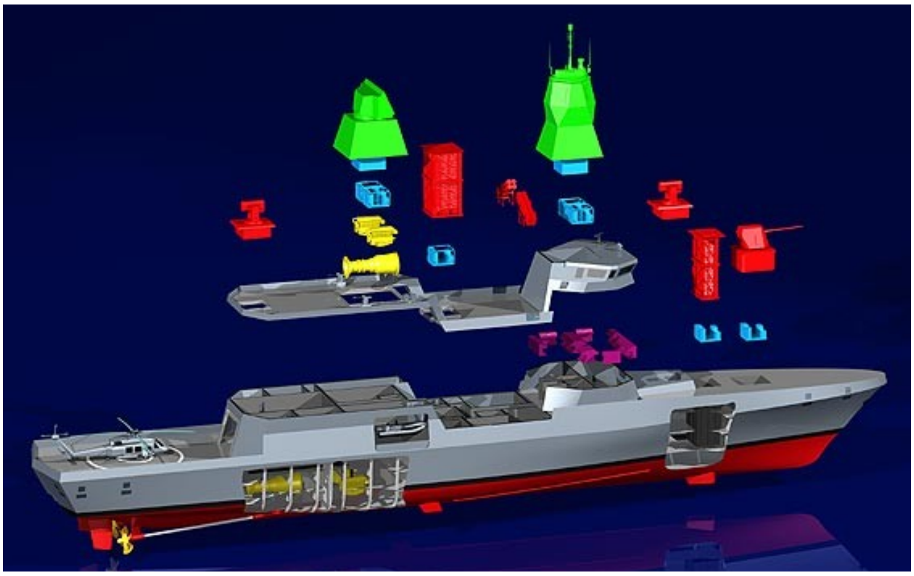


Figure II.2. Blohm & Voss MEKO flexible warship with modular ship platform and combat systems (colour coding refers to different types of modularity within the warship design) [111].

II.3.2. Civil Industry

Traditional civil construction projects have low site productivity, which drives up construction time and costs [112]. Modularisation and prefabrication in the civil industry aims to increase the value-added time at the site by using the efficiency and productivity improvements from factory build to impact the project schedule. There is a wide variety of possible uses of modular build in the civil sector, including bridges (pre-stressed precast concrete bridge beams, Shay Murtagh [113]), municipal and industrial water treatment and waste-water treatment plants (Ross-Shire Engineering [114]) and construction of residential and commercial buildings [76] [84] [79]. The different stages of modular civil construction can be summarised in four categories, as listed below [91].

i. Traditional Construction

A custom product is built using an on-site, tailor-made delivery process. This is the most common build strategy in the civil sector, but is also inefficient.

ii. Componentised Delivery

Standard components are delivered and installed on site; these modules have lower levels of outfitting and include precast concrete slabs, timber frame solutions, panels, and other two-dimensional units.

iii. Volumetric Solutions

Design, manufacture, and assembly processes are standardised but there is little scope for product customisation. Economics rely on high production quantities. Volumetric modules have a higher level of outfitting and are three-dimensional units, such as bathroom or kitchen pods, prison cells, and so on (for example, bathroom pods by Offsite Solutions [115]).

iv. Manufactured Solutions

Standardised design, manufacture, and assembly processes for mass-production of customisable solutions. These modules are highly outfitted and are sourced from suppliers as part of a holistic offsite ‘package’ that includes both standardised two- and three-dimensional modules, resulting in a large fraction of the final product being constructed offsite (for example, projects by MID group [116]).

The civil industry is similar to the nuclear industry in that modularisation is not a widespread construction method. Civil construction projects tend to conventional *in-situ* build, using modularisation if there are specific construction challenges to address. Uptake of modularisation in the civil sector, particularly for residential and commercial buildings as discussed here, will face many of the same challenges that it does in the nuclear industry, including unfamiliarity with offsite construction processes, lack of skills and expertise with modular build, perceived economic barriers to offsite construction, and a restricted supply chain [74]. Additionally, civil engineering projects are location-constrained in a similar manner to nuclear power plant projects, unlike the shipbuilding or automotive sectors where products and modules are smaller and more transport-flexible. Finally, concrete features heavily as a construction material in the civil industry and thus many of the challenges facing modularisation of concrete structures, such as ensuring overall structural integrity, avoiding module deformation during transport, and joining concrete modules *in-situ* will be the same in modular nuclear and civil construction projects.

There are some key differences between civil and nuclear projects that mean the experience of modularising these industries does not entirely overlap. The civil industry may be less motivated than the nuclear industry to use modular offsite build because of the smaller, less complex, lower value products that experience little pressure to build to schedule [76]. Additionally, the safety standards between the civil and nuclear industries are not comparable. Nuclear projects must maintain their structural integrity under a range of beyond design basis events that would not normally be considered in the civil sector; for example, accidental release of radioactive material, sustained high pressure release scenarios, and so on. These features can all impact the extent to which modularisation is used and it is reasonable to expect that SMRs may have more scope and greater motivation to employ modularisation than civil building projects.

Table II.3 shows that modularisation has been successfully adopted in the civil industry with reductions in both build time and cost; however, the projects that used modularisation had strong motivation to do so, since minimising construction time is critical for hotels and educational centres and minimising laydown space and the impact on the surrounding community is key for high rise buildings. The second example explains a radical civil modularisation concept, discussing what would be required to develop a modular product platform for buildings in the civil sector. While this second example is beyond the level of component development and delivery that is expected in SMR modularisation, it does demonstrate how far case-by-case civil structural modularisation currently is from true production-line thinking.

II.3.2.1. Prefabrication of Buildings

High-rise buildings are a candidate for prefabrication and a few examples are presented by Lawson *et al.* [82], who discusses two designs: modules can either be added to a central module, forming a cluster around a core, or they can be connected in series to form a corridor layout. Other modular elements, such as balconies, can be added to these housing blocks. The module design must account for all loading patterns each module will experience, not only during transport, but also in service: modules at the bottom of a high rise building will experience much heavier loads than those at the top. Table II.3 gives a number of examples of modular or semi-modular buildings and the observed cost and schedule reductions. These data show that specific modularisation savings depend on the project and its complexity; for example, even though the amount of work moved off-site for the Heathrow + Gatwick Pier segregation project was 15% greater than that of the Heathrow Terminal 5C nodes, the schedule reduction benefits were lower overall [91]. Interestingly, the schedule reduction from modularisation tends to be more significant in the civil sector than cost reductions.

Table II.3. Examples of semi-modular civil construction projects in the UK, from [82] [91]. Reductions are given as a % of: build time (1); build cost (2); and work content (3).

Project	**(1) Programme Reduction**	**(2) Cost Reduction**	**(3) Amount of work moved off-site**
Circle Hospital, Reading	20%	28%	*79% of components standardised*
Heathrow T3 Temporary FCC	38%	28%	75%
GlaxoSmithKline ‘Factory in a Box’	60%	Break even	*75% reduction in labour*
EcoCanopy Children’s Centres	50%	40%	90%
Heathrow + Gatwick Pier segregation	50%	36%	80%
Optimum Switch data centres	30%	30%	40%
Heathrow Terminal 5C Nodes	87%	25%	65%
‘Yotel’ hotel pods (various airports)	25%	40%	60%
Wolverhampton High-Rise [82]	45%		

II.3.2.2. Customisable Housing Products

Recent work by the UK’s Manufacturing Technology Centre and Bryden Wood employs manufacturing design and production techniques to develop a ‘product platform’ approach for the housing sector. The overarching objective is to enable mass customisation of housing, motivated by improving product competitiveness in a manner analogous to the automotive industry [89] [91]. One example is a DfMA modular ceiling cassette that resolves the common issues with conventional ceiling construction, where working at height is unsafe, the work face tends to be unproductive, and there are multiple systems within the ceiling void (ductwork, pipework, cable trays, etc.) [89]. The modular cassettes can be customised and mass produced using standard components and construction processes [89].

Prefabrication techniques are also used to develop a standardised, modular 'platform' which acts as the skeleton of a building, as shown in Figure II.3. The modules are designed to be easily replicable and have standard corridor widths and floor-to-ceiling heights. The platform modules are optimised around module geometry, building height, level of complexity and repeatability, and the number of buildings [89] and further modules can be added to the platform skeleton including cladding, facades, offices, HVAC and/or plumbing systems [117]. There are three general modular product platforms that are being developed [91]: a highly flexible small scale platform suitable for bedroom/living room spaces; a domestic scale platform for mid- to high-rise housing or offices; and a large scale platform for warehouses, distribution centres, etc. The estimated cost of fabricating a modular platform (£149/m^2, including materials, labour, and overheads) is about 12% less than using conventional flat-slab build (£169/m^2) and is 34% less than the estimated cost of steel composite slab construction (£225/m^2) [79].

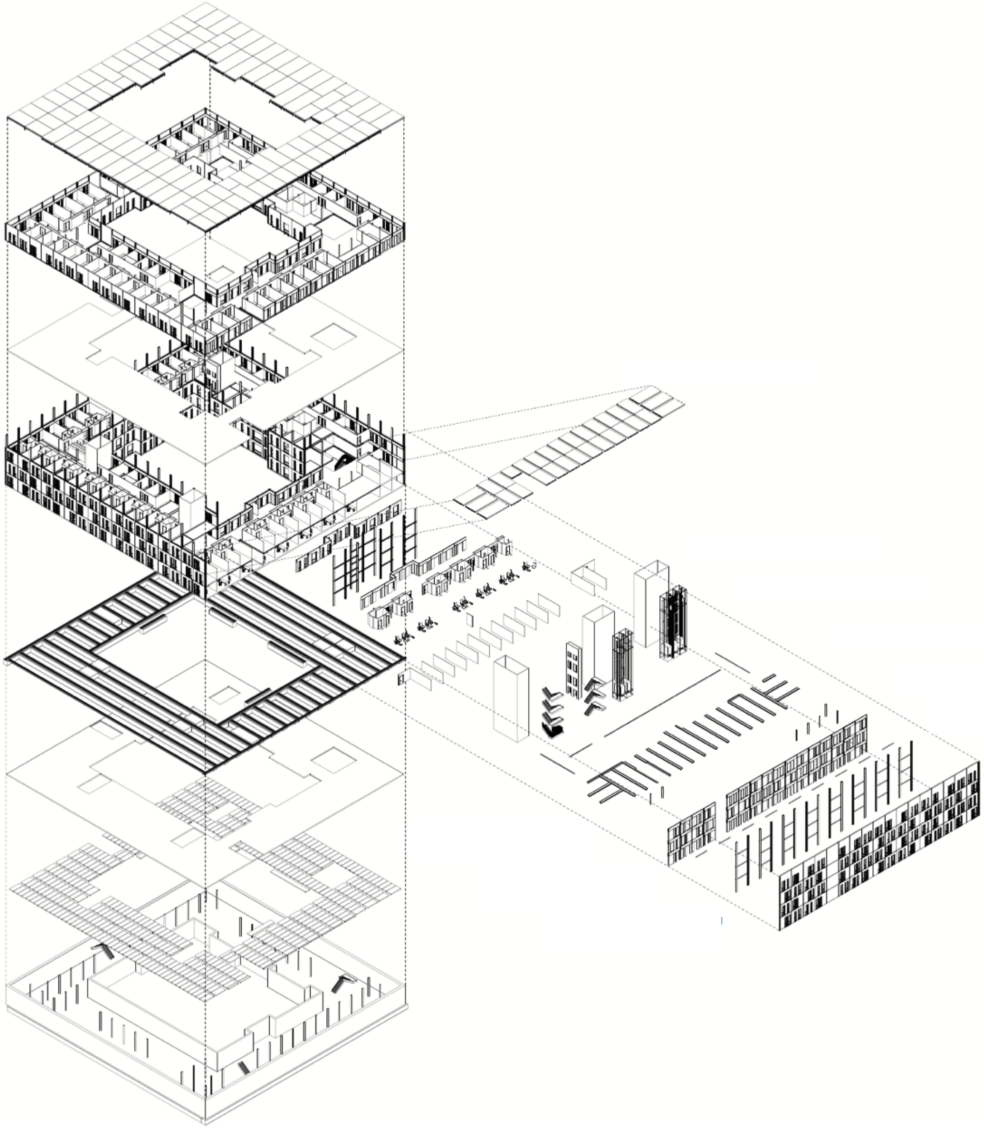


Figure II.3. Bryden Wood product platform for a modular building concept, from [89].

II.3.3. Aerospace & Automotive Industry

The primary objective of modular automotive and aerospace manufacture is to minimise the number of internal variants (modules and components) but maximise the differentiation of external variants (final products); that is, to simplify and standardise the design and construction process while simultaneously accommodating a range of customer requirements. The aerospace and automotive industries are similar to one another but very different to the nuclear industry, since they have high throughput and production rates, small products (and thus small modules and components), no concrete structural elements, low value products (relative to the nuclear industry), and can employ highly automated manufacturing techniques. These industries are also not location-constrained in the same way that nuclear power plants are; their small modules/products mean that there is a high level of flexibility for factory location, transportability, and so on. Finally, both the automotive and the aerospace industries, unlike the nuclear sector, have a well-developed supply chain, standard kit of components and modules, and well-established manufacturing processes and supply networks.

These two industries are examples of highly developed, precision manufacturing processes and are included as a learning opportunity for the nuclear sector, showcasing how highly manufactured, factory built products approach modular design. In summary, this section highlights how the aircraft industry designs around the functional and performance requirements of the product. In the aircraft industry, this is usually minimising weight; in the nuclear industry, where weight is not a constraint, the optimisation will likely prioritise maximising safety (ensuring containment and confinement of radioactive material) or minimising space, laying equipment and piping out in the most efficient manner [118]. The review of the automotive sector demonstrates how module standardisation is critical to developing a successful modular manufacturing process; this is driven in part by the need to produce a large number of identical units, but also it is a design philosophy that helps the industry respond to design changes and/or different customer requirements. While nuclear does not experience the same pressure for mass product customisation, the principle of module and product standardisation nonetheless needs to be incorporated from the design stages otherwise manufacturing benefits are not realised. Additionally, the nuclear industry could incorporate standardisation into civil or M&E components by defining a standard, repeatable structural or equipment unit that can be combined in many different types of configurations; for example, if a single civil precast ‘block’ such as that described in [119] could be used to configure different buildings (e.g. turbine building, containment, fuel pit, etc.).

In summary, the differences between the automotive/aerospace industries and the nuclear industry, particularly in terms of product value and production numbers, means that many of the specific cost and time benefits and the experiences from the automotive and aerospace industries can’t be directly translated into expected benefits for nuclear construction. As well-established manufacturing industries, however, they are useful in terms of identifying best practices that need to be adopted early in the development of a nuclear modularisation scheme, particularly the need for standardisation and to design modules around the product's physical and functional requirements.

II.3.3.1. Aerospace Sector

In the aviation industry, the criterion that determines successful design is the aircraft's weight. Gumpinger *et al.* [102] use a worked example to show how modular design needs to balance the trade-off between increasing the product's modularity and managing the number of module interfaces, which is proportional to module weight. Modules need to be lighter than their non-modular counterpart to compensate for the extra interface weight. This provides the overriding modular design constraint in the aerospace sector and effective solutions must optimise material, structural, and system requirements. Integrating more functions into a single module may result in weight saving, even though it may simultaneously increase product complexity and make modularisation more difficult [49]. While the success of the modularisation effort is easily assessed by measuring the net weight of the components, it is also important to re-establish the module/component hierarchy to ensure that the product fully addresses the original design requirements.

In a worked example, Gumpinger *et al.* [102] develop a conceptual modular design for an aircraft galley. The authors use a treemap structure that allows the weight of single parts and modules to be viewed in their hierarchical structure, simultaneously showing the characteristics of all parts. The treemap was used to identify the areas in which modules or components could be redesigned and their weight reduced, supporting the design process by removing complexity and reducing the product's weight. In a similar example, Janssen [120] uses modularisation to design landing gear for a range of aerospace programmes. Aircraft landing gear is a highly dynamic, integrated system that must absorb the landing shock under a complex range of normal and crash landing scenarios. Instead of the treemap structure, Janssen uses a 'building block approach' to modularise the landing gear equipment and validates the modules by simulating different landing conditions on the component, system, and/or subsystem levels. Since it is too expensive and complex to complete full-scale tests on the landing gear equipment, module testing and simulations are used instead.

II.3.3.2. Automotive Sector

The automotive industry uses modularisation to balance the business need for high external variety with the design need to reduce the number of different components. Because of the large production volumes in the automotive industry, standardisation is key to enabling successful modularisation. Components are standardised across different vehicle models and vehicle configurations are also standardised. Series construction in the automotive industry is used to improve manufacturing efficiency by providing production volumes.

Forg *et al.* [94] investigate how German commercial vehicle manufacturer MAN Truck & Bus AG employ modularisation in a market where the primary objective is mass customisation of specialised vehicles. High levels of variation between designs are motivated by internal factors such as methodological and organisational changes, or external factors like market changes, customer specification, competition, regulation, technology development. Product customisation is accommodated by using standardised vehicle layouts, reducing the impact of design changes. The modular kit system contains all the components and modules for the manufacturer's product platform, and uses a limited number of building blocks with a comprehensive set of combination rules. The overall design objective is to standardise the arrangement of components across 80% of the overall vehicle variants; the results is that MAN Truck & Bus AG has 11 basic attributes for vehicle configuration that can be combined into more than 15,000 variants [94].

II.3.4. Oil & Gas and Chemical Process Industry

The oil & gas and chemical process industries are very similar to the nuclear industry, which means that some of the current modularisation practices and principles can be imported into nuclear construction. Firstly, some of the equipment items are similar, if not the same, between the chemical process industry and the nuclear sector; specific solutions that could be used for nuclear applications include process pipe racks and a number of the equipment and/or turbine modules described for a solid fuel power plant, both of which are described in the examples below. Oil & gas facilities and chemical process plant construction projects also face similar location and transport constraints to NPPs and the examples below also demonstrate how the oil & gas and chemical process industries design modules for straightforward transport, providing valuable best-practice lessons for module transportation and design in the nuclear industry.

The key differences with the nuclear sector are that chemical plants, in particular oil & gas facilities, are often built in harsh and remote environments, introducing some additional construction constraints that are not typically experienced by nuclear projects (for example, offshore oil & gas plants or gas plants in Alaska, as described below). Moreover, while chemical plants have stringent safety requirements, these are typically concerned with preventing fire, chemical spills, or overpressure scenarios and do not usually have to address the additional safety case for radiation control and containment. While some of the equipment system modules may be the same between chemical plant and nuclear construction projects, the different safety cases between the two industries mean that nuclear-related equipment and systems will have more stringent safety requirements.

The objective of modularising a chemical plant is to optimise equipment configuration, since a plant's layout determines its cost, operational safety, and operability. The equipment in a process plant usually consists of off-the-shelf or prefabricated items such as heat exchangers, distillation columns, reactor vessels, etc. The general rule in the chemical process industry is to use a module if a certain equipment combination occurs frequently in a given configuration [93]; some examples might include a column system with a heat exchanger for thermal separation or dual-type equipment with a corresponding regeneration system, such as an ion exchanger or vacuum filtration unit. Kampczyk *et al.* [93] address how modularisation facilitates plant layout optimisation by minimising piping runs and determining optimal piping routes. Software-based methodologies are often employed for optimisation in chemical plants and the equipment and piping connections are typically used to develop the positioning rules and placement logic. Equipment can be grouped into a module depending on whether the items perform the same task (functional grouping) or whether it is part of the same process equipment/system. Connection points are defined; first to make module connecting pipes as short as possible (inter-routing), and then to reduce piping lengths within individual modules (intra-routing). This type of approach can be used for SMR M&E systems, as in Wrigley *et al.* [118].

II.3.4.1. Pipe Rack Design

Pipe racks are ubiquitous and critical in the chemical industry as they support pipelines, cable trays, and M&E equipment. The loading patterns that a pipe rack module experiences during transportation, lifting, stacking, and in-service operations often dictate its dimensions and weight instead of the module's functionality requirements [121]. Pipe racks used in the chemical process industry can be up to 10 km in length and modularisation can provide significant cost and installation time savings [90].

A study by Bedair [90] shows that modularising pipe racks can reduce installation time and cost but the amount of supporting structural steel may increase by 30%, depending on the application, which can cause assembly and transport costs to rise [90]. Modular pipe racks are typically fabricated off-site in small modules that are fully outfitted with piping, electrical, instrumentation, and/or mechanical equipment and are then transported and installed *in-situ*. Connecting modules is often a problem, since pipe racks are multilevel and must be stacked at the construction site [121]. Conventionally, base plates are welded to pipe rack columns and are used to align stacked modules. These are relatively high cost solutions; types of inter-module connection include using bolts and endplate connections, pinned connections (cannot bear large loads), and shear taps (easy to fabricate) [90].

II.3.4.2. Solid Fuel Power Plant

Gotlieb *et al.* [86] compare conventional construction with modular build for both a 300 MWe pulverised coal-fired facility and a 300 MWe circulating fluidised-bed boiler plant, both of which used modularisation to reduce build time. In each plant, major equipment groups were broken down into skid-mounted modules, sub-assembled in factories, and shipped to site. For both plants, modularisation reduced the build schedule by 20% and construction costs by 12% [86]. Labour savings were a significant source of direct cost reductions, since the net productivity improved by 15% for modular build, shop labour was 20% less expensive than site labour, and the shorter *in-situ* time reduced equipment rental costs and the number of construction staff [86]. Some of the key modularisation strategies are listed below.

- Turbine generators

  Modularising the turbine generators was critical for reducing construction time and cost. The turbine generators were lowered from a conventional elevation of 40 ft to 25 ft, allowing use of a modular steel pedestal and eliminating the turbine deck.
- Feedwater heaters

  Both the high and low pressure feedwater heaters were modularised and stacked vertically, saving space and reducing the total amount of piping.
- I&C components

  Modularising the control and instrumentation components (electrical switchgear, motor control centres, and power distribution centres) involved shipping split assemblies of control panels, pre-wiring, and installing in-line instruments and sensors on modules.
- Repetitive systems

  Multiple skid-mounted M&E modules were connected using a modular 'backbone' pipe rack and repetitive systems, such as the materials handling system and coal handling equipment, were prioritised for modularisation. As far as possible, modules arrived on-site complete with piping, structural elements, valves, electrical components, and instrumentation and control systems installed.
- Civil structures

  Modularisation of the civil structural elements was not directly addressed, but more efficient M&E arrangements could reduce building size and weight, reducing the size of column foundations accordingly.

II.3.4.3. Chemical Plant in Harsh Environments

Modular construction is often used for chemical plants that are located in geographically remote regions to simplify the procurement of skilled labour. Modular construction has been used for natural gas plants in Alaska since the 1970's [78]. Alaska has rich natural gas resources but the extremely cold temperature, lack of light, and sensitive tundra environment restricts on-site construction activities [48]. Designers aim to optimise module design by maximising the packaging of equipment and components into a compact, integrated module while keeping the module weight within easily-transportable limits.

Parra & Bono [61] propose constructing a modular gas treatment plant on the North Slope in Alaska. Upwards of 70,000 tons of steel and equipment modules would be built at suitably equipped facilities and shipped using barge (modules up to 5,400 tons) or road/rail (up to 100 tons) around the world to the North Slope location. Since module size is directly proportional to module cost, it is desirable to keep the module base dimensions to a minimum. Modular design of the gas treatment plant in [61] is constrained by transport issues since modules are shipped to the site by barge in a single sealift to make use of the ice receding during the summer. If this summer window is missed, the entire construction project could be delayed by a year.

II.4. Modularisation in Large Nuclear

Current large nuclear projects are either semi-modular, such as the AP1000 and ABWR which use an on-site shop for fabricating large components, or else they use conventional *in-situ* building techniques; for example, the EPR design which transports and assembles raw materials in the NI and BoP. Nuclear power plant civil structures are highly complex and have irregular geometries, thick walls, a large number of embedment plates and/or inserts (which can interfere with reinforcements), complicated reinforcement details, and specifications for large diameter rebar [5] [25]. These complexities make nuclear power plants difficult to construct in a traditional *in-situ* way and thus designers and contractors are turning to modular build strategies in order to reduce uncertainty and improve quality, bringing down build time and cost [119].

Some NPP elements are already constructed in a factory, including components and individual equipment items such as valves, pumps, heat exchangers, steam generators, the reactor vessel, the pressuriser, turbine generators, and the polar crane. These elements are produced in a factory either because the tolerances of the fabrication process must be highly precise (e.g. RPV, steam generators, turbines) or because the components are off-the-shelf items that are easily procured from sub-suppliers (e.g. valves, pumps, heat exchangers). Attempts at modularisation have limited scope, although designers have tried to incorporate modular build techniques into large nuclear power plant designs since the 1970's. A detailed modularisation scheme for a 950 MWe PWR, developed by Stone & Webster Corporation in 1977 [60] has formed the basis for subsequent modularisation efforts by Westinghouse [71] on the AP1000 reactor and the Westinghouse SMR. The NPP construction programme in South Korea (OPR-1000 and APR-1400) followed the example set by the Japanese with their ABWR modularisation and standardisation efforts, transferring some of the knowledge and strategies for this between the ABWR and PWR programmes. While large reactor modularisation initiatives have focussed on both the piping and equipment systems as well as the structural elements, designs tend to produce specific one-off modules (or super-modules) for fabrication near the nuclear site. This strategy allows for parallel construction but does not develop a set of standardised modules for a wide range of structures and systems across the whole NPP [25].

This section presents three types of modules that are currently used in the construction of large nuclear reactors. These modules include structural modules, equipment modules, and combined modules (these latter integrate both structural and M&E components). All the examples listed here are current state-of-the art modularisation for the civil nuclear construction industry. It is clear from this review that modular construction has limited scope in civil NPP construction in terms of both structural and M&E modules and is very unlike the industries described earlier, which use modularisation and factory build in a highly developed manufacturing process to reduce construction costs and build time.

The issue with the current state of nuclear modularisation is either that the modularisation solutions are hypothetical, such as the ASTRID (Advanced Sodium

Technological Reactor for Industrial Demonstration) steel-plate concrete structural modules, or are implemented to resolve a particular construction problem on a case-by-case basis. For example, the Laing O'Rourke precast concrete structural modules using headed bar joints are implemented in limited cases in the Hinkley Point C EPR to allow for parallel construction of specific complex concrete-pouring tasks [119]; similarly, the OPR-1000 containment liner plate modules are used to remove the need to work at height and reduce the total number of lifts [122].

While the modularisation solutions discussed here are useful as proof-of-concept and demonstrate that both the structural and M&E components of a NPP can be modularised, is is clear that systematic, widespread, standard development of modules for civil NPPs is far from being the current practice. The nuclear industry does not presently follow the modularisation best-practices previously identified and modules are not standardised, built in an off-site factory, or series-produced. The final sub-section presents the hypothetical Stone & Webster module breakdown (Section II.4.4) and describes the best available systematic modularisation scheme for a civil PWR NPP, developing over 1,400 structural, equipment, and combined modules. While this is a conceptual modularisation breakdown, it nonetheless helps set a useful reference scheme on which further modularisation efforts can be based.

II.4.1. Structural Modules

NPP structural modules are complex elements and perform multiple functions pertaining to safety, structural integrity, containment, and confinement. The design and manufacturing challenges for these modules are significant since they must be readily producible without compromising safety or functional integrity. Modular structures are typically incorporated on a case-by-case basis in LR design to allow for parallel construction activities in the NI, but have not been widely implemented as a manufacturing solution for structural elements [119] [122] [123]. A study by Laing O'Rourke [124] claims that up to 70% of NPP civil works could be fabricated in a factory, reducing time on-site by 80% for the civil elements.

For conventional NPPs, reinforced concrete is used for most structures and is laid *in-situ*. This is a time-consuming and error-prone process, particularly in nuclear construction where the amount of reinforcement is high and the reinforcement grid spacing is small. Structural modules, however, can be based on either reinforced concrete (RC) solution or a composite steel-plate concrete (SC) solution, as shown in Figure II.4.

i. Semi-Modular Reinforced Concrete

Modular units of prefabricated reinforcement cages and/or concrete formwork are fabricated off site and are filled with concrete *in-situ*. These solutions have been shown to reduce traditional *in-situ* costs by 20% and on-site hours by 35% [125].

ii. Solid Reinforced Concrete

Reinforcement cages are manufactured in a factory and concrete is poured off-site; the modules are then transported to site and joined *in-situ*. These solutions have been shown to reduce traditional *in-situ* costs by 20% and on-site hours by 75% [125]. An example assembly for nuclear applications is shown in Figure II.5.

iii. Steel-Plate Concrete

SC modules, shown in Figure II.6, are walls composed of two parallel steel plates that are connected to one another using ties. Anchor studs protrude from the walls into the centre of the module [123]. The module is installed *in-situ*, welded to the neighbouring modules, and concrete is poured into the centre void area. The faceplates (thickness can range between 6mm and 20mm) provide additional mechanical strength for the walls through composite action, replacing steel rebar used in traditional reinforced steel construction [123]. SC solutions are typically semi-modular to reduce weight, but fully modular precast SC solutions are an option.

SC modules are more expensive than RC modules because they require significantly more steel and greater manufacturing skill than rebar-based solutions. SC modules also require careful transportation and lifting strategies to avoid deformation of the faceplates. Certification of SC modules for nuclear applications may be an issue in Europe, although they have already been accepted in Japan [51] and Korea [126]. The high mechanical strength of SC elements gives a higher-quality final structure and the continuous steel outer wall has the advantage of providing tight containment and confinement. The steel faceplates also provide formwork for concrete pouring and SC modules do not require temporary supports during fabrication.

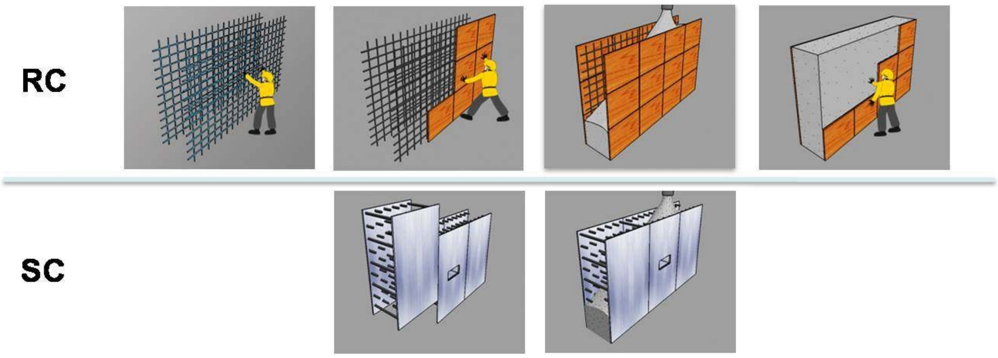


Figure II.4. Diagram of SC and RC structures [95].

Figure II.5. Test assembly of precast RC solid solutions using headed bar joints for NPP applications [124].

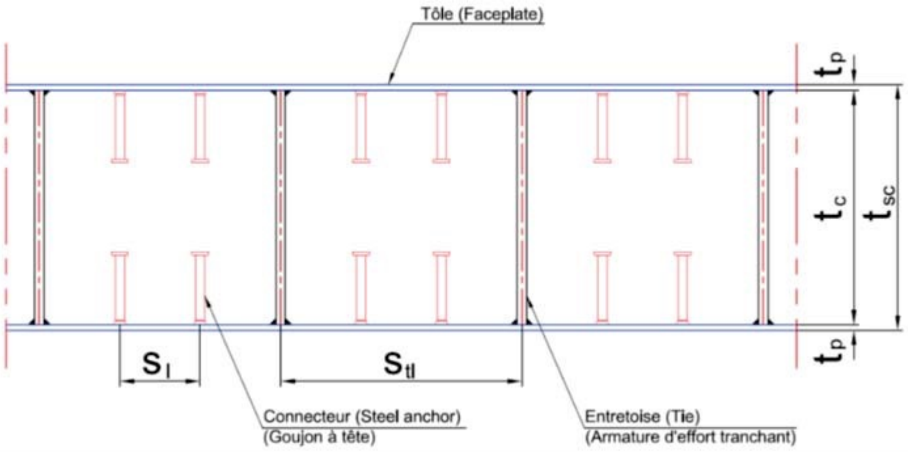


Figure II.6. Cross section of a SC wall [123].

Laing O'Rourke has focussed on modular RC solutions for nuclear applications [124] and has identified five key areas that need further work: standardisation of structural components, attention to complex structures, design of joints, manufacturing process, and on-site component assembly. Some of the manufacturing issues have been resolved by eliminating bent rebar in the module design and using straight rebar sections only. The formwork constrains reinforcement geometry and manual measurement is not necessary, improving the productivity of the steel-fixing process. Laing O'Rourke is also developing an interlocking headed bar joint connection for use between precast RC modules, as shown in Figure II.7, to enable rapid assembly on site. This headed bar joint arrangement allows for shorter lap lengths between precast panels but is susceptible to joint weakness since, like most precast solutions, it must be spliced and filled with concrete *in-situ*. Laing O'Rourke has tested this joint system to investigate the effect that concrete strength, spacing of the headed bars, splice length, transverse reinforcement and confining shear studs all have on joint strength and found that a lap length of 100 mm was enough to develop the joint's full strength (in concrete with 28 MPa cylinder strength) [119].

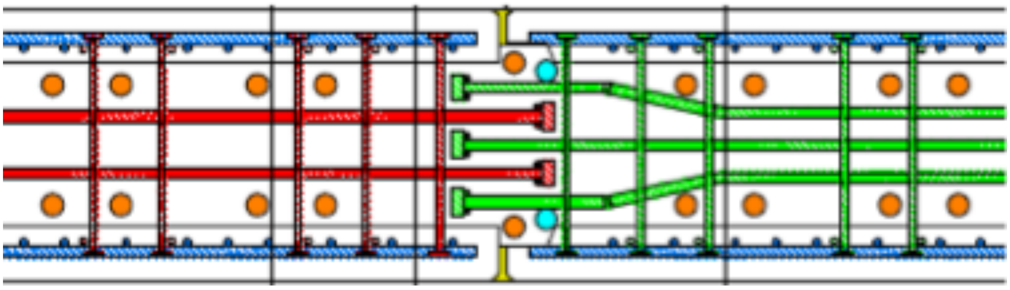


Figure II.7. Nuclear hybrid reinforcement using headed bar joints to connect precast concrete blocks [124]. Capable of meeting manufacturing tolerances < 10 mm.

II.4.1.1. ASTRID Steel-Plate Concrete Modules

Saunier *et al.* [123] examine the application of SC modules in the ASTRID nuclear reactor, a 600 MWe Gen IV sodium-cooled fast reactor demonstrator that is currently under development by the Atomic Energy Commission (CEA) in France. The intent is to fabricate the SC walls in a dedicated off-site factory and they will be transported to site using barges; modules will be approximately 30m long, 8m high, and weigh 100 tonnes [123]. A heavy lift crane will place the modules and they will be welded together before the concrete fill is poured. Modular SC walls in the ASTRID reactor will provide an estimated 12-month savings in the construction schedule over use of standard reinforced concrete; this is commensurate with a similar application of SC walls in the Japan Sodium-cooled Fast Reactor (JSFR) concept, which estimates a 20% savings in construction time [123]. The application of SC walls in the ASTRID reactor is illustrated in Figure II.8; the rationale for using SC modules in specific structures is as follows:

- Reactor pit
  Withstand severe accident load case and avoid large vertical rebar.
- Steam generator bunkers
  Provide mechanical strength against high pressure release.
- Inner steel sheet of the reactor building roof
  Act as formwork during concrete pouring and provide mechanical strength.
- Confinement walls (reactor building)
  Provide containment, remove confinement wall structures from the critical path, and provide mechanical strength against different operating/accident load scenarios.

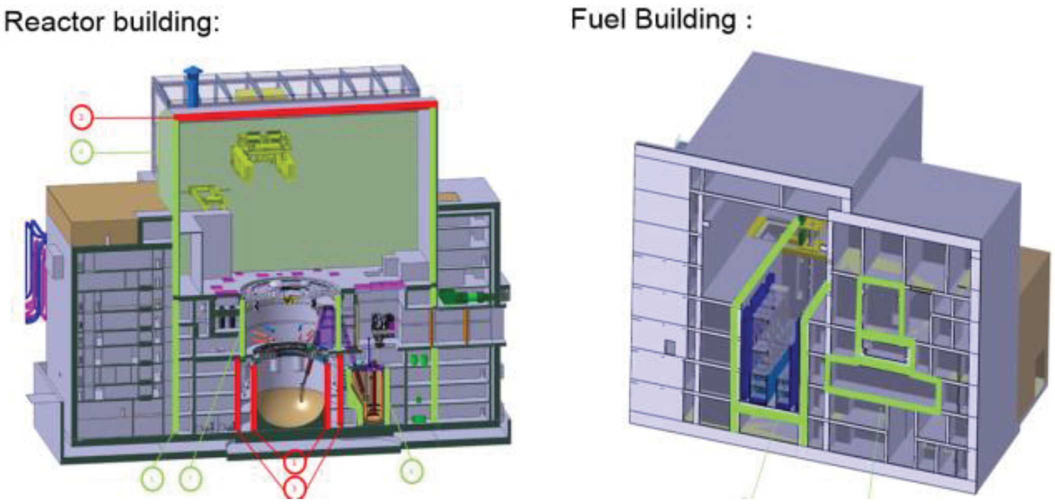


Figure II.8. Structures in the ASTRID NI where the CEA has studied (green) or will study (red) the potential use of SC modules [123].

II.4.1.2. APR-1400 Steel-Plate Concrete Modules

The APR-1400 reactor is a South Korean 1400 MWe PWR that also uses SC modules in its major buildings. The SC modules are used in the reactor building and auxiliary building; their locations are shown by the shaded red areas in Figure II.9. Lee *et al.* emphasise the concerns with SC module durability and recommend using the modules selectively while giving particular attention to the module joints [95].

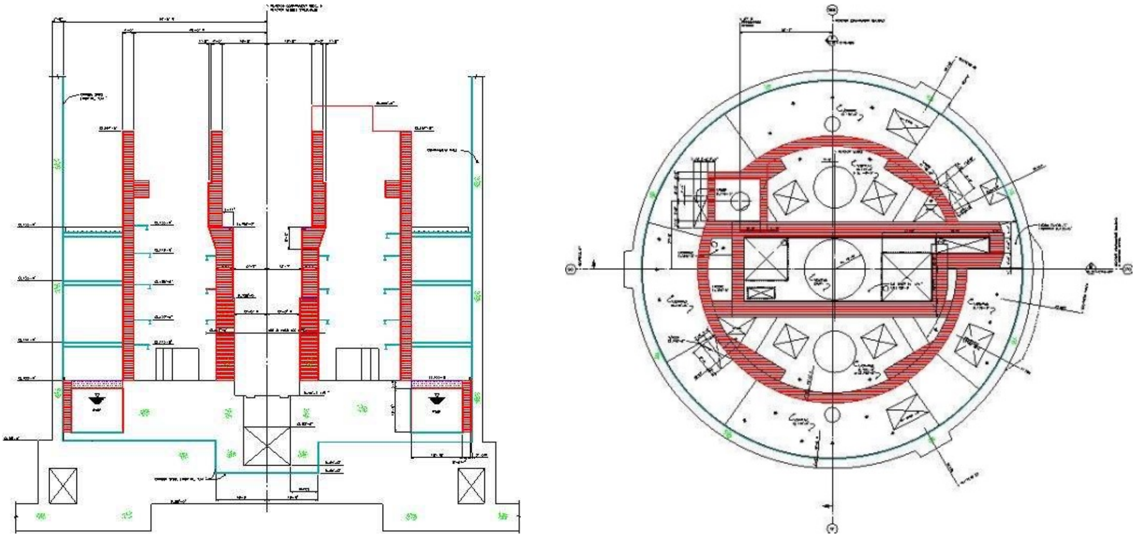


Figure II.9. Placement of SC structures (shaded red areas) inside the APR1400 reactor building [95].

II.4.1.3. OPR-1000 Containment Liner Plate Modules

Another type of structural module that does not involve concrete are the containment liner plates, which perform containment and confinement functions for the reactor building. The limiting factor for liner modules are dimensions and constructability, not weight, and crane capacity and transport logistics are not an issue [122]; however, the lifting plan and the lifting wires need to ensure that module deformation does not occur during placement.

The stacking procedure for the installation of the containment liner plate modules in the OPR-1000 PWR at the 2-unit Shin Wolsong site in South Korea combines smaller ring modules into a larger super-module before lifting it into place [122]. Modularisation of the containment liner plates reduced the number of construction steps at the Shin Wolsong site from 11 to 8 and provided a 30-day reduction in build schedule [122]. Modularisation allowed earlier rebar placement and the installation method made sure that rebar did not interfere with the containment liner plate. Finally, modularisation reduced the total number of lifts, enabling 54% of welding jobs to be performed instead at ground level, improving both worker safety and weld quality [122].

II.4.1.4. Westinghouse AP1000

The Westinghouse AP1000 reactor is an 1100 MWe PWR that attempts to incorporate modularisation in the construction of its structural, M&E, and piping systems within the containment building, auxiliary building, and turbine building [25] [127]. Most of the major structural modules are made from sub-modules that arrive via road or rail, are assembled into super-modules in the on-site shop, and are installed using a heavy lift crane [25]. Barge transport, where possible, permits off-site super-module fabrication and is currently under investigation by Westinghouse [30]. The AP1000 reactor uses five types of structural module [127]. There are 160 structural modules total, most of which are in the containment building (66 modules) and turbine building (52 modules) [25]

- Steel formwork modules filled with concrete; e.g. walls, floors
- Remain-in-place steel formwork modules with concrete poured around them
- Structural modules not outfitted with mechanical components; e.g. platforms, grating
- Structural modules that are also outfitted with commodities
- Steel stairway modules

II.4.2. Equipment Modules

Equipment modules for nuclear applications are summarised in a best-practice report by Barry [51], who conducted site visits and semi-structured interviews with experts from Hitachi-GE Nuclear Energy (HGNE), Mitsubishi Heavy Industries (MHI), and General Dynamics Electric Boat (GDEB). Equipment modules include piping, piping supports, components, platforms, and structures, but not electrical and/or I&C systems. All three companies performed qualification activities at the modular manufacturing facility, including weld inspection, stress analysis, stress reports, and continuity checks on electrical equipment. Inspections performed at the module facility are typically not performed again on site. HGNE states that, since adopting modular build techniques, construction periods have reduced by nearly 20% and site construction labour-hours by nearly 40% (since 1990). GDEB has observed the 1-3-8 rule-of-thumb: modularisation and related benefits have reduced the labour hours for Virginia class submarines by approximately 40%.

The common finding from these three companies indicates that module transport and lifting is the primary constraint on module size; however, HGNE and MHI transport solutions can be contrasted with that of GEDB, where modules are used in a naval application rather than civil nuclear construction. The maximum module size is typically 500-600 te and companies both design and build their own modules for a wide range of structural, mechanical, and/or equipment applications.

II.4.2.1. Hitachi-GE Nuclear Energy

HGNE uses 7 types of modules in their NPP designs: piping block, piping, platform, equipment, cable tray, special, and civil modules. A total of 193 modules are used in a current plant (as of 2009), compared to only 18 modules in 1985. Barry [51] finds that HGNE module and NPP design is 90% complete before construction begins, reducing rework by 20 times. Module weights vary from 5-650 tonnes and are shipped using trucks, trailers, or barges depending on the module weight, size, and site location.

II.4.2.2. Mitsubishi Heavy Industries

MHI uses four types of modules: large size modules (500 te), such as the containment dome; SC modules, such as piping sleeves; component and equipment modules; and piping modules. MHI's criteria for considering an area or location for modularisation include the number of welds, areas that have little need for lifting/movement after module installation, locations where structural strength is required and/or regions where modules will help fulfil shielding requirements. The modules are placed using an over-the-top method in which all modules and components are installed at a given level before progressing to the next. The module construction location is limited by transport constraints; small modules are built in an off-site factory and large size modules are constructed on-site.

II.4.2.3. General Dynamics Electric Boat

GDEB divides their Virginia-class nuclear submarines into 8 modular areas based on functionality. Each module is a stand-alone functioning unit: stern/aft end, habitability, auxiliary machinery room, weapons stowage/handling, and command & control systems. These modules are then further broken down and suppliers provide components or equipment skids.

II.4.2.4. Westinghouse AP1000

Westinghouse uses four types of mechanical module in the AP1000 [127]. There are 56 mechanical modules, most of which are in the auxiliary building (41 modules) [25]. These modules are typically placed in a steel frame for support and easier transport.

- Equipment modules include the equipment unit, associated valves, and piping
- Piping & valve modules contain piping, valves, and in-line piping components
- Commodity modules consist of piping and cable trays
- Service modules are a standardised configuration of service utility connections

II.4.3. Combined Modules

Combined modules integrate civil structural modules with other components, such as piping, cable trays, or ducting; and example r is shown in Figure II.10. Combined modules are typically selected if the equipment layout in a given area is very compact. The density of bulk commodities inside combined modules is a key parameter for module selection and design. Material acquisition and build sequence may be an issue for combined modules and may require extra planning or risk-reducing measures [95].

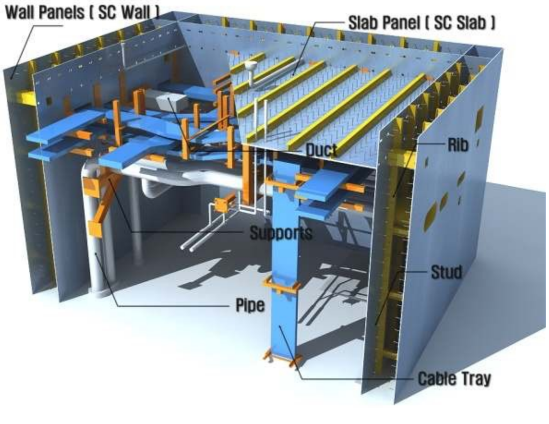


Figure II.10. APR-1400 combined module schematic, from [95].

II.4.4. Stone & Webster's Hypothetical Modularisation Scheme

Stone & Webster Corporation, an engineering service company in the US now owned by Westinghouse, developed a detailed modularisation scheme for a PWR in 1977 [60]. The scheme was proposed for a generic 950 MWe Westinghouse PWR, to eventually be used in the Sundesert NPP in California [71]. The Sundesert plant was cancelled by the state government of California due to public resistance to nuclear power [71]. Although the S&W modularisation scheme was never implemented, it likely informed subsequent Westinghouse modularisation efforts on the AP1000.

The S&W work is highly detailed and is used in this dissertation to set a baseline modularisation scheme for a generic NPP, as described in Section II.4.4. S&W use time and cost savings to determine final module selection; this dissertation adds to this requirement by applying UK road transport limits to constrain module size and weight. Feasible modules need to provide a least 5% cost saving (on materials or labour) with a minimum savings of $75,000 in 1976 US dollars (USD) while also reducing the critical path by at least 1 day [60]. The S&W report lays out in detail a set of over 1,400 feasible modules and describe each module in terms of its dimensions and weight, fabrication methods and guidelines, and contribution to cost and schedule reduction. S&W use an on-site shop for module fabrication, simplifying transport constraints to lifting logistics only. Table II.4 summarises the relevant module types and their quantities and Appendix II highlights key module fabrication details.

Advantages: S&W Modularisation Scheme

Some of the main advantages of using the S&W work as a baseline modularisation scheme for this dissertation are listed below.

i. Data Availability

The S&W module scheme is the only such scheme that is publicly available for a PWR.

ii. Data Detail

The level of detail, in terms of module numbers, weight, and geometry, is invaluable and provides comprehensive design and decision-making data for modules.

iii. Rigour of Modularisation Scheme

The modularisation scheme rigorously considers modularisation of structures, equipment, and piping components across the whole plant, not just the reactor components (as in Chen & Goldberg, who consider manufacture of the IRV unit only), or specific buildings (as in the Westinghouse AP1000, South Korean OPR-1000 and APR-1400, ASTRID fast reactor).

Disadvantages: S&W Modularisation Scheme

i. Age of S&W Report

Developments since the 1970's may affect how representative the S&W scheme is of current PWR reactors. Nuclear design and technology has evolved and regulations are more stringent. Components or systems that S&W considered well-suited to modularisation may require further design effort and/or justification in today's NPPs. Additionally, manufacturing technologies have evolved and elements that S&W may have considered as un-modularisable or too difficult to manufacture in an off-site factory may now be feasible. Finally, the relative costs of materials, construction, and labour have changed since S&W times and may alter the outcome of the module cost/time feasibility assessment.

ii. Limited Application of Modularisation

Although the S&W modularisation scheme has a broader scope than most modularisation work, it still does not modularise the entire NPP. This project assumes that the scheme can be applied to and is representative of a generic NPP in its entirety.

iii. Incomplete Feasibility Criteria

Scheduling and economic criteria alone may not be sufficient to determine whether a module should be implemented. The S&W constraints on time and cost may be too stringent and/or may not be the only criteria for determining a module's feasibility. For example, HGNE developed 200 NPP equipment modules, most of which were implemented to reduce the number of workers on-site and improve NPP constructability. Only 10 of the HGNE modules directly contributed to schedule reduction [51].

Table II.4. Summary of S&W module types, number of modules, total weights, and location in the NPP, data from [60].

	Number	**Weight (te)**	**Specific Types**	**NPP Building Locations**
Structural Modules				
Reinforcing steel	664	13,670	mats, walls, floor and roof slabs	containment, annulus, turbine
Precast concrete	379	78,340	walls (exterior & interior circumferential, radial & cubicle, shield) and slabs	annulus, turbine, diesel-generator, control
Structural steel	185	5,250	floor, roof	annulus, turbine, control
Liners	36	1,580		containment, transfer canal, spent fuel pit
Polar crane supports	14	1,110		
Mechanical Modules				
Skid-mounted equipment	70	940	sump, demineraliser, filter, moisture separator/reheater, feedwater pump & turbine, condensate polishing equipment	annulus, fuel, turbine
Condenser	7	190	tube bundle, steam inlet assembly, water boxes	
Tanks	12	1,420	auxiliary feedwater, refuelling water storage, miscellaneous	annulus & other miscellaneous
Piping	13	150	main steam, reactor plant service water & component cooling water, decay heat removal, containment spray, primary coolant piping	annulus, containment
Pipe racks	39	1,240		annulus
Electrical Modules				
Non-seismic cable trays	N/A	N/A	N/A	N/A
Non-class 1E cables	N/A	N/A	N/A	N/A

II.5. Pre-fabrication Facility Considerations

This section briefly introduces some of the strategic issues that surround designing and building a factory to produce modular components for a specific product. The role of the factory in modular build is to provide an off-site construction environment to improve productivity and enable learning. Using modular construction techniques pre-supposes that a suitable factory facility can be built which is capable of producing the required set of modules at the volumes and times required. This project focusses on the benefits of using modular construction for building a NPP and does not consider issues beyond the construction site, except for the constraint transport requirements place on module design. While the S&W scheme assumes an on-site module factory, to simplify transport logistics, it does identify six factors that are critical when determining the nature of the module factory [60]:

- The type of access to the site (barge/rail/roadway)
- The site's geographical location
- The structural integrity of the modules during transport
- Whether the module production facility can be temporary or permanent
- The nature of construction labour contracts
- Whether module production is subcontracted

In general, a module production facility can be located close to the construction site (an 'on-site shop') or at non-negligible distance from the site (an 'off-site factory'). The decision of where to locate the factory depends in part on the type of product being constructed and whether it is geographically constrained (a bridge or NPP) or not (automobile). The level of outfitting of the factory is another factor that determines the type and location of the factory. The facility could essentially be a covered workspace/shed that provides a protected space for workers to build bespoke modules, as in Forterra's Bison precast component production facility [23]. On the other extreme it could be a fully equipped production line with configurable robotic equipment and automated systems, like in Laing O'Rourke's Explore Industrial Plant [24] or an automotive factory. The capabilities required of the factory are also important; this deals with the types of modules that are produced and influences whether the factory needs to be capable of building formwork, fixing rebar, pouring concrete, welding, forging steel vessels, laying electrical wiring and cables, and so on. The factory layout and production rate enables learning and deals with the order in which modules are fabricated, the arrangement of the factory floor, the flow between work stations, and the frequency and extent of retooling. Finally, independent equipment and component suppliers can be considered part of the factory supply chain. Their production methods will pass learning and productivity benefits on to the final product and should be considered part of the factory supply chain. The extent to which these benefits can be incorporated depends on the supply chain organisation, as in [16].

II.5.1. SMR IRV & Factory Learning Rates

Factory layout, work flow, lot size and production rate, and factory outfitting are crucial to manufacturing quality and cost. Chen *et al.* [35] model the factory production of IRV components for a generic 100 MWe PWR. Their study is limited in scope since it considers only the IRV unit and does not extend the analysis to piping systems, mechanical and electrical systems or equipment, or civil structures. The IRV components include the integrated reactor pressure vessel, reactor core, control mechanism, coolant pumps, steam generator, and pressuriser. Chen *et al.* used software from the manufacturing industry (specifically, SEER-MFG project estimation software [128]) to conduct a bottom-up estimation of model labour, material, tooling, and fabrication costs for the IRV unit.

The production lot size is key to the factory layout and is defined by Chen *et al.* [35] as the number of units produced by the factory before the production line is retooled or reconfigured. This introduces a trade-off, since changes to the factory cause a short-term increase in production costs but are accompanied by the potential for a longer-term decrease in cost arising from the production changes. The minimum lot size is the lowest number of units a buyer would have to purchase in order to ensure the factory production environment remains cost efficient.

Chen *et al.* modelled IRV factory manufacture in lot sizes of 1 through 12 over a total production of 120 units, and concluded that lot sizes of 5 units or more had the greatest degree of cost efficiency. The greatest incremental gains occur across lots of 1-

4 units; for lots larger than 5 units, further cost benefits are negligible, as shown in Figure II.11 below. Chen *et al.* sets the optimal lot size at 6 to enable the factory to sustain small variations in order size [35]. Interestingly, the optimal lot size was found to be independent of the specific IRV design details. Chen *et al.* [35] assume the learning rate is independent of production rate and estimate that a SMR IRV could achieved a learning rate of 6.7%. This is slightly lower than the learning rates achieved in other manufacturing sectors; for example, the electronics industry (5%-10%) and aerospace (15%) [34].

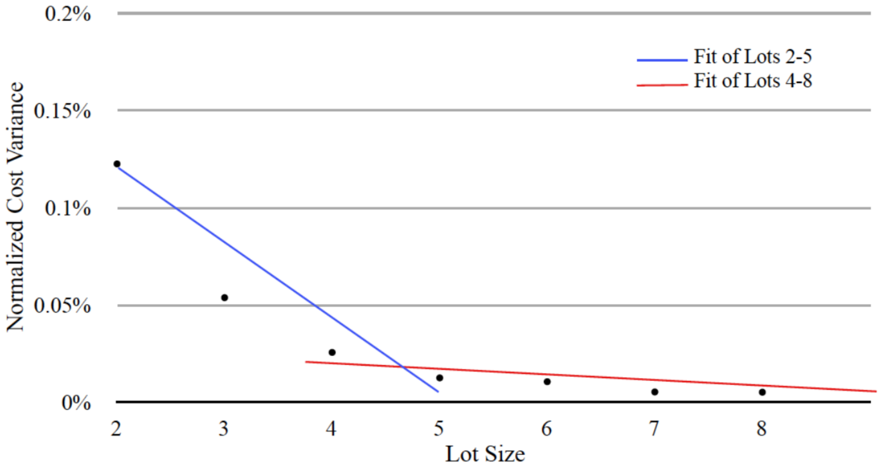


Figure II.11. Reduction in SMR IRV production cost based on lot size [35].

II.6. Conclusions

Modularisation moves complex construction work in discrete packages, or modules, from the site to a production facility. DfMA needs to be a priority and, for NPPs, requires a shift in how the final product is viewed, how the production process is developed, and the criteria that are used in designing and developing modules. Much of this modularisation best-practice can be identified from theory in literature and practice in already-modular industries. The key constraint limiting modularisation of NPPs is module transport and will affect the module’s design, weight, and geometry.

This Chapter collates a body of evidence, based on literature studies and industrial experience to demonstrate that modular build has been successfully adopted in a variety of industries and to show some of the benefits modularisation can have in terms of schedule and cost reduction, quality improvements, and better safety. A review of modularisation in the shipbuilding, civil, aerospace, automotive, and oil & gas and chemical process industries shows how module development and application of modularisation depends on the specific needs of the industry. Modules are typically developed around sector-specific or project-specific constraints, such as minimising time in the dry-dock (shipbuilding), maximising product customisability (automotive, aerospace, and some civils), or minimising the length of piping runs (chemical process). The specific benefits of modularisation in terms of on-site time and cost reductions depend on the degree to which a product is modularised as well as the design and location of the module production facility.

The work in this Chapter lays the basic foundation for answering some of the critical questions for NPP modularisation in general and SMR modularisation in specific; that is: how the power plant should be divided into modules, based on functional and physical areas, how much of the plant can be feasibly modularised, and what the resulting time and cost benefits are. If modularisation is to be used in SMR applications, it will need to be applied more extensively than it has been in any LR design to date, which tend to use a few hundred modules, or a few dozen super-modules, to allow parallel construction. The S&W scheme approaches the level of modularisation that SMRs would need to have with over 1,400 structural, mechanical, equipment, and liner modules.

CHAPTER III
ESTIMATING SMR COST & SCHEDULE

III.1. Introduction to Cost and Build Time Modelling

To date, 56 different SMR designs are proposed worldwide, according to the IAEA [37] and two based on military technology are being built (KLT40S in Russia and ACP100 in China), but no civil land-based PWR SMR power plant has been constructed or is currently under construction. This creates an experiential gap between theoretical SMR designs and real construction practice, and no useful schedule or cost data are available for SMR construction.

This Chapter uses the construction cost of SMR civil structures as an example to demonstrate how estimates can be used to fill the knowledge gap arising from the lack of actual SMR construction data [129]. In the first instance, a top-down method is used to scale construction data from similar, completed LR projects to generate an estimated SMR data set. In the second instance, a conventional bottom-up approach is used and couples raw material with labour inputs for a complete reactor plant design to generate an overall cost estimate. This Chapter compares the two estimating methods in terms of their advantages and disadvantages as well as the similarities and differences between the results, and selects and justifies one for use throughout this dissertation.

III.2. Top-Down Modelling: Power Scaling

Top down estimation methods are appropriate if detailed design information is not available for a power plant construction project, or if the cost estimate is performed during preliminary planning stages when fundamental design, strategic, or procurement changes are likely [129]. Power scaling is widely used for estimating the costs of power project, both in the nuclear industry as per the OECD [9] and for conventional power generation [130]. The power scaling method is derived from power-to-size geometric observations and is commonly used in power generation industries for sizing or estimating the cost of a new power plant, a section of the plant, or a major piece of equipment.

III.2.1. Derivation of Power Scaling

Scaling is used in many different energy applications, including cost estimates for process equipment, electric equipment and technologies, fossil-fired power plants and NPPs, electric utilities, fuel and operation & maintenance costs, and more [131]. The cost of a piece of equipment is proportional to its area, while the equipment capacity (power output) is proportional to its volume. As the volume doubles, the surface area increases by a factor that is less than two (this is dependent on the surface geometry); therefore, a larger piece of equipment will cost less per unit power than a small one [131]. Equation III.1 gives the scaling equation in its most general form, where K is cost, Y is the capacity (or power output) of the unit, a and b are constants, and n is the scaling exponent. Note that n, a, and b must be determined based on real build data and construction experience.

$$K = a + bY^n$$

Equation III.1. General form of the power scaling equation [131].

Comparing between two units of different capacities means that the constants a and b can be eliminated to give Equation III.2, the scaling relationship used throughout this dissertation. In Equation III.2. the subscripts i and *ref* refer to the reactor in question and the reference baseline reactor, respectively, *Power* refers to the rated capacity of the reactor (in kWe), and *Parameter* refers to either module weight (in kg), task duration (in days), or equipment and commodity cost (in 2017 USD) depending on whether the transport, schedule, or cost model is being developed. As before, n is the commodity-specific scaling exponent. This scaling approach has been used by recent studies and literature related to cost estimations for nuclear power generation and the approach in this project is consistent with the literature and industry cost estimation practice (Bowers *et al.* [132], OECD cost-estimating guidelines [129], Carelli *et al.* [12], NuScale [133]). Scaled SMR cost estimates from Carelli *et al.* [12] are shown in Figure III.1.

$$Parameter_i = Parameter_{ref}\left(\frac{Power_i}{Power_{ref}}\right)^n$$

Equation III.2. Power scaling equation.

Bowers *et al.* [132] derive the values for n, the scaling exponents, based on historical nuclear power plant construction cost data from the Nuclear Energy DataBase (NEDB). The scaling exponent values are assigned according to the 2-digit COA commodity headings as listed in Table III.1. To derive the scaling exponents listed below, Bowers *et al.* reviewed 34 different sources published between 1968 and 1982 which reported NPP costs for reactors between 400 MWe and 1200 MWe. Bowers *et al.* also include a summary of estimates for cost-size scaling exponents based on experiential observations from the architect-engineer, contractor, utility, and manufacturer, to further confirm the reasonability of the derived scaling exponents.

Large changes between power plant sizes may entail design or concept changes; for example, the number of cooling towers that are required usually increases with plant size. Appropriate use of the scaling exponents is outlined in more detail in the NEDB summary report; however, the 'derived' scaling exponents can be used even if there is a large NPP size difference because they are based on a wide range of source data and take into account non-trivial design differences [58].

Table III.1. Power-scaling exponents[1], from Table 2.12 p. 31 [58], repeated by [132].

Account Name & Number	**Scaling Exponent, *n***
Direct Costs	
Land & Land Rights	0.00
21 - Structures & Improvements	0.59
22 - Reactor/Boiler Plant Equipment	0.53
23 - Turbine Plant Equipment	0.83
24 - Electric Plant Equipment	0.49
25 - Miscellaneous Plant Equipment	0.59
26 - Main Condenser Heat Rejection System	1.06
Indirect Costs	
91 - Construction Services	0.69
92 - Home Office Engineering & Services	0.60
93 - Field Office Engineering & Services	0.69
Owner's Costs	0.64
Cost-Weighted Average	0.64

---

[1] Coefficients derived from PWR/BE cost models; applicable for large changes in plant size.

III.2.2. Application of Power Scaling to NPPs

The belief that larger power nuclear reactors will be cheaper, per kWe, than small ones has been responsible for the ever-increasing size of NPPs [18] [134]. In light of the rising costs and build times of nuclear power, several literature studies have examined the veracity of the perceived economies of scale. The studies published by Cantor & Hewlett [19], Ganda & Hansen [135], Ramana [136], Rothwell [20], and Berthélemy & Escobar-Rangel [44] are very useful in separating out the factors that contribute to NPP cost, explaining why economies of scale may not be observed in LRs. This is not to say that scaling does not hold true in relation to the individual cost components of power plant construction but, coupled with the logistical problems of managing increasingly large projects, the limitations of economies of scale have become apparent in US construction data from the late 1980s. This is also observed in IAEA data on historical reactor construction times, where reactor build time increases with NPP size (Appendix I.1).

Cantor & Hewlett [19] present an econometric analysis of 67 nuclear plants within the US, showing how the economies of scale for LRs are often offset by longer construction schedules, management difficulties, regulatory stringency, and other factors related to the complexity of large plants. Build times also increase with power plant size, perhaps because management of the project becomes progressively more difficult, and Cantor & Hewlett [19] find that OCC rises by approximately 10% for each one-year delay in construction schedule, further offsetting the economies of scale. The net effect of each 1% size increase is a 0.13% rise in NPP OCC [19].

Greater design complexity also leads to both decreased labour productivity and to an increased number of regulatory changes. The correlation between greater regulatory activity and increased NPP construction cost is echoed by Ganda & Hansen [135], Ramana [136], and industrial experience [4] [47]. Rothwell [20] examines economies of scale in steam-electric power generating units, and is able to observe and quantify the scaling effect in coal power plant construction. In the nuclear industry, however, the evidence for economies of scale is less clear, which Rothwell [20] attributes to the small number of observations and the lack of NPP size variation in the nuclear industry. Rothwell [20] estimates the relationship between NPP size, lead time, and construction cost; Berthélemy & Escobar-Rangel perform a similar, more recent, analysis in [44].

More recently, and with respect to SMR cost estimates, Carelli *et al.* [12] apply scaling to both the direct and indirect cost elements of a SMR facility (equipment, material, and labour) as shown in Figure III.1. Stick-built SMR specific cost estimates are very high; the smallest units (100 MWe) can have an expected average specific capital cost about 2.75 times that of the reference LR. There are four ways in which SMR-specific savings can reduce the final specific SMR capital cost to 1.05 times that of a reference LR through co-siting multiple units, unit replication and standardisation (achieving learning), financial aspects (smaller units are easier to finance as they can be built in stages), and modularity and design solutions [12]. SMR vendors are also beginning to use scaling to estimate the costs of their concept designs; NuScale has used a method very similar to the one adopted by Carelli *et al.* [12] to estimate the total construction cost of their SMR design [133].

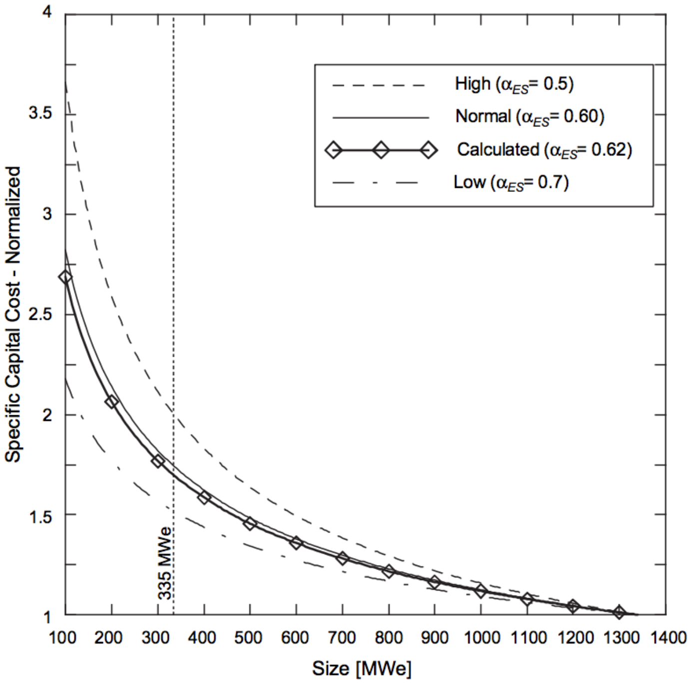


Figure III.1. Economies of scale as a function of NPP size for low, normal, and high scaling exponents (α_{ES}), from Carelli *et al.* [12].

III.3. Bottom-Up Modelling

A bottom-up estimate uses raw material and labour inputs, on a cost per unit basis, to provide a total cost estimate for the power plant facility. This method requires a detailed power plant design with known or quantifiable material and labour inputs. There are three main PWR design technologies that are relevant.

- **Gen II Reactors:** typical as-built PWRs from the 1970's and 1980's. A comprehensive set of Gen II reactor construction data, based on median experience from NPP construction in the US, are in the EEDB Phase IX update report [57].
- **Gen III Reactors:** also called 'evolutionary' reactors, these LWRs have a more advanced reactor plant design and construction than Gen II designs. A Gen III reactor example is the ABWR.
- **Gen III+ Reactors:** these LWRs adhere to higher safety requirements than Gen II reactors by reducing core damage frequencies and protecting the system against both internal and external hazards. Gen III+ reactors include the AP1000, which uses passive safety systems, and the EPR, which has extensive, highly engineered safety systems.

In general, Gen III/III+ reactors are subject to higher safety requirements than Gen II reactors which preceded the incidents at Three Mile Island (1979), Chernobyl (1986), and Fukushima (2011). This significantly affects the design and material requirements between Gen II, Gen III, and Gen III+ reactors [62] [137]. The materials required for NPP construction also depend on specific siting and location factors.

Finally, indirect costs including overheads, design and engineering, supervision, and so on, are usually estimated using multiplicative factors which are applied to raw material and labour inputs to reflect the expected overhead and preliminary costs that will be incurred by projects of a similar type, scale, and build duration [138].

III.3.1. Derivation of Bottom-Up Estimate

This section explains how an example bottom-up cost estimate was performed for different Gen II/III/III+ PWRs, both LRs and SMRs. The bottom-up cost estimate calculation is the sum of each input quantity multiplied by its unit cost, as shown in Equation III.3, where K is the total number of commodities and i is each specific commodity type. In this case, only the cost of civil structures is estimated and includes excavation, fill, formwork, structural concrete, concrete fill, reinforcing steel, embedded steel, or structural steel.

$$Specific\ Cost\ = \frac{\sum_{1}^{K}\big((Material\ or\ Labour\ or\ Overhead\ Input\ ) \times (Unit\ Cost\ Rate)\big)_{i}}{(Reactor\ Power)}$$

Equation III.3. Bottom-up cost estimation calculation.

Material input quantities for the civil structural commodities are listed in Table III.2. Experience-based quantity data are available from the EEDB for a Gen II PWR (Table 4-1 and Table 4-3 in [57]) and for a current Gen III+ PWR [138]. Material input quantities for Gen III and Gen III+ PWRs are estimated as per Figure III.2 using experience-based conversion factors available in literature from Peterson *et al.* [62] and the OECD [137]. For this second assessment, unit cost rates for each commodity type were provided by construction experts [138] based on actual experience of recent NPP construction in the UK and include both material and labour costs, providing the as-installed cost of civil structures. Specific construction costs for each reactor type are normalised with respect to the estimated EEDB Gen II 1144 MWe reactor construction cost to protect the commercial sensitivity of the experience-based values.

Material inputs for SMRs are more difficult to determine because no experience-based data are available. There are two solutions to this issue, shown in Figure III.2. The first solution scales the input material quantities for SMRs based on LR quantities, using the derived cost scaling exponent for the ‘structures and improvements’ category from Table III.1. Peterson *et al.* use this method in [62] to estimate material inputs for reactors where actual quantity data are unavailable. The second solution uses what rough conceptual designs and/or plans of a SMR plant are available to estimate the expected amount of steel, concrete, and formwork required. This method was used on the NuScale SMR (600 MWe) design, according to Figures A.I.9 and A.I.10 in Appendix I.3, assuming that the available designs are complete, accurate, and to scale. The results presented here also assume that an integral reactor will not have significantly different structural concrete and steel requirements, relative to NPPs that are not integral. Whether or not the NPP makes use of forced or natural convection for primary loop cooling will increase the size of the reactor building structures and will consequently have a substantial impact on the construction quantities of concrete and structural steel. The potential structural construction cost differences between active and passive cooling are ignored in this analysis.

A comparison of the bottom-up and top-down cost estimates is provided in Section III.4.

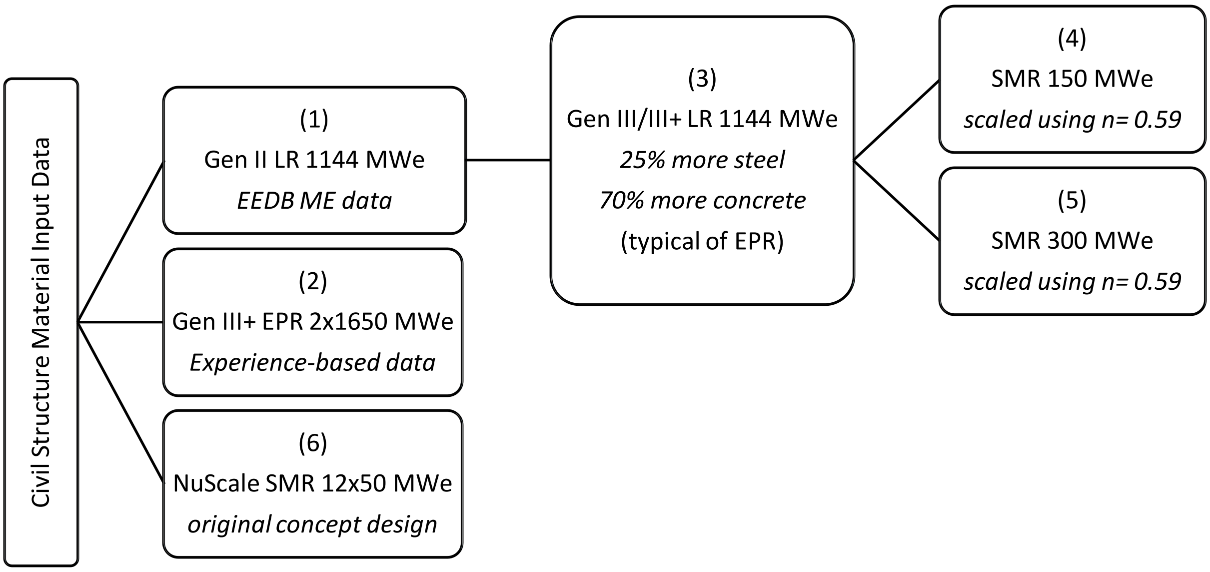


Figure III.2. Sources and derivation of material input quantities for bottom-up estimates.

Table III.2. Summary of material input quantities for Gen II, III, and III+ LRs and SMRs. Quantities with an (*) are inferred based on EEDB values [57].

		(1)	(3)	(4)	(5)	(6)
		Gen II LR *Baseline EEDB data*	**Gen III LR** *EEDB data + conversion factors*	**Gen III/III+ SMR** *150 MWe scaled*	**Gen III/III+ SMR** *300 MWe scaled*	**NuScale SMR** *12x50 MWe concept design*
Power	MWe	1144	1144	150	300	600
Excavation (rock/earth)	m^3	455,625	774,563	233,603	351,631	234,000
Fill (rock/earth)	m^3	278,049	472,683	142,558	214,585	-
Formwork	m^2	198,861	338,063	101,958	153,471	86,467
Concrete		196,598	334,216	100,798	151,725	135,092
Structural Concrete	m^3	121,829	207,109	62,463	94,022	-
Concrete Fill	m^3	74,769	127,107	38,335	57,703	-
Steel		34,614	43,267	13,049	19,642	61,052*
Embedded Steel	te	1,743	2,178	657	989	3,074*
Structural Steel	te	9,894	12,367	3,730	5,614	17,451*
Reinforcing Steel	te	22,977	28,721	8,662	13,039	40,528

One limitation with the bottom-up cost estimation method is that there are no detailed SMR designs available; therefore, the SMR estimates presented here assume that the known material input quantities from large reactors can be scaled to accurately estimate material quantities for SMRs. Alternatively, in cases where very high level design details are available, the information is assumed to be accurate and to-scale, allowing SMR material inputs to be estimated. Neither of these methods provides a true bottom-up cost estimate.

Finally, the estimates presented here assume indirect costs are not included in any of the bottom-up data provided. This is a limitation of this method since indirect, or preliminary, costs will be incurred on top of the direct, as-installed, costs presented in the bottom-up estimate. The magnitude of these costs depends on the size and duration of the project and, for the civils and structures category, are assumed to include [138]:

- Engineering (civils & structure)
- Site supervision
- Commercial (including risk) construction management
- Design and project management
- Planning and project controls
- Procurement and logistics management
- Quality management/assurance
- HR and training, HS&E management

III.4. Comparison of the Two Estimation Methods

This section compares the top-down and bottom-up construction cost estimates for the civil structures of different PWR NPPs. Results are shown in Figure III.3. Estimates are for civil structural site material and site labour only; indirect and preliminary costs are not included.

- **Top-Down Method:** uses cost-power scaling according to Equation III.2 and applies the scaling exponents (Table III.1) to EEDB cost data [57] for structural accounts only (Account 21 and Account 261).

- **Bottom-Up Method:** multiplies each commodity input quantity by its unit cost rate (as in Section III.3.1) and uses experience-based material inputs (Table III.2) and unit rates [138].

It is worth noting that Gen III+ LRs, specifically the AP1000, have significantly lower projected material input quantities than Gen II and Gen III reactors. This is a consequence of more compact equipment arrangement and passive safety systems which require less structural concrete and steel [25]. Gen III+ reactors are not included in the analysis below because the available data on material inputs is incomplete and very limited.

The cost estimates in Figure III.3 show that the bottom-up results for Gen II and Gen III LRs (bars (1), (2), and (3)) are all within a ±25% range of one another as well as the top-down LR estimate (solid black line). This is an acceptable degree of variation given that these estimates are performed at a high level on conceptual designs, and substantial material quantity and cost data are not available.

Similarly, the SMR bottom up estimates (bars (4) and (5)) are comparable to the scaled SMR cost estimates (black diamonds, as marked). The bottom-up estimates indicate that a Gen III SMR will cost 2.5-3.25 times the cost of the bottom-up baseline (bar (1)). Scaled estimates suggest that SMRs will cost 2.0-2.5 times the cost of the top-down baseline Large Reactor (solid black line). These findings agree with the scaling effects calculated in literature by Carelli *et al.* [12] where a 150 MWe SMR, for example, is expected to cost about 2.5 times as much as the LR baseline, as shown in Figure III.1.

It is worth noting that the bottom-up NuScale estimate (bar (6)) is of a similar order of magnitude to the 300 MWe scaled SMR cost estimate (bar (5)). The NuScale design consists of a single large reactor building with 12 small reactors. While the safety systems are simplified in the NuScale design, it has a very large pooling and containment area, which means the civil costs can be expected to be higher than a single medium-sized 600 MWe reactor. Figure III.3 suggests that the NuScale cost would indeed be higher than that of a 600 MWe unit, since it is more in line with the cost of a 300 MWe SMR.

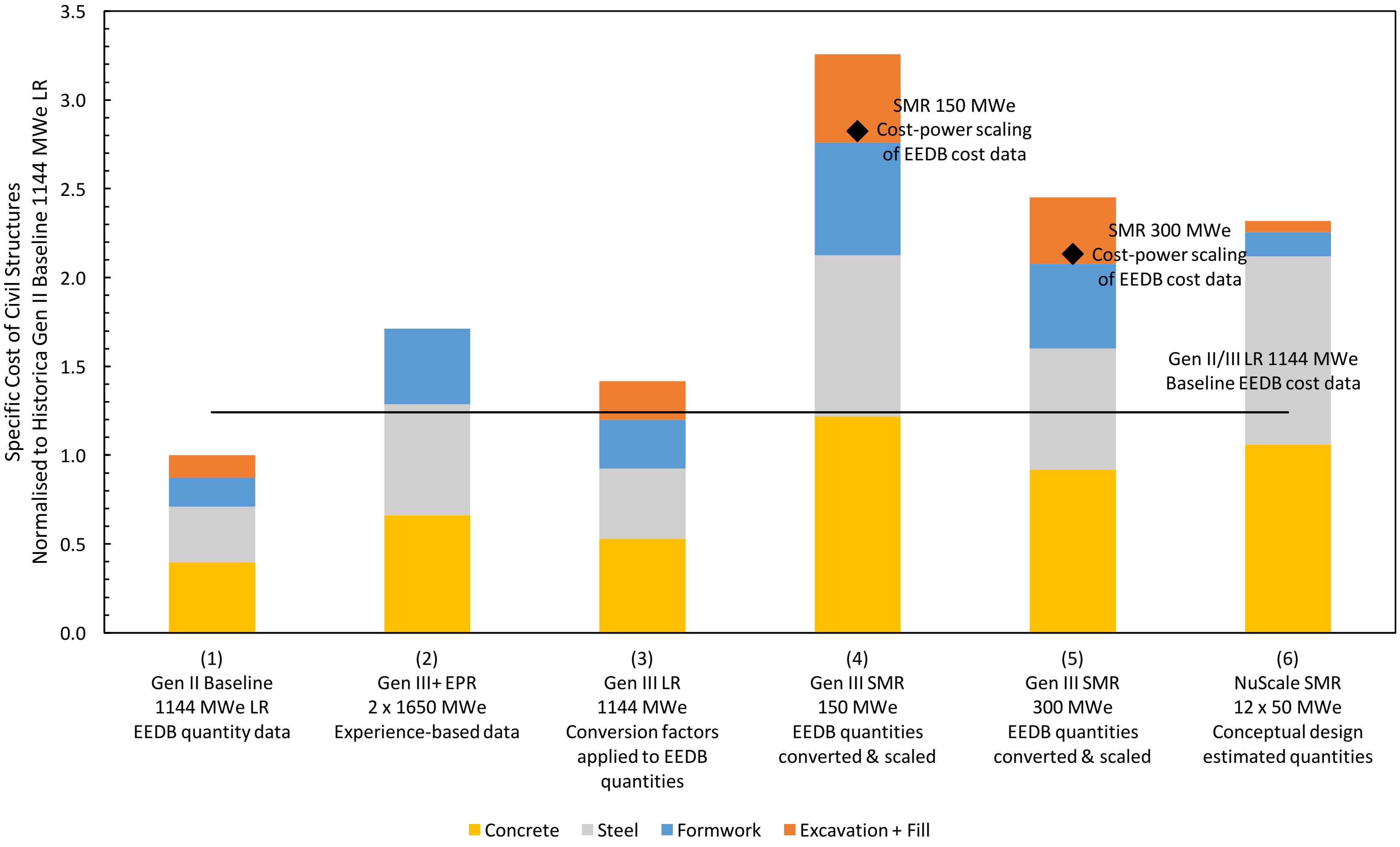


Figure III.3. Comparison of bottom-up (bars) and scaling (lines) construction cost estimates for civil structural elements; normalised to historical data from (1) Gen II Baseline 1144 MWe LR.

III.5. Conclusion

Power scaling is a widely accepted method for estimating construction costs across power generation industries, not just the nuclear sector, and is recommended for use at the proof-of-concept stage [129]. The scaling method is used throughout this dissertation and seeks to provide relative schedule and cost estimates for SMRs based on LR reference data. It is an appropriate estimation method, especially given that similar NPP designs are being scaled and compared. The results from the top-down and bottom-up cost estimates for civil NPP structures fall within a ±25% range of one another, which is not a significant difference given the level of accuracy expected from this type of preliminary study (uncertainty is discussed in Chapter VII; acceptable accuracy of preliminary estimates is shown in Table VII.3). The comparison between the bottom-up and top-down cost estimates in this section is intended to increase confidence in the use of scaling and show how it offers similar accuracy to bottom-up estimates while providing significant methodological advantages. Chapter VII assesses the resilience of the transport, schedule, and cost models in response to scaling exponent variability.

The major advantage to using scaling is the availability of LR baseline data, particularly given the absence of equivalent SMR data. The baseline modularisation scheme, build time, and construction cost data are all suitable for use with top-down methods. Input quantity data, on the other hand, are much more difficult to procure and restrict the use of bottom-up cost estimates – even for LRs, which have worldwide construction experience. Carrying bottom-up cost and build-time estimates forward at a level of detail and accuracy comparable to that of top-down estimates requires much more detailed SMR design information than is currently available. This lack of sufficient SMR design data poses a real challenge to confidently generate a bottom-up SMR cost estimate.

A second advantage to using top-down estimates is that power scaling can be applied to any size of reactor, thereby allowing trends in construction cost and build time to be be estimated as a function of reactor power. Using bottom-up methods for this would require specific and distinct designs for each different reactor size. Power scaling is also derived and set up according to the COA structure, making it easy to integrate the cost, schedule, and transport work developed through this thesis. The COA structure is also used widely in nuclear cost literature, making it straightforward to compare the findings from this thesis with other studies and estimates. While specific modular SMR designs and rigorous bottom-up cost and schedule estimates would be valuable in subsequent, more detailed, stages of SMR development, this type of analysis is beyond the scope of this project.

CHAPTER IV
TRANSPORT CONSTRAINTS ON MODULARISATION

IV.1. Introduction to Transportation Considerations

Off-site manufacture is used to reduce the high construction costs and long build durations that are typical of NPPs by moving site construction activities to facilities that are conducive to efficient and rapid production. The central premise of this project is that SMRs need to be produced using a manufacturing-type process to realise the full extent of off-site construction benefits and become economic. If modules are intended for off-site production, then they must also be transportable between the manufacturing location and assembly location using practical means of transport. Nuclear power has large components and systems; individual modules can weigh up to 500 te [51] and super-modules can weigh as much as 1,000 te [139],which means transport constraints are central to the development and application of a modular build scheme.

This Chapter seeks to quantify how the physical constraints imposed by road transport define the module's geometry or weight and ultimately govern the proportion of construction work that can be moved off-site. In this project, road is the preferred method of SMR module transport because it means modules can be constructed in a central, specialised factory instead of requiring that an on-site shop built beside each SMR site. There are many practical and logistical advantages to having a centralised factory facility for SMR module production, because it is more feasible that a manufacturing production line can be established with the following features [140]: an optimised factory design, a higher level of outfitting and construction process automation, improved quality control, in-factory testing and commissioning, and greater throughput and production volumes (achieving better learning). Road transport also means that the SMR site and factory location have minimal access constraints and requirements, which increases the number of sites available for SMR construction [66]. Barge transport, for example, requires suitable port facilities and access throughout the life of the plant, which may be challenging in the UK if a large number of SMR sites are to be found [45] [141].

Feasible module dimensions and weight are identified based on the road transportation limits outlined by Highways England in The Road Vehicles (Construction and Use) Regulations 1986 [142]. These UK road limits establish a conservative case for SMR module transport and are similar to European standards and more restrictive than US regulations. Barge transportation of reactor modules has been studied in the US (discussed below) and although water transport allows the construction of much larger modules, it also constrains the location of SMRs and SMR factories, restricting the deployment of SMRs [66].

IV.2. Integration of Transport Constraints

The factors that determine how a modular industry develops its transport logistics include the nature of the product, the physical size of the modules and product, the quantity of modules being produced (this is related to the production volume of the overall product), and the locations of the factories and assembly sites. Other national and international issues may also play a role in the assessment and selection of transport options and may include supply chain strategy, access to preferred suppliers, and economic and geo-political factors [141].

IV.2.1. Transport Strategies in Modular Industries

Different transport strategies are used by the modular industries in Chapter II, depending on the manufacturing objectives of the sector. In the shipbuilding, aerospace, and automotive industries, modules tend to be small and the final products are themselves transportable units. This reduces the restrictiveness of the transport constraints and allows the factory and assembly locations to be varied based on geography, proximity to key suppliers and/or skills, or other criteria. In the automotive industry, for example, highly specialised factories are required for product assembly. The aerospace industry is less driven by the need for high production volumes; instead, availability of skills and investment capital drive selection of the factory location. As the Airbus modularisation strategy demonstrates [143], transport constraints become important in the aerospace industry since the modules and components tend to be large and the factory locations are more constrained than in the automotive industry. Consequently, the aerospace industry has worked to integrate the modularisation and the transport schemes. The module transport approach used in shipbuilding exploits the advantage of the necessity for a coastal or river-based location to use barges for transporting very large modules to the final assembly area or dockyard.

By contrast, the size and weight of modules in the civil sector, chemical process industry, oil & gas industry, and large nuclear projects reduces module transportability and tends to confine module fabrication to a location that is close to the installation site. The available transport options play an important role in defining how these large structures and systems are modularised, and the limitations of the available transport options constrain the characteristics of the modules. Such constraints may be imposed by the load limits of cranes as well as dimensional and weight limits imposed by rail, road, sea, or air vehicles.

IV.2.2. Transport Strategies for Large Reactors

Projects in the large nuclear industry attempt to use modularisation to enable parallel construction. The modularisation scheme developed by Westinghouse for the AP1000 reactor heavily utilises an on-site module assembly building, in which modules are constructed and assembled into super-modules which are lifted into place using a large crane [25]. The need for road transport is largely eliminated since smaller components and sub-modules, such as pumps and piping systems, are transported by rail, while bigger components or equipment items, such as the turbines and reactor pressure vessel, are brought to site by barge [26]. The AP1000 modularisation scheme claims to make extensive use of off-site modularisation and manufacture; in practice, however, it is an on-site modularisation scheme with some low-value components fabricated off-site [25]. By contrast, the Hitachi ABWR provides an example of nuclear modularisation driven by transport constraints, and successfully resolves some of the challenges that Westinghouse faced – and largely failed to address – in their construction of the AP1000. More detail on the Westinghouse modularisation approach is included in Chapter II, Section II.4; however, it is important in the context of this Chapter to note that the Westinghouse strategy, for both their large and small reactor designs, focusses on super-module assembly near to the build site for parallel construction and does not develop a set of off-site, factory-built modules that fit within the limits of the available road or rail transport options [25].

IV.2.3. SMR Transport Strategies

This section discusses the modularisation and transport strategies used by the Westinghouse SMR (USA) and proposed for an SMR at Trawsfynydd, Wales. Both these strategies do not design the SMR modules around the available transport options; instead, they adapt the mode of transport to suit the excessively large and/or heavy modules, as designed. This limits the choice of sites for the SMRs and does not facilitate extensive production of a large number of modules in an off-site factory.

IV.2.3.1. Westinghouse SMR Transport

Recent work by Maronati [30] examines the scope for extending the modularisation of the Westinghouse SMR by using barges to transport super-modules, thereby increasing the number of super-modules that can be brought to the nuclear site. Maronati [30] argues that, while a generic SMR nuclear island can be constructed from 600 rail-shippable modules, only 10 super-modules are required if barge transport is used to extend the scope of modularisation. Barge transportation of super-modules reduces on-site labour hours relative to the rail-shippable module scheme through reduction in assembly time according to the 1-3-8 rule. Maronati [30] reports that the super-module scheme reduces TCIC by 5.8% and the project duration can be shortened by 81 days, relative to the original scheme. Furthermore, super modules may reduce the number of composite modules, providing further reduction in assembly time and cost; Maronati [30] concludes that the 'best case' TCIC reduction is 18%.

In the Westinghouse SMR super-module scheme, modularisation is not extended beyond the NI. It is unclear whether super-module construction is equally feasible for the BoP elements. Maronati also reports only the schedule reduction from the super-module strategy and does not make the distinction between which reductions are off-site and which are on-site. Finally, Maronati's work shifts the focus of the modularisation problem and, instead of developing an easily producible set of SMR modules, develops an alternative transport strategy and does not deal with the standard set of modularisation issues, such as DfMA and/or module producibility. This limits the modularisation benefits because the modules are not designed for volume production. Moreover, requiring barge transport methods will limit the feasible SMR sites to major inland waterways or areas on the coast.

IV.2.3.2. Transport of Abnormal Indivisible Loads

In light of the decommissioning of the Trawsfynydd Magnox nuclear power station in Gwynedd, Wales, the Snowdonia Enterprise Zone Advisory Board is studying the feasibility of placing a SMR power station at the Trawsfynydd site [141]. Transport logistics are key to furthering this study, since the Trawsfynydd site is located in Snowdonia National Park and the transport options for SMR modules and components need to be comprehensively assessed. Part of the proposed SMR development scheme details transport and access arrangements for Special Order shipments; that is, loads weighing over 150 te (gross) [141]. The loads are also classed as Abnormal Indivisible Loads (AILs) which means the load cannot, for economic or manufacturing reasons, be divided into 2 or more loads for the purpose of carriage on roads.

Government policy in the UK is to maximise the use of water-based transport for movements of Special Order AILs wherever possible [144]. The report provided by the Snowdonia Enterprise Zone Advisory Board [141] therefore investigates a number of local port options that can accommodate SMR module shipments and investigates potential routes by which the modules can be transported, by road, from these ports to the Trawsfynydd site. Although the option of rail transport is considered, it is found to be too restrictive and difficult to manage and is unlikely to provide a feasible option for modules that are classed as AILs. The proposed routes are technology agnostic; however, the dimensions set for the analysis are representative of the most extreme transport scenario and the number of these movements is on the order of a few dozen [141]. The report does not address normal traffic movements that fall within The Road Vehicles Construction & Use Regulations (C&U).

There are additional costs to consider when moving Special Order AILs. The Highways Act 1980 allows the highways authority to charge the user/transporter if damage is caused during the transport process. For transport to the Trawsfynydd site, the local ports require upgrades before they are able to receive SMR modules as they are used mostly for recreational purposes. Modules would be loaded and unloaded onto roll-on/roll-off (RoRo) barges using trailers, thereby avoiding the need for cranes and lifting equipment at the port. The nearby land could be used for temporary equipment storage and lay-down, if needed.

The study in [141] also looks at route negotiability and its ability to accommodate the various load dimensions and weights. It is interesting to note that the number of axles on a vehicle (which is, in turn, based on load weight) may change the ability to negotiate the route. The report examines five possible route options in great detail, traversing each route step by step, providing photos for each step and problem area. This includes information on any overhead wires that need to be moved, whether full occupation of the highway is required by the transport movement, low-hanging trees that need to be trimmed, the narrow 'pinch points' on route, and any bridges that require further load-bearing assessments [141]. One route proves to be most feasible; in all other options, the bridges on the route do not allow enough headroom for the maximum 'worst case' load height. For all routes, any loads that are over 5 m in height need to be attended and overhead wires managed. The report also identifies which authorities would need to be notified and where permissions would need to be obtained for different transport routes.

A few key observations from the report on SMR module transport for Trawsfynydd are worth noting. The study is focussed on enabling access to the Trawsfynydd site and is not concerned with designing SMR modules. It serves to highlight the crucial element of transport to SMR construction, as well as the amount of work that needs to go into the planning and logistical elements of transport. If the size of the AIL exceeds the Road Vehicles (Authorisation of Special Types) (General) Order (STGO) limits, then Special Order permits are required and the transport movement is difficult to organize. The preference for water transport of AIL loads beyond STGO limits significantly restricts SMR siting, as projects with large modules need to ensure they have easy access to suitable port facilities. The frequency and regularity with which these loads are transported will also affect route feasibility. There will be a much more significant push to make loads fit within C&U regulations if the number of loads is large. Furthermore, the access route must remain open during the lifetime of plant for maintenance work and replacement of equipment and modules.

IV.2.4. UK Road Transport Constraints

In the UK, the Department for Transport division Highways England (HE) is responsible for managing the road networks.

- Normal road transport limits are defined by the Road Vehicles (Construction & Use) Regulations 1986, as amended [142].
- Special transport loads are defined by STGO Categories 1-3 from The Road Vehicles (Authorisation of Special Types) (General) Order 2003 [144].
- Beyond this, a Special Order from HE is required if the load dimensions exceed STGO Category 3 limits [141] (6.1 m width, 30 m rigid length, and 150 te gross weight of vehicle + load).

As stated earlier, AILs are loads which cannot, for economic or manufacturing reasons, be divided into two or more loads for the purpose of carriage on roads. AILs are heavier than 44 te (gross vehicle weight) and cannot be carried under C&U regulations. AILs can fall within STGO categories 1-3 or, if they are excessively heavy, under Special Order Permission Limits. The UK government's preferred policy for Special Order AILs is water-based transport, as seen in the SMR for Trawsfynydd study, and road transport of these loads will typically be denied if a feasible waterway can be used. This decision rests with HE and is based on if the load is divisible, availability of a suitable route, traffic congestion that could be caused, and the justification for the load movement [141].

This project defines four Transport Envelopes that set limits on module weights and dimensions based on C&U, STGO, and Special Order limits. The four Transport Envelopes are identified in Table IV.1. More detail on the specific requirements for each envelope are listed in Appendix IV.A, which includes the details of load escorts and notification to authorities.

Table IV.1. Transport envelopes based on UK C&U [142] and STGO [144] restrictions.

Transport Envelope	Weight (te)	Length (m)	Width (m)	Height (m)	Notes
1	ISO: 28.8 C&U: 44.0	ISO: 12.032 C&U: 16.5[2]	ISO: 2.34 C&U: 2.55	ISO: 2.292 C&U: 4.95	ISO standard container is used for the *module's* size ISO containers meet C&U (and STGO Category 1) requirements Rail, road, barge transport possible
2	80	18.65	2.9	4.95	Routine relaxation of C&U limits C&U dimensions but STGO Cat 2 weight limit
3	150	30.0	6.1	4.95	Large loads within STGO Category 3 restrictions 2 days notice to police plus other req's; vehicle must be attended
4	> 150	> 30.0	> 6.1	> 4.95	Special Order loads Barge transport is preferred Permission must be obtained from HE AIL team

Transport Envelopes 1 and 2 represent the most common loads; it is expected that modules within these limits will not encounter any atypical logistical transport challenges. Transport Envelope 1 describes the weight and dimension limits of a standard ISO container which also falls within the normal load identified in the C&U regulations. Envelope 2 slightly relaxes the restrictions of Envelope 1 by using the C&U dimensions and increasing the weight to STGO Category 2 limits from [144]. In this case, the transporter is required to notify the Road and Bridges Authority (RBA) 2 days prior to transport; however, this is not an onerous requirement and is typical of routine relaxation of the more stringent normal UK road transport limits [145]. A feasible SMR modularisation scheme will develop modules within the weight and dimensional criteria of at least Transport Envelope 2.

Transport Envelope 3 limits are set based on STGO category 3 loads from [144]. The requirements for these loads are more stringent and require both advance notice to the relevant authorities as well as load escort during transit. While this is still a feasible transport option, the number of modules of this size should be minimised in order to reduce the complexity of transport logistics [141].

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[2] This C&U length limit applies to an indivisible load on an articulated truck & trailer; if the load is divisible and a road train can be used, the C&U length limit increases to 18.75 m.

Transport Envelope 4 makes provision for Special Order loads that exceed the maximum limits of STGO Category 3. While transport of these loads is possible, careful route planning is required and a Special Order application to HE is required 8 weeks in advance of transport. Frequent transport movements in this category are undesirable, but this ‘catch-all’ envelope is necessary because even the smallest SMRs will have a few indivisibly large components, such as the RPV and/or steam generators. The transport study presented here focusses on large numbers of routine transport movements and these special case modules are considered to be non-transportable.

Finally, it is worth noting that an upper limit is not set on load height in the UK. Practically, however, the maximum bridge headroom in the UK is 5.03 m on main motorway and trunk roads. This headroom isn’t guaranteed, however, and the best-practice for UK electric suppliers and plant manufacturers is to operate under a 4.95m travelling height, giving some margin for flexibility [141]. While is possible to transport loads higher than 5.03m, this may require some infrastructure changes and additional cost.

IV.3. Approach to Modelling NPP Modularisation & Transport

IV.3.1. Reference Module Data

The modularisation scheme developed by S&W [60] [146] is used as the reference scheme in this project. It was originally developed for a 950 MWe Westinghouse PWR but was never implemented or built. The scheme is described in Chapter II, Section II.4.4 and relevant module details are provided in Appendix II. A total of 1,419 modules are proposed in the S&W report and consist of various module types that occur within various locations across the nuclear plant. The total weight of each module type, within a given location, is given in Table IV.2, together with the number of modules from which this total weight is comprised. While the S&W report acknowledges that transport is a key constraint in the modularisation process, it indirectly resolves transport issues by assuming that all modules are fabricated in an on-site factory.

Table IV.2. S&W module weights (tonnes) and number, by category and location, for the reference 950 MWe PWR. Values in parentheses correspond to the number of each type of module.

Module Type **Module Location**	Reinforcing Steel	Precast Concrete	Structural Steel	Liners	Polar Crane	Mechanical Modules	**Total, te** (number)
Containment Building	11,625 (105)			1,237 (9)		72 (2)	**12,934** (116)
Auxiliary Building	1,675 (250)	62,477 (278)	741 (68)			1,479 (80)	**66,372** (676)
Turbine Building	367 (309)	3,084 (17)	3,739 (83)			896 (16)	**8,085** (425)
Diesel Generator Building		2,258 (12)					**2,258** (12)
Control Building		10,522 (72)	772 (34)				**11,293** (106)
Fuel Building				340 (27)		22 (26)	**362** (53)
Main Condenser Equipment						190 (7)	**190** (7)
Miscellaneous Equipment						272 (10)	**272** (10)
Total, te (number)	**13,667** (664)	**78,341** (379)	**5,252** (185)	**1,577** (36)	**1,107** (14)	**2,931** (141)	**102,875** (1,419)

IV.3.2. Methodology: Modelling Module Transport

The methodology described in the steps below is used to develop a modularisation scheme for a range of reactor sizes and to assess how the modules are distributed across the four transport envelopes.

i. Categorise original S&W modules

The S&W modules are grouped in terms of their location and type to provide the reference modularisation scheme breakdown in Table IV.2.

ii. Scale S&W modularisation scheme

The S&W module scheme is scaled on a power-weight basis to account for size differences between reactors. A generic modularisation scheme is calculated for a reactor of any size according to Equation IV.1, where the weight of each module from the S&W reference design (subscript *S&W*) is scaled to the target reactor size (subscript *i*) using the commodity-specific exponents, *n*, from Table III.1 in Chapter III. Dimensions are then calculated to maintain relative proportions as per the reference

S&W module. There is precedent for scaling commodity material input weights with respect to power from [61] [62].

$$Weight_i = Weight_{S\&W}\left(\frac{Power_i}{Power_{S\&W}}\right)^n$$

Equation IV.1. Power-weight scaling relationship.

iii. Determine module distribution across the four Transport Envelopes

The set of scaled modules, for each reactor power output, are sorted into the four different Transport Envelopes (Table IV.1) by weight and dimension. If modules are significantly constrained by transport limits, further refinement of the modularisation scheme must be considered.

Three options from improving module transportability are discussed below; this dissertation uses Option C.

- **Option A: Alternate Transport Strategies**
  This option changes the definition of what is considered transportable by considering alternative transport strategies, similar to work by Maronati [30] and the Trawsfynydd AIL study [141]. This option focusses on managing transport logistics and imposes location-based constraints on individual SMR projects.

- **Option B: Different Modularisation Scheme**
  This option uses a modularisation scheme that is different to the one developed by S&W. Generalising the S&W scheme may be challenging because it was not specifically developed for a SMR and also because of its age. However, developing a new modularisation scheme from scratch is outside the scope of this project because it requires a detailed SMR design and also requires expert knowledge of nuclear construction and modularisation.

- **Option C: Subdivide S&W Modules**
  This option divides the S&W modules further to fit within Transport Envelopes 1, 2, and 3 as described in Table IV.1. This option has the advantage of using a modularisation scheme that is based on a real reactor design and focusses on how modules can meet the transport limits, instead of expanding the transport limits to fit the modules. This option does, however, depend on the ability to break modules into sub-units that can be re-joined. Chapter II, Sections II.3 and II.4, address some feasible modular solutions.

iv. Find the minimum MDF necessary to make each module transportable
Use Module Division Factor (MDF) to set an upper limit on the number of times any dimension can be subdivided. This represents the maximum number of times a module can be divided with respect to length, width, height, or weight.

For each reactor power, perform the smallest number of subdivisions (up to the defined MDF value) that allow the module to fit in the smallest possible Transport Envelope and re-calculate each module's weight and dimensions. If the module does not fit in any of Transport Envelopes 1, 2, or 3, even when subdivided to the full extent allowed by the MDF, then it is left unchanged and assigned to Transport Envelope 4.

This is repeated across all dimensions (width, length, height), subdividing each dimension or not, as required. Theoretically the maximum number of times a module can be subdivided is $(\text{MDF})^3$, although in reality the limiting case is usually in only one dimension and this many subdivisions are not necessary.

v. Determine the new Transport Envelope distribution
Modules are re-distributed across the four Transport Envelopes. The transportable weight fraction of modules becomes the maximum DoM for a particular reactor.

vi. Final logic check
In some instances, subdividing the S&W modules does not make physical sense; in such cases these modules are left at their scaled weight/dimensions. This applies to

equipment modules such as tanks, demineralisers, sumps, or condensate polishing components and is discussed in Section IV.4.2.

There may also be scope to include some modules from Transport Envelope 3 in the transportable weight fraction. Section IV.4.3 investigates the effect of including Transport Envelope 3 modules, in addition to those in Transport Envelopes 1 and 2, on net transportability and the maximum DoM.

IV.4. Transport Results & Discussion

This section presents and discusses the results generated using the method described in Section IV.3.2, demonstrating how transportation constrains module feasibility and why the S&W modularisation scheme must be further subdivided if the modules are to be transportable within UK road limits. SMRs are shown to have a greater fraction of transportable modules and therefore can achieve a higher maximum DoM than large NPPs.

IV.4.1. Transportability of Scaled S&W Modularisation Scheme

The first case that is considered is the modularisation scheme that results from simply scaling the S&W modules for range of NPP sizes. The distribution of modules falling within each of the four Transport Envelopes (as per Table IV.1) is shown in the bars in Figure IV.1, together with the total weight of modules, plotted on the secondary vertical axis.

The modules from the S&W scheme, even when their dimensions and weights are scaled down to account for smaller SMR sizes, mostly fall within Transport Envelopes 3 and 4. Even the smallest reactors (150 MWe) have a considerable fraction of modules that exceed the limits of Transport Envelope 3, as 25% of modules, by weight, fall into Transport Envelope 4. The weight fraction of modules in Transport Envelope 4 increases to 90% or more for reactors 600 MWe and larger. This suggests that transport severely constrains the potential Degree of Modularisation for all but the smallest SMRs.

In Figure IV.1 below, large reactors do not get a significant benefit from off-site manufacture as most of the modules are not feasibly transportable. This may explain why the modularisation attempts of current large reactors, such as the AP1000, have turned to a module assembly building to provide an intermediate construction area for super-modules [26]. Furthermore, this may explain why Maronati studied the effect of increasing the upper transport limits by using barge-transport, in order to allow off-site manufacture of super-modules.

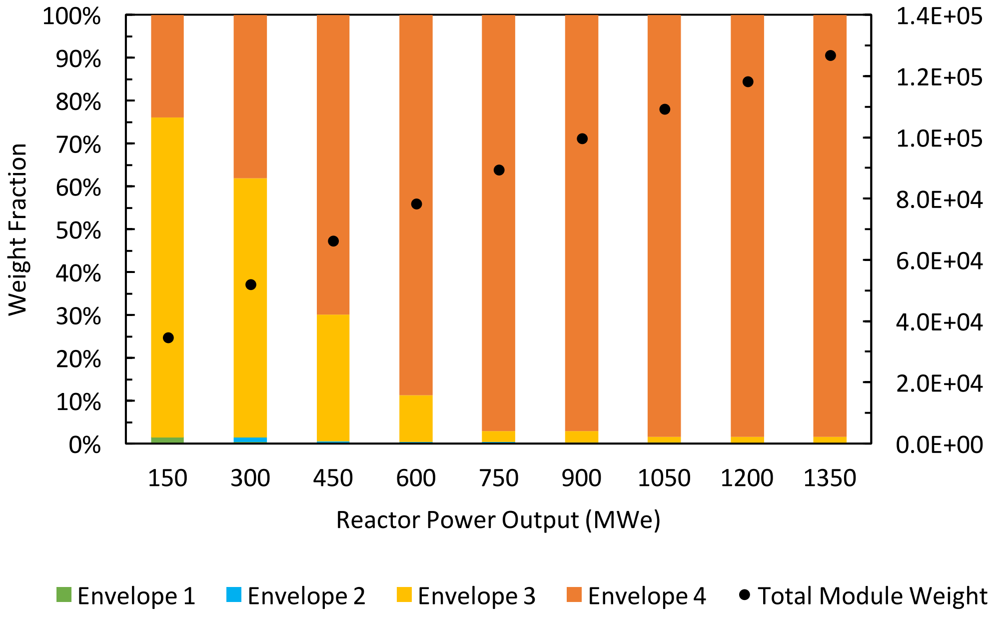

Figure IV.1. Distribution of scaled S&W modules across Transport Envelopes 1-4.

IV.4.2. Scaled and Subdivided S&W Modularisation Scheme

Most of the S&W modules are too large and/or heavy for routine road transport, even when scaled to account for smaller reactor sizes. To improve the feasibility of off-site manufacture, a set of smaller modules must be developed.

IV.4.2.1. Applying & Selecting MDF

In this dissertation, the transportability of the NPP modules is improved by dividing the S&W modules according to the subdivision logic described in Section IV.3.2. Modules are subdivided up to a maximum of three times (MDF = 3) as an example, and the distribution of the modules across the four Transport Envelopes is re-assessed and shown in Figure IV.2. Module subdivision has a substantial effect on transportability and the majority of SMR modules are now readily transportable, with at least 75% of modules falling within Transport Envelopes 1 and 2. Large reactors are still not very transportable; only 10% of modules are easily transportable for reactors larger than 600 MWe. Modularisation has greater potential to reduce the cost and build duration of SMRs; since a greater fraction of modules can be transported, a greater fraction of the SMR plant can be fabricated off-site and the potential for productivity improvements will increase.

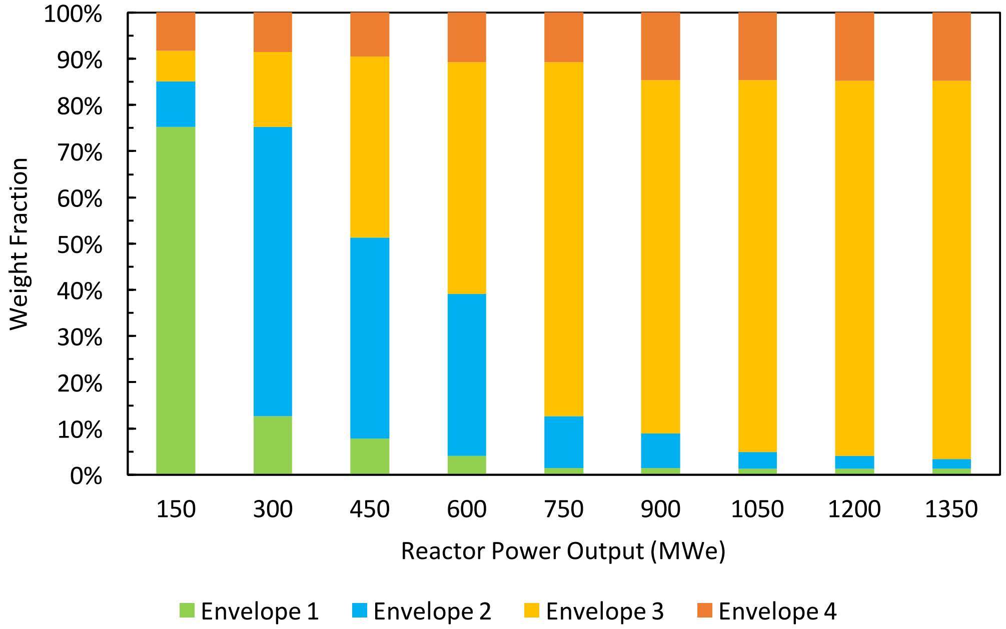

Figure IV.2. Distribution of scaled and subdivided S&W modules across Transport Envelopes 1-4 (MDF = 3)

It is clear that the number of times a module is subdivided will have a significant impact on the distribution of modules across the four Transport Envelopes. This in turn affects transport feasibility and, ultimately, the cost and schedule reductions that can be achieved. Figure IV.3 shows how the module transportable fraction (by weight) increases with increasing MDF over a range of reactor powers. For reactors within the SMR range, the most significant transportable fraction benefits are gained at a MDF value of 3. While greater subdivision will yield an even higher transportable fraction, the incremental benefit of further dividing modules is minimal. Figure IV.3 shows that the modules would have to have a MDF = 6 applied to their design if there is to be a significant increase in the transportable weight fraction of modules over the MDF = 3 case.

While there is no theoretical upper bound on the number of times a module can be subdivided, it is practically desirable to limit the number of subdivisions in order to ensure the proposed modules are still constructible. Moderate subdivision of the scaled S&W modules is reasonable (up to MDF = 3) but very high levels of subdivision are impractical from a constructability perspective. Higher MDF values also mean that there will be more modules to transport between the factor and nuclear site, which in turn places more importance on smooth organisation of the transport logistics and which may introduce additional risks associated with management of transport routes and timing. Additionally, the drive to reduce the number and complexity of joins between modules makes limiting the MDF desirable, in order to manage assembly cost and time, as well as manufacturability and build quality. The relationship between MDF and the total number of modules is investigated in further detail in Appendix IV.2.

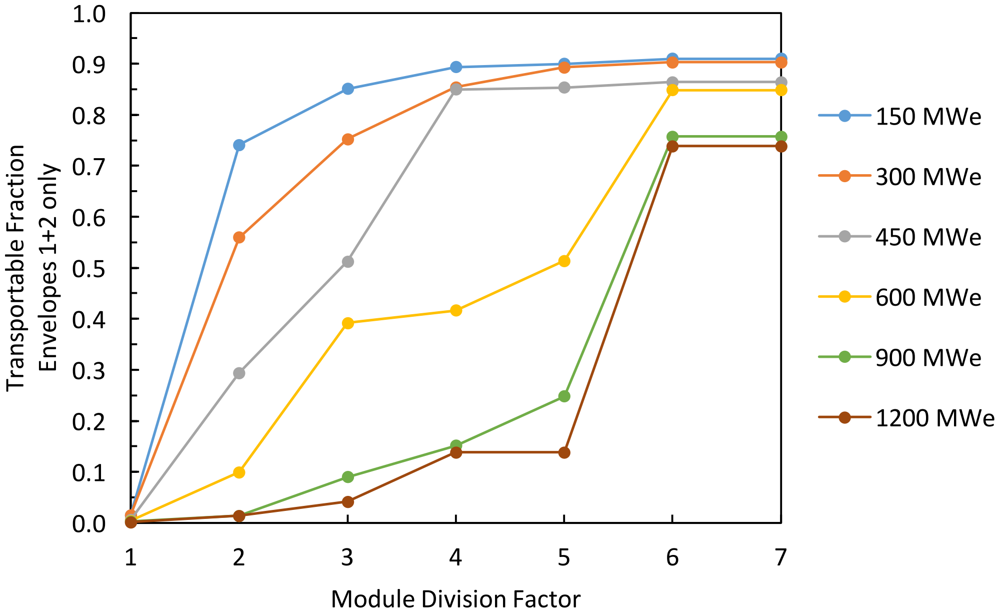

Figure IV.3. Module transportable fraction (by weight) with respect to MDF for different reactor sizes.

IV.4.2.2. Practical Feasibility of Module Subdivision

This section demonstrates the implications of module subdivision in the context of specific modules. Three examples of S&W modules are considered here, together with a discussion of whether subdividing the module to MDF ≤ 3 is practically feasible or not.

i. Module subdivision is not feasible

This is typical of single equipment items or sets of components and applies to 82 mechanical & equipment modules of the original 1,419 modules described in the Stone & Webster report [60]. The solution in this instance is to leave the module in its original form, with only scaling to account for the size differences between reactors. This does not significantly affect the net transportability since many of these modules are small and are typically transportable to begin with.

- Skid-mounted condensate polishing component (turbine building)
  In the S&W scheme, this mechanical module is already divided into 9 constituent modules and it is unlikely that further subdivision would be feasible. In this case, the modules are already transportable and further subdivision is not necessary.
  Module descriptions and drawings are provided in Appendix II.2.
- Moisture-separator-reheater (turbine building)
  The four moisture-separator reheater units in the turbine building are complete equipment units and cannot be divided up further. In this particular case, the modules are weight and width limited and, for reactors 600 MWe and larger, are non-transportable. Alternative transport or *in-situ* construction methods should be found in this case.
  Module descriptions and drawings are provided in Appendix II.2.

ii. Modules are transportable for MDF ≤ 3

An example of this case is subdivision of the 36 precast exterior circumferential walls used in the annulus building. This is a widely applicable example, since all precast walls are constructed in a similar manner and the annulus building alone also includes 91 interior circumferential walls, 113 radial and cubicle walls, and 38 cubicle slabs (module descriptions are in Appendix II.1). Table IV.3 shows the exterior circumferential wall module weights and dimensions for both a 300 MWe and 1200 MWe reactor. The modules are not transportable for either the large or small reactors; the transport solution is limited by both weight and width. When subdivision is applied (MDF = 3) the modules are divided along their width, the weight is reduced accordingly, and they become transportable – as shown in Table IV.4. Since length is not a limiting factor, there is no need to subdivide this dimension. Height data are not provided by S&W and must be assumed to fit within the selected transport envelopes.

Table IV.3. Exterior circumferential walls for the auxiliary building, as per the scaled S&W scheme.

Reactor Power	Number	Weight (te)	Length (m)	Width (m)	Transport Envelope
300 MWe	36	130.95	13.45	6.69	4 (not transp)
1200 MWe	36	296.70	20.25	10.07	4 (not transp)

Table IV.4. Subdivided exterior circumferential walls (precast) for the auxiliary building, MDF = 3 is applied to the scaled S&W modules.

Reactor Power	Number	Weight (te)	Length (m)	Width (m)	Transport Envelope
300 MWe	108	43.65	13.45	2.23	2
1200 MWe	108	98.90	20.25	3.36	3

According to the S&W report, the joining process is the primary issue with precast concrete elements. The use of precast elements is therefore limited to large modules only. Simplified joining methods, such as the headed bar joint technology proposed by Laing O'Rourke [124], would allow smaller precast panels to be considered. This increases the modularisation potential beyond that of the original S&W scheme and allows sub-division of precast elements without compromising buildability or safety. Precast modular solutions for nuclear construction are discussed in Section II.4.1.

iii. Module subdivision requires MDF > 3

This example is typical of the containment building liners described by the Stone & Webster report [60]. The shapes of these modules are complex and result in excessively heavy, long, wide, and/or high modules, regardless of reactor power (described in Appendix II.1). Most scaled containment liner modules are non-transportable regardless of reactor size. In these cases, it may be more feasible to consider extensively redesigning the modules so they fit within the transport limits.

Redesigning these components is outside the scope of this project; therefore, these components are classed as unsuitable for modularisation and are constructed and transported according to current practice.

IV.4.3. Extended Transportable Fraction

The definition of what modules are transportable can be extended to include a small number of larger modules. A fraction of the modules from Transport Envelope 3 can be added to the total set of transportable modules according to Equation IV.2, in which $Weight_i$ is the weight of modules in a given Transport Envelope, i, and the value of x can be varied from 0 (no modules in Transport Envelope 3 are included) to 1 (all modules in Envelope 3 are transportable).

$$Transportable\ Fraction = \frac{(Weight_{Env\ 1} + Weight_{Env\ 2} + x\ Weight_{Env\ 3})}{Weight\ _{TOTAL}}$$

Equation IV.2. Extended definition of Transportable Fraction.

Figure IV.4 shows how the transportable fraction varies with reactor power across a range of values of x, for a constant MDF = 3. It is clear that small reactors are less sensitive to the value of x that is chosen; the point at which x becomes significant is for reactors larger than 300 MWe. This behaviour is as expected, since LRs have a significantly greater net module within Transport Envelope 3.

In this project, a value of $x = 0.2$ is assigned to all reactor sizes; this means that 20% of the weight of modules in Transport Envelope 3 can be transported, assuming special permits are obtained as necessary. The remaining 80% of modules in Transport Envelope 3 are not transportable. The value of $x = 0.2$ is chosen based on the rationale that limiting the number of STGO Category 3 loads is desirable to simplify transport logistics, and ideally should not exceed roughly 100 modules [141]. Table IV.5 shows the correlation between reactor power and the number of transportable vs non-transportable modules that fall into Transport Envelope 3 based on MDF = 3 and $x = 0.2$. The smallest reactor (150 MWe) requires only 29 special-transport movements; however, the number of modules transported in Envelope 3 increases significantly for large reactors, where nearly 300 special transport movements would have to be arranged for a 1350 MWe reactor.

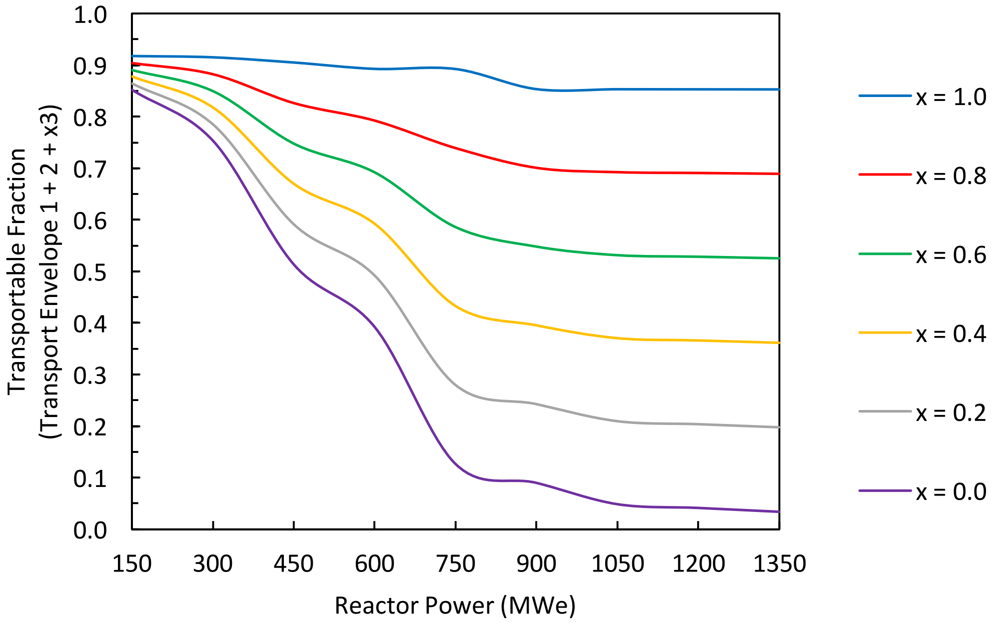

Figure IV.4. Module transportable fraction (by weight) with respect to variable weight percentage, *x*, allowed in Transport Envelope 3 at constant subdivision, MDF = 3.

Table IV.5. Number of modules in each transport category for MDF = 3 and *x* = 0.2. For reference, the number of modules in the original S&W scheme is 1,419.

Reactor Power (MWe)	Envelope 1	Envelope 2	Envelope 3 (transport)	Envelope 3 (no transport)	Envelope 4	Total Number
150	2,463	124	29	114	65	**2,795**
300	1,905	773	53	210	75	**3,016**
450	1,832	922	95	382	83	**3,314**
600	1,532	947	122	489	92	**3,182**
750	1,369	705	190	759	92	**3,115**
900	1,361	469	198	793	137	**2,958**
1050	1,347	408	222	890	137	**3,004**
1200	1,347	203	250	999	137	**2,936**
1350	1,334	109	287	1,148	137	**3,015**

IV.4.4. Application to Degree of Modularisation (DoM)

This Chapter has shown how the amount of work that can be moved off-site depends on the modularisation scheme, the reactor size, and the transport constraints. The combination of these three factors gives the DoM_{max} for the NPP, which represents the greatest amount of site work, by weight, that can be contained in modules and moved off-site. The following conditions are used to set the cases for cost and schedule modelling and are based on the combination of parameters that offers the greatest transportable weight for the least additional design effort above and beyond the original modularisation scheme.

- S&W modularisation scheme: weight-power scaled for different reactor sizes
- Module subdivision: MDF = 3
- Special transport: 20% (by weight) allowed in Transport Envelope 3

Figures IV.5 and IV.6 show how DoM_{max} varies with reactor power on the basis of module type (symbols), as well as overall (solid line). A comparison of Figures IV.5 and IV.6 highlights the effect of subdividing the modules has on the transportability of each module type and shows that it has a particularly noticeable effect on increasing the modularisability of precast concrete and structural steel components which, in turn, contributes greatly to increasing the overall DoM_{max}. Similarly, Figure IV.7 shows how DoM_{max} varies with NPP size on a module location basis. The DoM_{max} values generated in this Chapter are shown in Appendix IV.3 and are used in the schedule and cost models in Chapters V and VI.

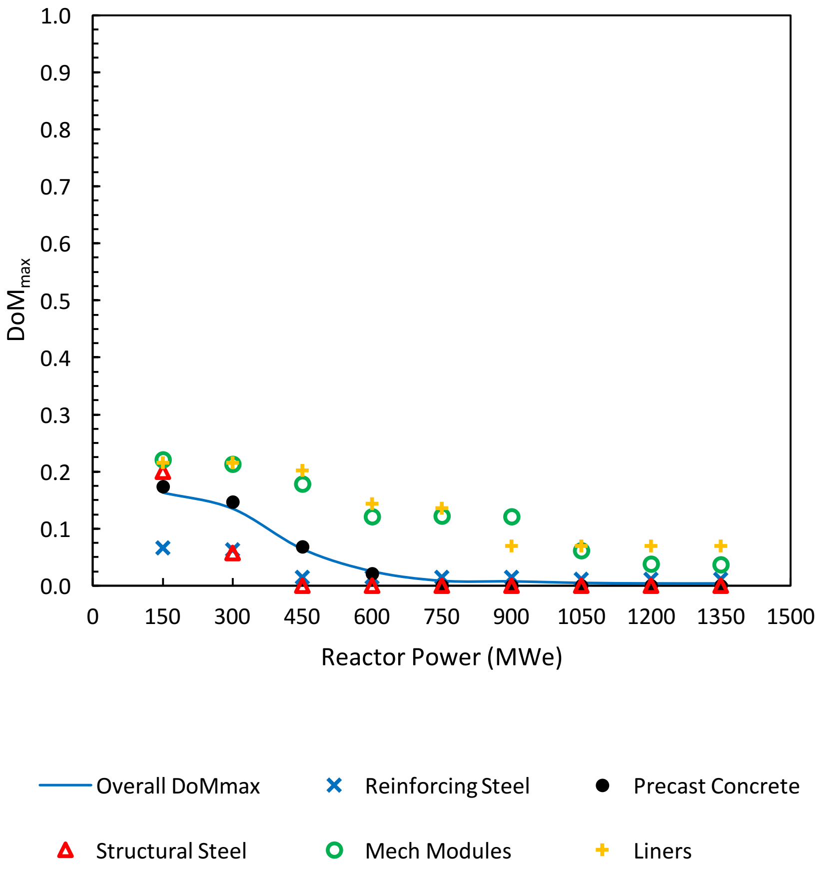

Figure IV.5. Transportable weight fraction of modules (DoM_{max}) by module type; no subdivision. Variable reactor power, MDF = 0, $x = 0.2$.

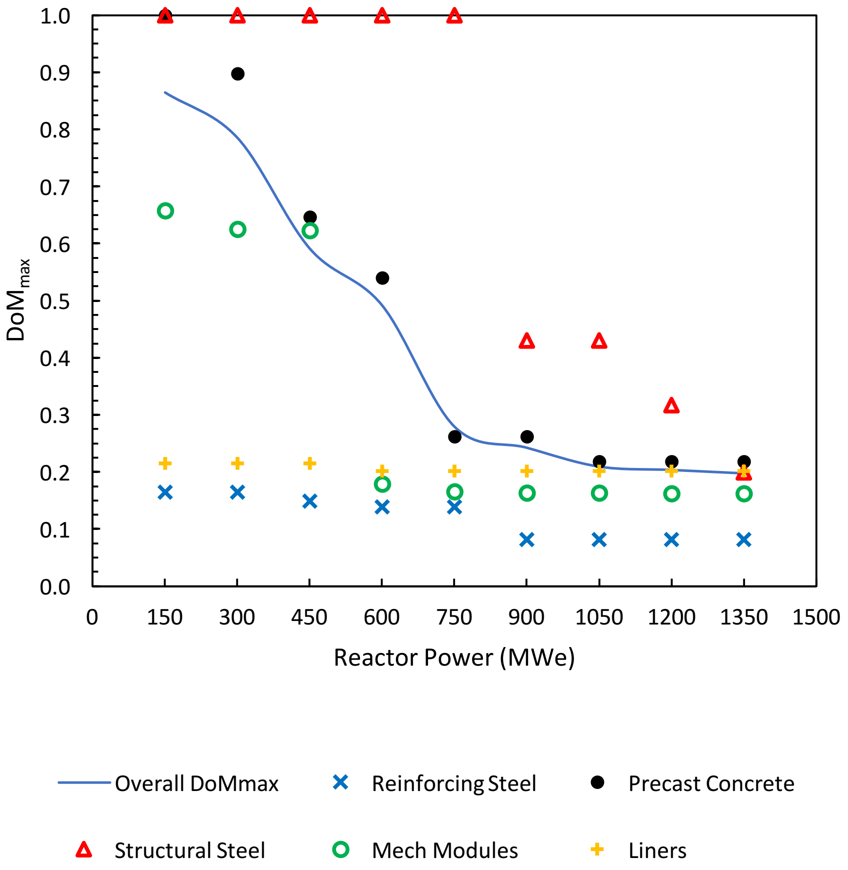

Figure IV.6. Transportable weight fraction of modules (DoM_{max}) by module type; with subdivision. Variable reactor power, MDF = 3, $x = 0.2$.

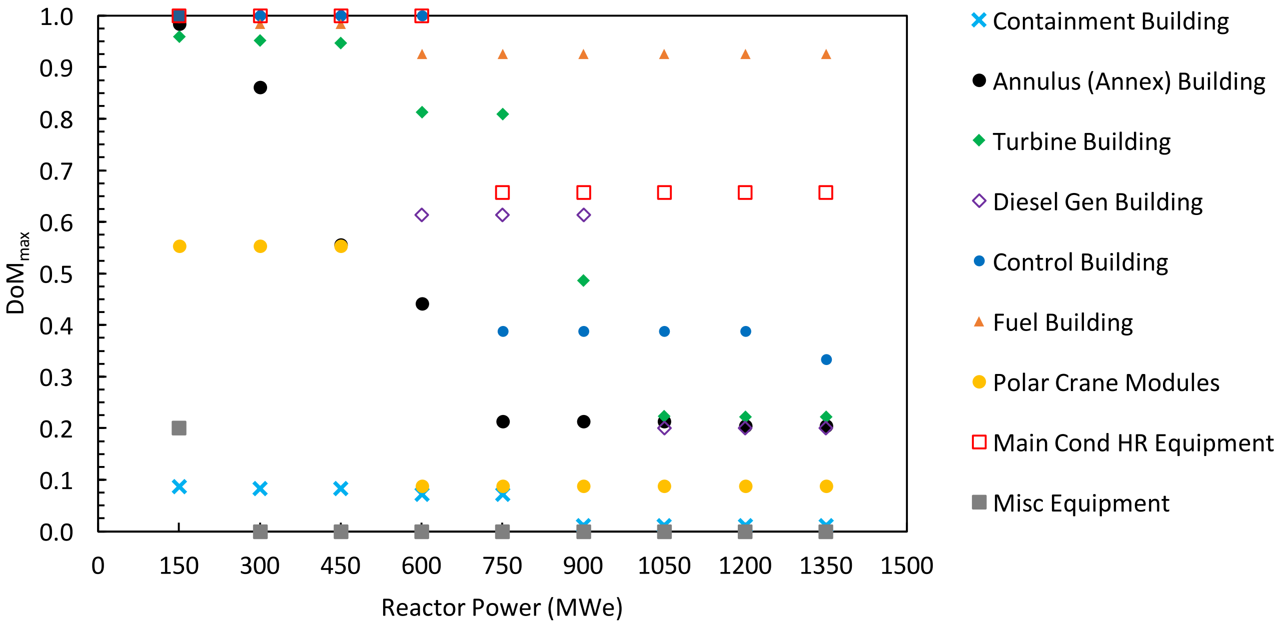

Figure IV.7. Transportable weight fraction of modules (DoM$_{max}$) by module location; with subdivision. Variable reactor power, MDF = 3, x = 0.2.

These figures show that modules need to be smaller than the reference S&W modularisation scheme before road transport becomes a feasible option. SMRs have a definite advantage over LRs in this regard; particularly with weight-limited modules such as precast concrete elements and structural steel modules. In these cases, module subdivision (MDF of a factor of 3 or less) results in modules that fit within Transport Envelope 1 or 2. This applies to the majority of the proposed modules and it is feasible to expect that subdividing these types of modules is possible, given the current precast and structural modular solutions developed by Laing O'Rourke and Westinghouse. By contrast, this analysis indicates that length-limited modules are difficult to modularise, regardless of reactor size, and must be divided on the order of 5 times or more before they are feasible for road transport. This is especially applicable to liner and polar crane modules, and these elements should be considered for redesign.

This analysis also indicates which specific structures and buildings in the NPP are worth more attention and modularisation effort. The greatest potential for modularisation is in the auxiliary building, diesel-generator building, turbine building, and the main condenser heat rejection equipment. SMR designers should focus on these areas for modularisation and DfMA, particularly the mechanical modules, precast modules, and structural steel modules that are used in these areas/structures, since this is where the greatest fraction of work can be built into modules and moved off-site. Areas that will be more challenging to modularise include the containment building, polar crane structures, and miscellaneous equipment items; SMR designers should prioritise these areas for re-design of the modularisation scheme.

Finally, it must be mentioned that the I&C and electrical system modules are noticeably absent from the S&W data. While seismic and non-seismic class electrical cable tray modules are developed in the S&W report, dimension and weight data are not provided and thus cannot be included in this transport analysis. It is assumed that these modules will not substantially change this analysis or present any challenge during design and/or construction.

IV.5. Conclusions on Transport-Limited Modularisation

IV.5.1. Summary

This Chapter shows how transport logistics constrain the modular scope of a generic NPP, based on a reference modularisation scheme from S&W. This work is based on the premise that transport by road is the preferred mode of transport because it facilitates fully off-site manufacture. The original S&W modularisation scheme does not have a significant number of transportable modules, even when scaled to account for size differences between large and small reactors. Consequently, subdividing the modules is essential: if this is not done, the modules cannot be transported by road, off-site manufacture will not be feasible, and the full range of benefits from factory build will not be realised. This might explain why current ‘modular’ large reactors and SMR designs, including the AP1000, Hitachi’s ABWR, and the Westinghouse and NuScale SMRs, attempt to solve the transportability issue by expanding the feasible transport envelope, using an on-site shop or barge transport, instead of re-designing modules for off-site manufacture and assembly.

SMRs do indeed have greater modularisation potential than LRs; especially once a subdivision strategy is implemented, since SMRs gain a significant transportability advantage over LRs. The module transportability is further improved when the transport restrictions are slightly relaxed and a number of semi-routine special transport movements for extra long/wide/heavy loads are allowed. The number of times modules are subdivided must be balanced against the practical and logistical issues surrounding fabricating, transporting and joining many small modules versus a few large ones. A subdivision factor of MDF = 3 seems to offer an optimal solution because it moves a significant fraction of work off site while maintaining the manufacturability and managing the number of joints between modules. Under these conditions, SMRs can achieve a maximum transportable weight-fraction of modules, or a DoM_{max}, of >80% which is a significant improvement over the typical LR DoM_{max} of about 20%. In order to get a high degree of modularisation, reactors should be 450 MWe or smaller, where overall DoM_{max} values are $\geq$ 60%.

All commodities in all areas of the plant should be considered for modularisation, and modules should be used wherever possible, but this analysis shows that the two high-impact commodities are precast concrete and structural steel elements. Both of these elements are feasible candidates for the necessary subdivision, given current structural modular solutions, and modularisation of these commodities significantly improves the modularisability of the whole plant. Some of the components that are not modularisable might need redesign. This applies to a small number of components that are either length-limited and/or infeasible for subdivision, such as the containment liners, turbine building MSRs, and polar crane support structure modules. In this model, these components are considered un-modularisable and will be fabricated and transported using conventional methods.

The work presented in this Chapter is the first time a comprehensive modularisation scheme has been systematically applied to a SMR within the limitations imposed by road transport regulations. Past work has focussed on modularising large reactors (AP1000, Hitachi, ASTRID), modifying and extending module fabrication methods (AP1000 module assembly building), or investigating alternate transport options (barge transport of super-modules [30]). This work is unique because it focusses on the design-for-manufacture efforts that are required for substantial off-site manufacture of NPPs and constrains modules so that they become easily road transportable units. The increased modularisation potential of SMRs, captured through the DoM_{max} results presented here, is carried forward into the cost and schedule modelling in Chapters V and VI, and offers a series of knock-on benefits for SMRs: greater modularisation increases the amount of construction work that can be performed off-site in a factory and, in turn, increases productivity, reduces re-work, and reduces time on-site, ultimately reducing SMR build duration and construction cost.

IV.5.2. Future Work

There are some points that should be addressed if a transport-constrained modularisation scheme were to be developed in more detail.

i. Additional Modularisation Scope & Feasibility

The reference modularisation scheme from S&W was developed for a 950 MWe LR in the mid-1970's; however, it might be desirable to develop an SMR-specific modularisation scheme, since small reactors may have additional scope for system and component modularisation due to their smaller size and more compact arrangements. Furthermore, advancements in NPP design – such as incorporating more passive safety systems, thereby reducing the amount of piping, pumps, and valves – may either eliminate or reduce the need for certain components or equipment items that were essential in the S&W design, further increasing the scope for modularisation. Similarly, manufacturing techniques may have progressed since the 1970's and the cost and/or time required to fabricate certain modules may be reduced, increasing the number of feasible modules in contemporary SMR designs relative to the original S&W scheme.

ii. Transport Costs and Trade-Offs

The issue of transport costs is not extensively investigated in this dissertation. Chapter VI models the impact of modularisation on SMR cost and assumes that the transport costs are 2% of each module's direct cost as per guidelines provided by the EMWG [21]. Although this approximation does reflect an increase in transport costs that is proportional to increasing module weights, it does not account for the cost differences between different modes of transport. Transport Envelope 3, for example, will prove to be a costlier option than Envelopes 1 or 2, since special transport vehicles are needed and escorts are required.

This project assumes that the only method of transport for the modules is via road and, while road transport was deliberately chosen because it provides the greatest flexibility in terms of factory and SMR siting, it may also unnecessarily constrain the module weights. Further work should investigate the increased module size and factory/SMR plant siting trade-off that is introduced with barge transportable modules in [30] or by using an on-site shop. The transport scheme could be even further extended to include international fabrication and export of modules as part of a global SMR supply network, as considered by Lyons [16] [147]. This would substantially alter the transport strategy from the UK-only manufacture and construction scenario assumed in this project.

iii. Crane Requirements & Costs

Crane requirements should form part of an extended transport study in terms of their impact on required lifting capacity, construction scheduling and critical path, and module installation costs. This project assumes that crane lifting capacity places no additional constraint on module weight, that no additional costs are incurred by the potential need for extra cranes, and that crane availability has no impact on the module installation schedule. A NPP constructed from a large number of modules, or a few very heavy super-modules, may require additional crane capacity: the Westinghouse AP1000, for example, uses a heavy lift derrick crane for installing super modules.

iv. Module Design for Transport

While design for manufacture is commonly discussed in modularisation work, the design of modules for transport is a factor that has not received attention in this study. Extra structure will be required for supporting each module internally and for attachment to the transport vehicle. Additionally, the module's structural design must also consider loading patterns the module might experience during transport and lifting that may not be characteristic of the typical in-service loads placed on the modules. The cost estimates provided in Chapter VI assume 5% additional material cost for this extra structural/support requirement, according to [21]; however, this project does not consider how the need for supporting structural elements for individual modules may affect module design or transport feasibility.

CHAPTER V
MODULARISATION & BUILD SCHEDULE

V.1. Introduction

Build time is one of the primary cost drivers in the nuclear industry where skills are scarce, hourly labour rates are high, and construction overhead costs are significantly reduced in shorter projects [138]. Furthermore, if the construction schedule can be demonstrably shortened, the financing and interest during construction costs are reduced and the financial risk of the project is decreased. Also, the large capital investment committed in build begins to generate revenue sooner, improving returns for investors. Literature has attempted to define and quantify the relationship between the size of a nuclear power reactor, its lead time, and its construction cost[3]. While many factors affect NPP construction duration, reactor build time generally tends to increase with reactor size. Appendix I.1 shows a plot of historical reactor build times versus reactor power, using data from the IAEA. SMRs are expected to have shorter overall build times than LRs because of their smaller physical size, but the exact nature of the relationship between build time and size is not easily quantified. The size benefit may be partially offset for a conventionally built SMR because of the greater congestion on smaller construction sites that increases *in-situ* inefficiencies [19] [138]. Some construction tasks are also not strongly correlated with reactor size and may, in part, be governed by other independent factors; for example, concrete curing times and inspection and testing procedures.

This Chapter investigates how modular build transfers construction time from the NPP site to off-site factories, reducing the number of complex construction tasks that need to be completed *in-situ*, shortening the critical path on-site, and improving the overall construction productivity. As Chapter II discusses, the shipbuilding, automotive, and aerospace industries have all substantially reduced their build times by using modular build techniques and improving the productivity of factory manufacture compared to conventional *in-situ* construction. The main drivers of these productivity

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[3] For example: Cantor & Hewlett [19], Rothwell [20], Berthélemy & Escobar-Rangel [44].

improvements are: better access to the task, improved tooling and equipment, the availability of jigs and fixtures, and the improved ability to capture and apply best practices. Quality control is also much simpler in the workshop environment compared to *in-situ*.

This Chapter uses historical data from a large, conventionally built, PWR construction project to develop a generic scheduling model that can be used to estimate the build times of a range of reactor sizes. This scheduling model is calibrated to the extent that is possible against the available literature studies. Modularisation is then incorporated in the build schedule by transferring a fraction of the *in-situ* work to an off-site factory, according to the transportation constraints developed in Chapter IV. In this way, the scheduling model includes the effects of reactor size, modularity, and transport constraints, on the estimated NPP build time and its critical path.

V.2. Approach to Modelling NPP Build Schedule

There is little detailed work published, either in the academic literature or from industry, about NPP construction project scheduling. The reason for this is because studies of NPP scheduling issues have not been conducted and also because the relevant data are not generally in the public domain. This section describes how a generic NPP construction schedule is generated from a set of reference NPP build data. It defines the parameters that allow variation in the NPP size and modularity. The results of the schedule model are discussed in Section V.3 in terms of total on-site time and the detailed critical path.

V.2.1. Reference Schedule Data

The reference construction schedule is developed using primary data from the UK PWR Sizewell B [47] [51] [3]. Sizewell B is a 1198 MWe PWR built in the UK with a planned and delivered construction schedule of 79 months. First concrete was placed in June 1988 and commercial operation of Sizewell B began in February 1995.

Advantages: Sizewell B Build Schedule

There are a few reasons why Sizewell B scheduling data were chosen to provide the baseline data set for modelling a LWR SMR.

i. Representative LR Design

The Sizewell B unit is a good example of both the type of design and build duration of the most prevalent nuclear reactor family. It is based on Westinghouse PWR technology and design and its schedule lies in the middle of the larger French build experience, supporting the view that Sizewell B is a representative example of a stick-built PWR built in a time when the nuclear industry had both the necessary skills and experience for large nuclear construction projects. The design of Sizewell B was modified from the Westinghouse SNUPPS reactor and, at the time, was the most advanced reactor of its type. Its design concept was the end of a series of similar Westinghouse designs and is similar to the French 4-loop PWRs, although it has four safety trains and some additional engineering-in safety features. While it was the first of its kind in the UK, resulting in some design changes and supply chain challenges, its build time is nonetheless similar to its contemporary French 4-loop 1250 MWe units.

ii. Representative Stick-Built LR Construction Experience

No structural modularisation is incorporated into the Sizewell B design, unlike the later AP1000 reactor (also designed by Westinghouse), and it therefore provides a good reference point for a LR built according to strictly conventional methods.

iii. Minimal Project Delays

The planned schedule for Sizewell B was also the achieved schedule. While there were some small delays on a few construction activities within the project, the overall project was managed so that the whole construction schedule did not experience a corresponding overrun. Most other NPP construction projects have experienced significant schedule overruns, making it difficult to identify which schedule to use – the predicted schedule, or the as-built schedule.

iv. Data Availability

The Sizewell B project is the only NPP build programme that this thesis study was able to access and use. NPP build schedule data are typically unavailable because of the commercial sensitivity of this type of information. Additionally, there was the support of people involved in the build [47] [4] to help with interpreting the charts and data, providing a valuable resource to structuring the generic scheduling models.

v. Data Detail

The Sizewell B build schedule data are sufficiently detailed to work with and consist of about 120 construction task items, including: pouring concrete, fixing rebar, installing M&E and piping systems, finishing buildings, and testing and commissioning activities for the key buildings.

Disadvantages: Sizewell B Build Schedule

Some aspects of the Sizewell B NPP, in particular the reactor's age and date of construction, that mean the build schedule may not be representative of reactors built today.

i. Technological Developments

Improved construction practices since the time of building Sizewell B could be used to further shorten build times; one such example is the use of automated welding processes [47]. These have been used with success in Japan and Korea, but there is no breakdown of their effects and little experience of their successful use in the West. Sizewell B power station also has a few extra safety and/or technological features that are not typically found in PWRs (e.g. its design includes an ultimate heat sink and it has two turbines) [70].

ii. Regulatory Changes

Regulatory changes and/or possible increased stringency of testing and inspection procedures in the UK since the construction of Sizewell B, particularly post-Fukushima, may lengthen the project duration or may increase the impact of inspection tasks for new reactors though there is little evidence to back this up. The impact of Fukushima has been on external hazards protection systems rather than the regulatory processes which were arduous for Sizewell B and remains largely unchanged as no new civil reactor have been built since.

V.2.2. Methodology: Modelling Build Schedule

The setup of the scheduling and modularisation model is presented here. In order to collate the scheduling data into a logical construction sequence, a couple of inferences are made about the nature of the on-site time (Section V.2.2.1). Power scaling is then applied to the original large reactor construction task durations (Sections V.2.2.2. and V.2.2.3) to generate a construction schedule that is specific to a given reactor size. Finally, the SMR schedule is modularised according to a set of possible modular construction scenarios (Section V.2.2.4).

The date for FPSC of Sizewell B was entered into Excel and the reference LR schedule construction dates were generated mathematically from this start point using both the known task durations and the specific task connectivity of each of the 120 work items available from the base data. Task durations were then adjusted to reflect the different modular construction scenarios that are described in the following sections. For example, the task durations of a 300 MWe stick-built reactor were power scaled using the logic presented in Section V.2.2.2, to generate a set of 120 task starting and ending dates for a conventionally-built 300 MWe SMR, based on an arbitrarily fixed starting date. The task dates for a selected number of scenarios (as presented in Appendix V) were imported to MS Project from MS Excel and were plotted as Gantt charts, each with a critical path. This was an automated process using MS Project software capabilities; if the schedule breakdown and task durations changed, MS Project would update the critical path automatically. Finally, the results for the scheduling scenarios and their related critical paths were also checked manually for errors.

V.2.2.1. Inferences About On-Site Time

The Sizewell B schedule does not explicitly provide all the information necessary to create a complete, fully-linked scheduling model for a reactor build sequence. Both the task connectivity and the type of construction time must be inferred from the given data, which are provided as task start and end dates. The concepts presented here build on preliminary work developed by Lloyd & Roulstone [148], confirmed with external assistance from Carruthers [47].

Task Connectivity

Task connectivity is inferred in order to develop a fully linked and interdependent construction sequence. The connection between tasks is based on expert input [47] and logical deduction; for example, the sequence of construction activities at increasing elevations is obvious. The task connectivity logic is static, regardless of reactor size, modularity, and/or construction techniques. Again, this is a conservative simplifying assumption. Once modular build is proven it may be possible to recast both the sequence of build tasks and the critical path.

There are two types of task connectivity relevant to this thesis. A start-to-start (S-S) connection means that the current task cannot begin before the previous one has started. A finish-to-start (F-S) connection means that the current task cannot begin until the previous one has ended. These are illustrated in Figures V.1 and V.2, respectively [148].

An example of both connection types can be seen in the tasks associated with Account 218a Control Room/Diesel-Generator Building, which consists of a set of structural and M&E construction tasks at various elevations. The M&E work at any given elevation cannot begin until the structural work on that level is complete (F-S connection) but the structural work at one elevation merely needs to commence, it does not need to be fully complete, before beginning work on the next stage (S-S connection). This is shown in the reference reactor baseline Gantt Chart in Appendix V.1.

Type of Construction Time

The available Sizewell B data provides the as-achieved start and end dates for 120 on-site, value-added construction tasks in the original schedule; this is defined as **Task Time (T)**. The time in-between tasks must also be included in the scheduling model and is the **Wait Time (W)**, or non-value-added on-site time. It is inferred from the sequence and interdependency of the value-added tasks. The difference between task time and wait time is illustrated diagrammatically in Figures V.1 and V.2 [148].

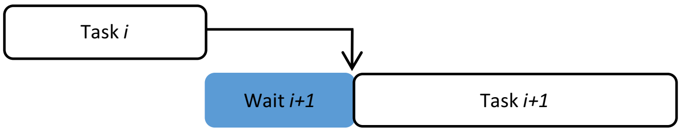

Figure V.1. Finish-to-Start (F-S) connectivity for sequential tasks.
Task *i* must be fully complete before the following Task *i+1* can begin. The date on which Task *i+1* begins is determined according to: Task $i+1_{\text{start date}}$ = Task $i_{\text{finish date}}$ + Wait $i+1_{\text{duration}}$.

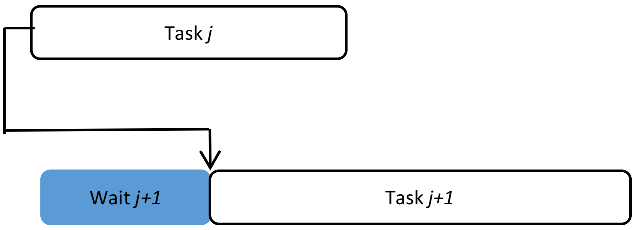

Figure V.2. Start-to-Start (S-S) connectivity for sequential tasks.
Task *j* must begin (but not necessarily completed) before Task *j+1* can start. The date on which Task *j+1* begins is determined according to: Task $j+1_{\text{start date}}$ = Task $j_{\text{start date}}$ + Wait $j+1_{\text{duration}}$.

A comparison of the two figures above shows that the duration of Wait_{i+1} does not have the same physical meaning as Wait_{j+1}. This is consistent with the three types of wait time defined previously. The wait time between activities that connect S-S will be affected by modularisation in a different way than activities that connect F-S; this thesis uses the following assumptions:

- **Enforced wait time** occurs between tasks that are connected S-S. If the task time governing the duration of the enforced wait time is reduced through modularisation, the wait time duration will also be affected by modularisation.
- **Inspection-based wait time** occurs in the gap between tasks that are connected F-S. Assuming that testing and inspection of individual processes and systems is done on-site, inspection-based wait time is unaffected by modularisation[4].
- **Inefficient wait time** mostly occurs between tasks that are connected F-S and remains unaffected by modularisation.

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[4] With the exception of the final whole-plant commissioning, tasks 117-121, the only testing activities explicitly included in the Sizewell B data set.

V.2.2.2. Application of Scaling

A number of literature sources [20] [44] [19] report a strong correlation between construction cost and NPP build times. As a result of this correlation, and based on preliminary work in [148], this project applies power scaling to task time and wait time. Power scaling follows the relationship in Equation V.1 in which *Specific Duration* is the duration of a given task (in days/kWe), and *Power* is the NPP output (kWe). The values of the scaling exponents, *n*, are shown in Chapter III, Table III.1 and are derived from historical nuclear construction experience. Additionally, the scheduling model has been set up to reflect the fact that a certain fraction of on-site time will be strongly correlated with reactor size and the remaining fraction of on-site time is fixed in duration and has no dependence on reactor size, as illustrated in Figure V.3.

$$Specific\ Duration_{SMR} = Specific\ Duration_{LR} \left(\frac{Power_{SMR}}{Power_{LR}}\right)^{(n-1)}$$

Equation V.1. Power scaling relationship for specific task durations.

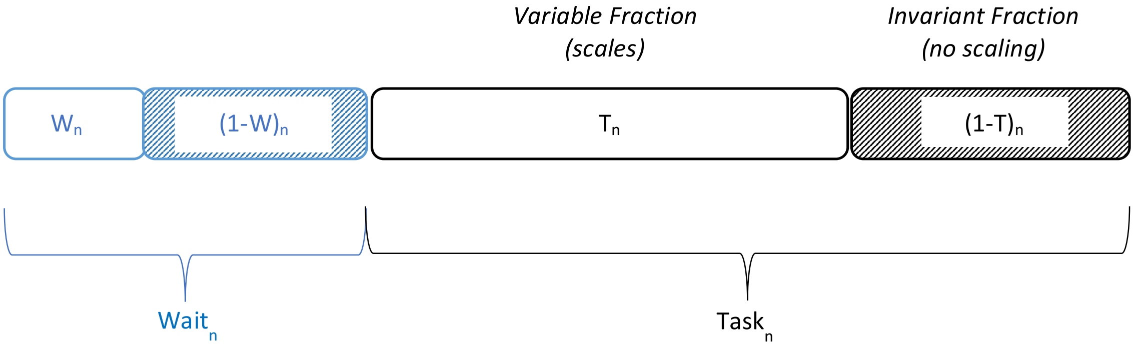

Figure V.3. Representation of the scheduling model: variable and invariant fractions (empty and shaded boxes respectively) for wait and task times (blue and black boxes respectively) for an activity, *n*.

V.2.2.3. Model Calibration

A number of additional factors affect build time but are not related to NPP size or modularity, including: reactor location, design standardisation, regulation changes, technological advances, construction process improvements, and supply chain structure. The impact of these factors on build schedule must be captured by calibrating the generic scheduling model set up here against relevant multi-parameter analysis in literature and/or previous construction experience [149]. Work by Berthélemy & Escobar-Rangel [44] uses a Cobb-Douglas production function to determine the relationship between reactor size and lead time. Equation V.2 gives the generic form of the Cobb-Douglas production function where *LT* is lead time, in years, and *CAP* is power output, in MWe, for a specific reactor, *i*. Constants *A* and *B* depend on an evaluation of other parameters[5] that influence build time.

$$ln(LT_i) = A + B\, ln(CAP_i)$$

Equation V.2. Cobb-Douglas production function for size and construction time of a reactor *i.*

Assuming the constants *A* and *B* in Equation V.2 are independent of reactor size, Sizewell B is established as a reference NPP and Equation V.2 can be simplified to Equation V.3 to give a relationship between NPP build time and size. Berthélemy & Escobar-Rangel develop four slightly different sets of constants, by using different data sets. The model presented here uses the parameters derived from the US & French data set for calibration, assuming the US & French data are roughly representative of UK experience [15]. The worldwide data set in [44] includes Asian, European, and South American experience and is provided for comparative purposes. The relevant calibration parameters are shown in Table V.1.

$$LT_i = LT_{SXB} \left(\frac{CAP_i}{CAP_{SZB}}\right)^B$$

Equation V.3. Simplified Cobb-Douglas production function to determine the build time of a reactor, *i,* relative to the Sizewell B baseline.

Table V.1. Parameters used from the Berthélemy & Escobar-Rangel parametric NPP lead-time model, [44].

Model	***B***	**Notes**
Berthélemy_World	0.395	Based on worldwide construction data from a range of small and large reactor programmes.
Berthélemy_US & France	0.188	Based on construction data from the US and France only, both of which were large programmes of reactor build.

Two scaling cases are described below to determine what conditions are necessary for this project's scheduling model to replicate the Berthélemy_US & France model. It is worth noting that the trends determined using the parametric model from

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[5] Parameters include: future electricity demand, # reactors built in each country, reactor size, market share index, vertical integration of Architect-Engineer (A-E) with utility, # reactors under construction, cement & labour cost indices, the effect of nuclear accidents [44].

Berthélemy's paper are only shown for reactors that have power outputs from 450 MWe to 1200 MWe, inclusive, since this is the range of reactor power outputs over which real lead time data exists.

Scaling Case I: Only Task Time (T) Scales

The first scaling case shows how construction lead times relate to reactor power on the condition that task times (T) follow power scaling and wait times (W) are held constant regardless of reactor power. Figure V.4 shows that the Berthélemy_US & France trend can be replicated when T = 0.8 (80% of the task time on site scales with reactor power) and W = 0.0; this is also within the range of historical construction data in the West (Appendix I.1).

This construction scenario is one where the duration of on-site tasks depends heavily on reactor size. This scenario implies that smaller SMR structures, equipment, and components will be substantially faster to build than the large reactor equivalents. The wait time, however, is unaffected by reactor size – implying that the duration of non-scheduled tasks is independent of reactor power. The type of activities that make up the wait time are inferred to be mostly testing and commissioning activities, the duration of which is independent of the components or structures that are inspected.

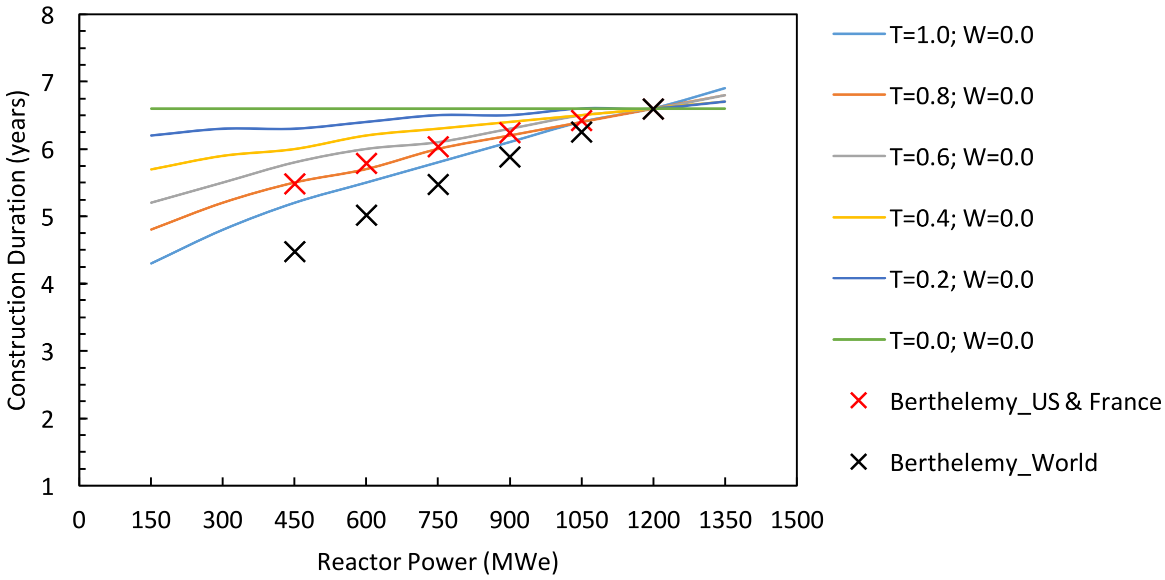

Figure V.4. Scaling Case I model: task time (T) scales with reactor size and wait time (W) does not. W = 0 for all values of T.

Scaling Case II: Equal Scaling of Task Time (T) and Wait Time (W)

The second scaling case shows how construction lead times relate to reactor power output if the same fraction of task and wait time follows power scaling laws; that is, when T = W. Figure V.5 shows that lead times predicted by the Berthélemy_US & France model are replicated in this case when T = W = 0.4. In effect, 40% of the on-site activities depend on the size of the structures and components while the remaining 60% does not scale for any reactor size and the duration remains the same as the baseline Sizewell B schedule.

In this case, the length of the 'non-active' time on-site is partially dependent on how long it takes for the scheduled construction tasks to be completed (e.g. concrete curing or rebar fixing). The wait time will reduce as the task time is reduced, meaning that a greater fraction of the overall schedule is determined by the actual scheduled construction activities. Case II contrasts with Case I in that this model is less governed by process inefficiencies and/or the time taken for commissioning and testing.

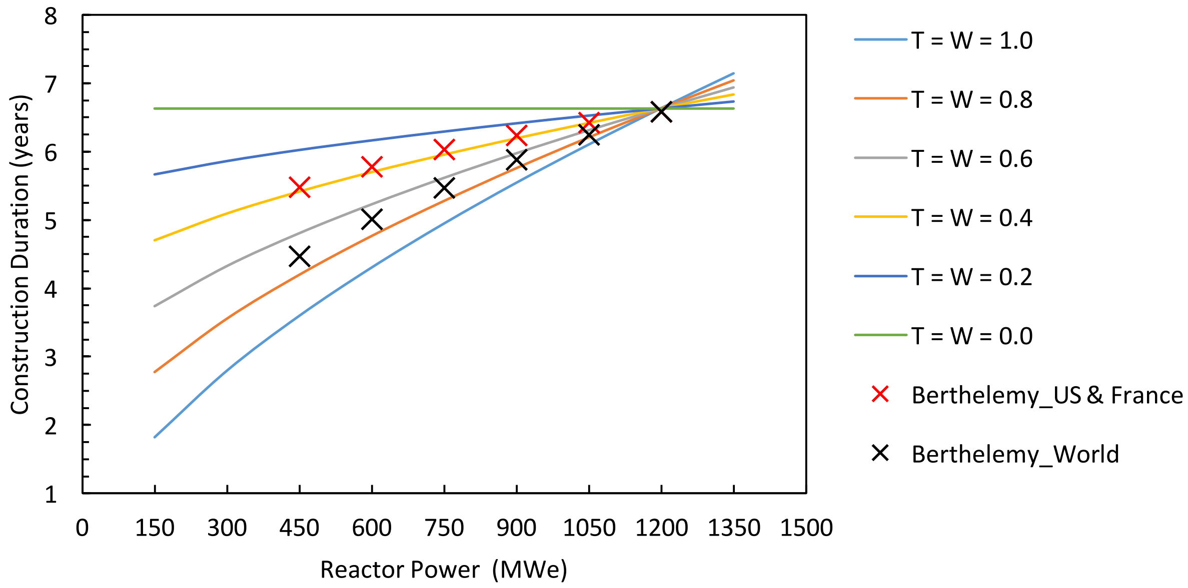

Figure V.5. Scaling Case II model: task time (T) and wait time (W) scale equally with reactor size. T = W for all values.

Additional Possible Scaling Cases

There are other theoretically correct cases where Berthélemy's parametric model can be reproduced using the scaling model developed here. For example, another extreme case could be suggested, where task time does not scale ($T = 0.0$) and wait time does (W = some number). While this might produce another mathematical solution to the model, it is not a realistic case; it is in practice illogical to anticipate a construction scenario where non-active times depend on the reactor size and the value-added construction time has no dependency on reactor size at all.

Mathematically, the solutions to matching the variable scaling model in this project with Berthélemy's parametric model falls within a 3-D space in which T and W are varied simultaneously, generating a 'carpet plot' of results. To examine the full solution space overcomplicates the problem and examining all the potential mathematical solutions without the context of their practicality is not useful. The goal of this model is not to exactly replicate Berthélemy's parametric study. The purpose of this calibration exercise is to identify reasonable values for the parameters T and W that mean the variable scaling model provides a reasonable approximation of an expected NPP construction schedule.

The work above has postulated two such feasible cases which both appear reasonable when applied to the larger context of NPP construction, and both cases will be carried forward in a comparative scenario-type analysis in this project.

V.2.2.4. Application of Modularisation

The fraction of site work that can be moved off-site to a production facility is constrained by the maximum fraction of modules that can be transported, as per Chapter IV. The stick-built NPP construction schedule is therefore modularised by applying a task-specific DoM to each of the 120 activities in the NPP schedule, up to a maximum value (DoM_{max}) based on module commodity type and location. Appendix IV.3 shows the specific alignment of the DoM_{max} from Chapter IV with reactor size.

Modularisation of Task Time

When modularisation is applied to task time, the corresponding schedule line item is shortened in proportion to the fraction of work that is being moved off-site. The work that is moved off-site must be replaced with on-site assembly time for the modules; this is set at 5% of the time that is transferred off site for the given module [21].

Equation V.4 shows how the duration of the total on-site task time can be calculated for a given value of DoM, where $t_{modular\ task,i}$ is the remaining on-site time for the modular task, i, and $t_{baseline\ task,i}$ is the original duration of the task from the baseline schedule.

$$t_{modular\ task,i} = (1 - DoM)t_{baseline\ task,i} + 0.05(DoM)t_{baseline\ task,i}$$

Equation V.4. Residual on-site construction time after modularisation.

Modularisation of Wait Time

Whether wait time is affected by modularisation or not depends on if the wait time is enforced, inspection-based, or inefficient. Only enforced wait time is affected by modularisation: because enforced wait time occurs between S-S connected tasks its duration is governed by the length of the previous task, which is itself affected by modularisation. Equation V.5 shows how modular enforced wait time is calculated, where $t_{S\text{-}S\ modular\ wait,i}$ is the duration (days) of the modularised enforced wait time for task i, $t_{S\text{-}S\ baseline\ wait,i}$ is the enforced wait time duration of the original stick-built task (days), and *DoM* is the Degree of Modularisation.

Inspection-based and inefficient wait times, both F-S connected tasks, are not affected by modularisation, as per Equation V.6, where $t_{F\text{-}S\ modular\ wait,i}$ is the duration (days) of the on-site F-S connected wait time for task i, $t_{F\text{-}S\ baseline\ wait,i}$ is the F-S connected wait time duration of the original stick-built task (days). This is a simplification of what may actually occur on-site and, in reality, the modularisation of different types of wait times may not be as clear-cut as this section supposes. Given the absence of more detailed data, however, the simplifying assumptions made here are reasonable.

$$t_{S-S\ modular\ wait,i} = (1 - DoM)t_{S-S\ baseline\ wait,i}$$

Equation V.5. Residual on-site wait time for S-S connected tasks after modularisation.

$$t_{F-S\ modular\ wait,i} = t_{F-S\ baseline\ wait,i}$$

Equation V.6. Residual on-site wait time for F-S connected tasks after modularisation.

V.3. Build Schedule Results

The results presented below take the scheduling theory developed in Section V.2 and examines what happens to build times for reactors of different sizes and of varying modularity. The full range of large and small reactor sizes is studied here, demonstrating that SMRs are indeed expected to benefit more from modularisation than LRs. Conventional build time is dictated by the capability of a project to place large volumes of material *in-situ*; governed by the plant complexity, manpower, and curing processes [46]; therefore small stick-built reactors are expected to have shorter build times than LRs because they are smaller projects requiring less material.

Two potential scaling cases for schedule approximation are carried forward in the following analysis. These are both determined based on the earlier calibration of the scaling cases with the parametric model developed by Berthélemy & Escobar-Rangel [44].

- **Scaling Case I**. T = 0.8; W = 0.0 High task time scaling, no wait time scaling
  See Figure V.4 for calibration
- **Scaling Case II**. T = W = 0.4 Moderate and equal task + wait time scaling
  See Figure V.5 for calibration

V.3.1. Establishing Upper and Lower Bounds on Construction Duration

Figure V.6 compares the construction duration of a stick-built NPP with that of a fully modular NPP. This is a useful initial comparison because it shows the upper and lower bounds for construction duration across the full range of reactor sizes. The maximum DoM is plotted versus reactor power on the secondary vertical axis to highlight how SMRs have a greater modularisation potential than LRs.

The ‘best case’ modularisation conditions used in Figure V.6 are as follows:

- Modularisation is applied as extensively as possible to Wait and Task times
    - S-S connected Wait Times are affected by modularisation.
    - Full modularisation is applied to all Task Time activities and includes construction of structures, liners, M&E and piping systems, equipment items, and finishes (Table I.1).
- The maximum possible DoM is applied to each reactor size (Appendix IV.3).

Small stick-built reactors inherently have shorter build durations than stick-built LRs because of their size differences. Applying a ‘best case’ modularisation scenario significantly reduces the construction duration of small and medium size reactors; however, the benefits of modularisation decrease with increasing size. For large reactors 750 MWe and greater, the DoM_{max} reaches a plateau of about 0.2. This means that a roughly 20% of a large reactor’s stick-built site content can be moved off-site in modules, compared to 80-90% for SMRs. The corresponding reduction in schedule durations is significant. The ‘best case’ modularisation scenario for a large reactor reduces the build schedule by only 0.75 years but the build schedule can be reduced by as much as 2.0 years for a 150 MWe reactor.

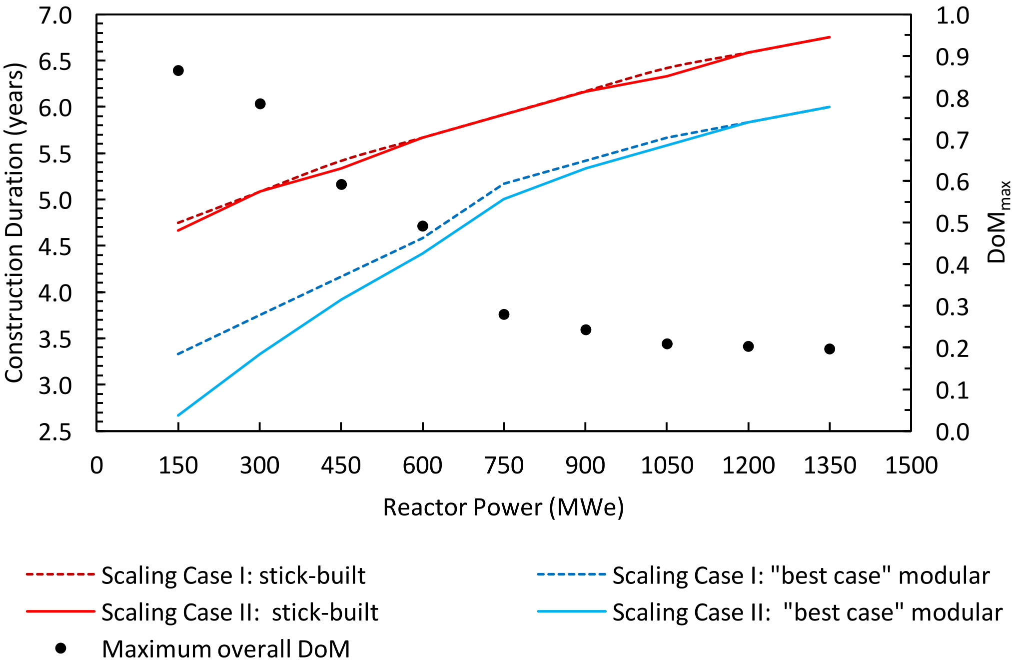

Figure V.6. Stick-built and ‘best case’ modular build times in terms of build duration (primary vertical axis) and DoM_{max} (secondary vertical axis) versus reactor power.

Figure V.6 also provides an interesting comparison between the results generated by Scaling Case I and Scaling Case II. The two cases provide very similar results for assessing the stick-built schedules of any reactor size (upper dashed and solid lines in Figure V.6, respectively). However, the two cases are substantially different for SMRs if a large degree of modularisation is incorporated. The reason for this is because of the different modelling of wait time scaling. In general, wait time is less affected by modularisation than task time because modularisation is only applied to the wait time of S-S connected tasks. In the Case I model, where wait times do not scale and are more dominant than task times in determining the overall schedule duration, modularisation cannot have a large impact on reducing the overall schedule. For the Case II model, task times play a more significant role in determining the overall schedule and modularisation has more opportunity to move 'value-added' construction work off-site.

This also explains why the difference between the two scaling cases is most significant for reactors smaller than 450 MWe. As reactor size decreases, scaled time contributes less to the total reactor build duration and unscaled portions of task and wait time begin to dominate the overall schedule. Modularisation, therefore, has less opportunity to impact the Case I model since the large contribution from the un-scaled and un-modularisable wait time (W = 0.0) governs the schedule duration more than the relatively small contribution of the highly scaled and modularisable task time (T = 0.8). The equal task and wait time scaling in the Case II model (T = W = 0.4) moderates the impact of wait time on the overall schedule and the high modularisation of the task time has more opportunity to reduce the total build time.

Figure V.6 cannot be used alone to draw conclusions about the accuracy of the two scaling cases and it is unclear which is more representative of reality. While the differences between Case I (T = 0.8 and W = 0.0) and Case II (T = W = 0.4) models are insignificant for stick-built SMR and all LR schedule estimations, there can be as much as a 0.67 year difference between the models for small, highly modular reactors. It is also very likely that these two models will trace different critical paths through the set of construction activities. A comparison of the critical path of the Sizewell B reference schedule and a 300 MWe stick-built SMR has been used to determine which of the two scaling cases is most representative of reality. The Gantt charts that have been plotted show that the critical path of the Case II scaling model, where T = W = 0.4, is almost identical to the original Sizewell B schedule critical path. The Case I scheduling model has quite a different critical path to the Sizewell B reference schedule; this suggests it is a less accurate scaling model than Case II. Section V.4.4 discusses the specific differences in critical path between Case I and Case II.

V.3.2. Varying Modularity

It is unlikely that the 'best case' modularisation scenario will be achieved in practice; therefore, it is necessary to consider how build time depends on variations in modularity.

- **Extent of Modularisation:** none, low, medium, or full
    - Wait Time: S-S connected tasks can be affected by modularisation. The extent of modularisation varies according to the categories in Table I.1. F-S connected wait tasks are not affected by modularisation in any instance.
    - Task Time: the extent of modularisation varies according to Table I.1.
- **Degree of Modularisation:** $0 \leq \mathrm{DoM} \leq \mathrm{DoM}_{\mathrm{max},i}$
    - A range of DoM is applied to the modularised time durations for each task *i* as per Chapter IV and Appendix IV.3.

V.3.2.1. Extent of Modularisation

The response of reactor build times to variations in wait and task modularity is shown in Figure V.7 and Figure V.8, for scaling Case I and Case II respectively. For all modularised cases, $\mathrm{DoM}_{\mathrm{max},i}$ is used and is specific to each task *i*. The 'medium' extent of modularisation is excluded from the following comparisons, since there is minimal difference between the build schedules of 'medium' and 'full' modularised NPPs, regardless of size or scaling case. This indicates that modularising the finishing elements of construction work (building façades and so on) offers little additional schedule reduction and 'full' modularisation benefits are effectively achieved once the M&E, piping, equipment, liners, and structures are all modularised.

Both Figure V.7 and Figure V.8 show that a ‘low’ extent of modularisation, which modularises only the M&E and piping systems, offers a consistent 5%-10% schedule reduction for a reactor relative to its original stick-built baseline. ‘Full’ modularisation considerably shortens the overall build duration by including liners and structural elements. Schedule reductions are on the order of 10%-15%, for reactors larger than 750 MWe and can reach nearly 45% for a 150 MWe SMR, relative to its stick-built baseline. This suggests that structural construction work falls on the NPP critical path and modularising these tasks is essential to reducing the overall build time. Section V.4 includes a discussion of a few specific cases of interest.

Figure V.7 and Figure V.8 also show what happens to the schedule reduction if only the task times are modularised, compared with modularisation of both the task times and S-S connected wait times. If the extent of modularisation is low and/or if the reactor is larger than 600 MWe, modularising the wait time has little additional impact on the schedule. For reactors 600 MWe and smaller, the importance of wait time modularisation increases because the applied DoM is higher and the critical path has more potential to be influenced by modularisation. If modularisation affects both wait time and task time, the construction schedule of a fully modular SMR is shortened by an additional 5% - 10% relative to the case when only the task time is modularised. This difference decreases to only 1% additional schedule reduction for reactors larger than 600 MWe.

In order to simplify the number of scenarios in this project, the subsequent analysis considers only the case where task time is affected by modularisation. In practical terms, wait times that are not affected by modularisation would consist primarily of inspection and testing activities, construction process inefficiencies, and other non-value-added time. This is an intentionally conservative estimate since it is clear that, should the wait time between tasks indeed be affected by modularisation, the construction schedule will be further shortened beyond the estimates shown here.

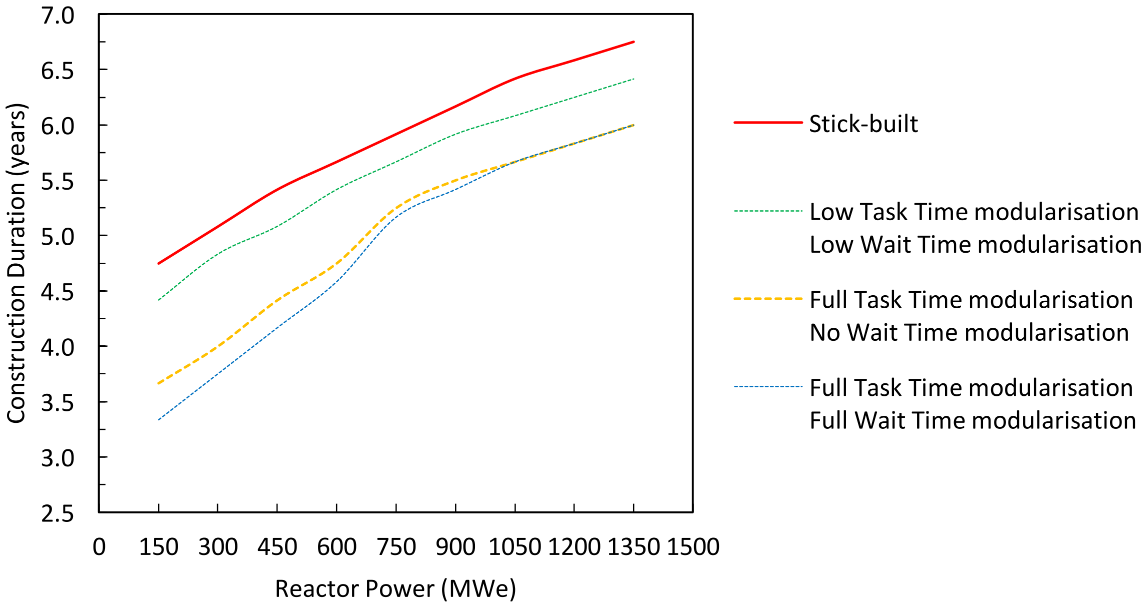

Figure V.7. Construction duration versus reactor power for variable modularisation of T and W. Scaling Case I (T = 0.8, W = 0.0); at DoM_{max}.

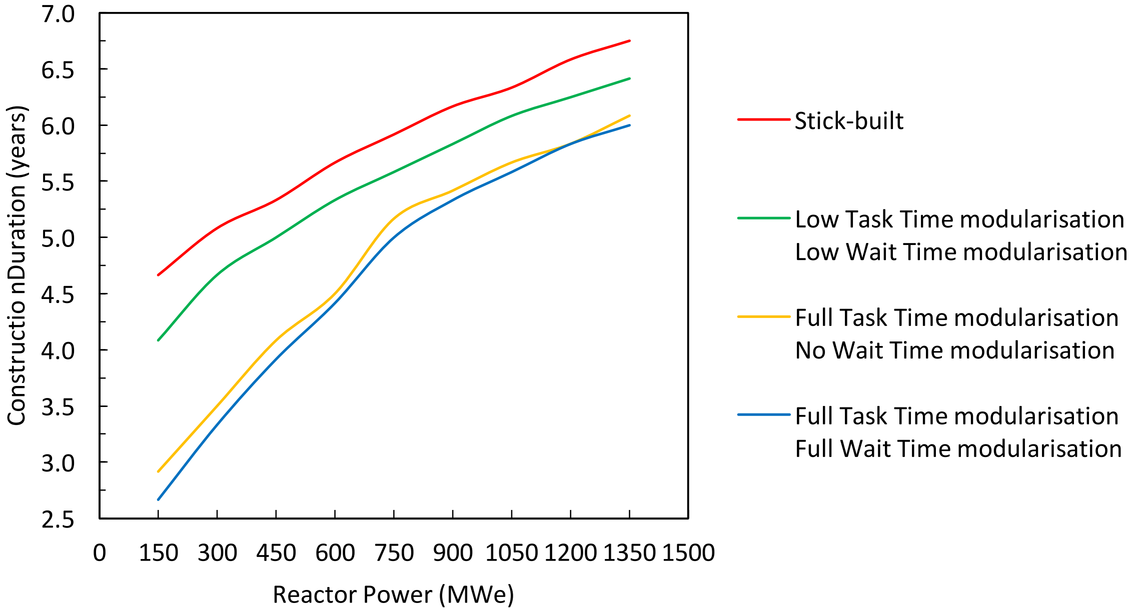

Figure V.8. Construction duration versus reactor power for variable modularisation of T and W. Scaling Case II (T = W = 0.4); at DoM_{max}.

V.3.2.2. Degree of Modularisation

Thus far only the two bounding cases for DoM are presented; that is the stick-built case, where DoM = 0.0, and the fully modular case at DoM_{max}. While this is useful in establishing the upper and lower limits of the expected schedule duration, it is also important to consider the optimal DoM value. Modularity may follow a law of diminishing returns, where additional schedule reductions are minimal and do not warrant the extra design effort that is required from further modularisation.

In the following section the build duration for a range of reactor sizes is calculated for both a 'low' and a 'full' extent of modularisation. Scaling Case I and Case II are both carried forward, for comparative purposes, giving four different scenarios. In each case NPP build time is plotted against reactor power for a range of input DoM, where $0 \leq \text{DoM} \leq 1.0$ or DoM_{max} (whichever is smaller), placing a practical upper limit on the input DoM depending on the maximum transportable weight fraction of modules. Different module types can have different transportability, as shown in Chapter IV, and the maximum DoM can be 1.0 for some commodities (e.g. M&E elements for SMRs) and 0.0 for others (e.g. the fuel building liners). The general trend is for the weight-average DoM_{max} across all modules to decrease with increasing reactor sizes.

The Effective Modularisation (M_{eff}), as defined in Chapter I, is also plotted with respect to reactor power, and indicates how extensive the schedule reduction is for each reactor power output. M_{eff} indicates how much schedule time is transferred off-site by modularisation at the maximum DoM relative to the stick-built construction time. The general trend is for M_{eff} to decrease with increasing reactor size, although in some cases the value of M_{eff} may rise slightly with reactor size, depending on how the schedule for a specific reactor scenario responds to modularisation and to what extent the modularity translates into reductions on the overall critical path.

'Low' Modularisation

Figure V.9 and V.10 show how NPP build time varies over a range of DoM for Case I and Case II, respectively, and assuming a 'low' extent of modularisation (M&E, piping systems, equipment). This chart shows that there is no schedule reduction benefit to modularising beyond an input DoM of 0.60; this holds true across all reactor sizes and for both Case I and Case II models.

The Effective Modularisation (M_{eff}) shown in Figure V.9 and V.10 is roughly constant when the extent of modularisation is low, with 5% - 7% of the overall site work moved off-site in modules. Since the magnitude of the maximum M_{eff} is small, relative to the optimal input DoM of 0.60, it is clear that the benefits to modularising just the M&E and piping systems are capped and the additional modularisation effort is absorbed by the other schedule activities and does not translate into large build time reductions. Furthermore, in spite of the additional modularisability of small reactors, SMRs don't have significantly more schedule compression than LRs. This suggests that the extent of modularisation in the 'low' scenario is what limits the achievable schedule benefits, instead of module transportability.

In the Case I mode, the NPP construction schedule can be reduced by 0.30 years, on average. Specifically, a 150 MWe SMR can be reduced from 4.8 to 4.4 years and a 1200 MWe LR can be reduced from 6.6 to 6.3 years. In Case II, the build duration of a 150 MWe reactor reduces from 4.7 years to 4.1 years, and for a 1200 MWe reactor the schedule reduces from 6.6 years to 6.3 years; with an average reduction of 0.36 years.

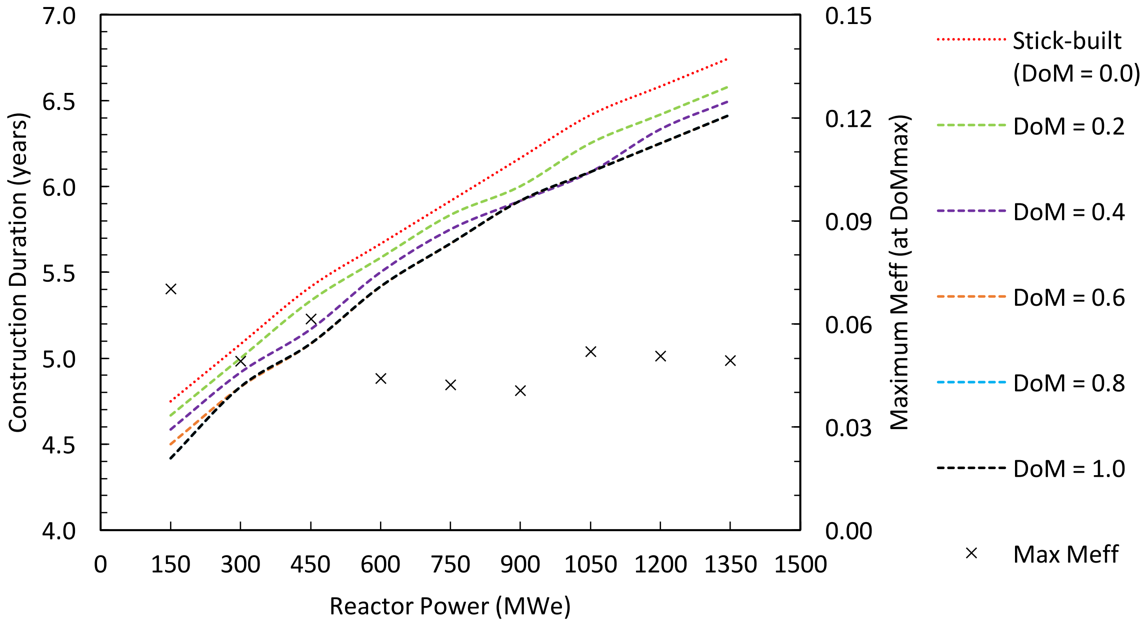

Figure V.9. Construction duration versus reactor power for variable DoM_{input} at **low modularisation**. Scaling Case I (T = 0.8 and W = 0.0); W unaffected by modularisation.

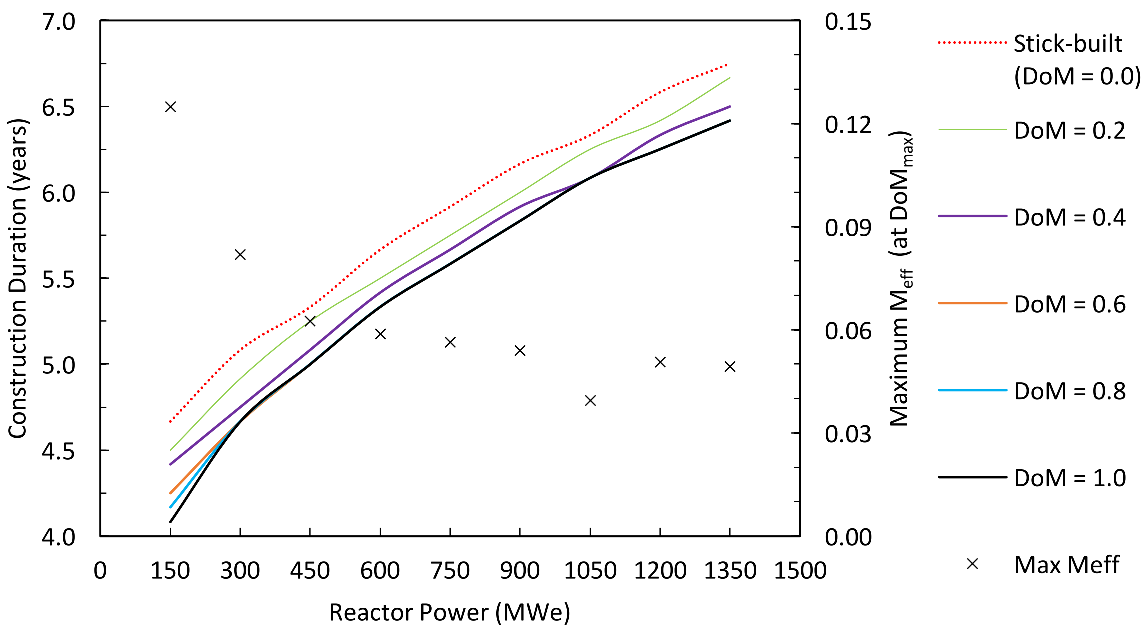

Figure V.10. Construction duration versus reactor power for variable DoM_{input} at **low modularisation**. Scaling Case II (T = W = 0.4); W unaffected by modularisation.

'Full' Modularisation

When modularisation is extended to the full range of NPP systems and structures (M&E, piping systems, liners, and structural elements), there is greater scope for reducing the overall construction duration. Figures V.11 and V.12 show the construction duration as a function of reactor power when a full extent of modularisation is applied to the Scaling Case I and Scaling Case II models, respectively. As mentioned previously, modularisation causes more significant schedule reduction in Case II models since task time plays a greater role in determining the schedule duration.

In both Scaling Case I and Scaling Case II the optimum DoM input for fully modular plants is 0.4 for reactors larger than 600 MWe. This increases to 0.6 for 450-600 MWe reactors (medium sized reactors) and again increases to 0.8 if the reactor is smaller than 450 MWe (SMR). In contrast to the 'low' extent of modularisation case, however, M_{eff} increases substantially as reactor size decreases. This indicates that modularisation of the structures is effective in moving a lot of on-site work off site and compressing the overall critical path.

It is worth noting that even in the ‘full’ extent of modularisation scenario the maximum M_{eff} still does not equal the optimal DoM_{input}. Firstly, regardless of how extensively the plant is modularised, there will always be residual construction work that must be performed at the site. This is primarily module assembly, site preparation, excavation, yard work, backfill, and final plant commissioning. Also, the wait time between all tasks is unaffected by modularisation, which further limits the maximum M_{eff} by restricting the net amount of build time that can be moved off-site by the use of modules.

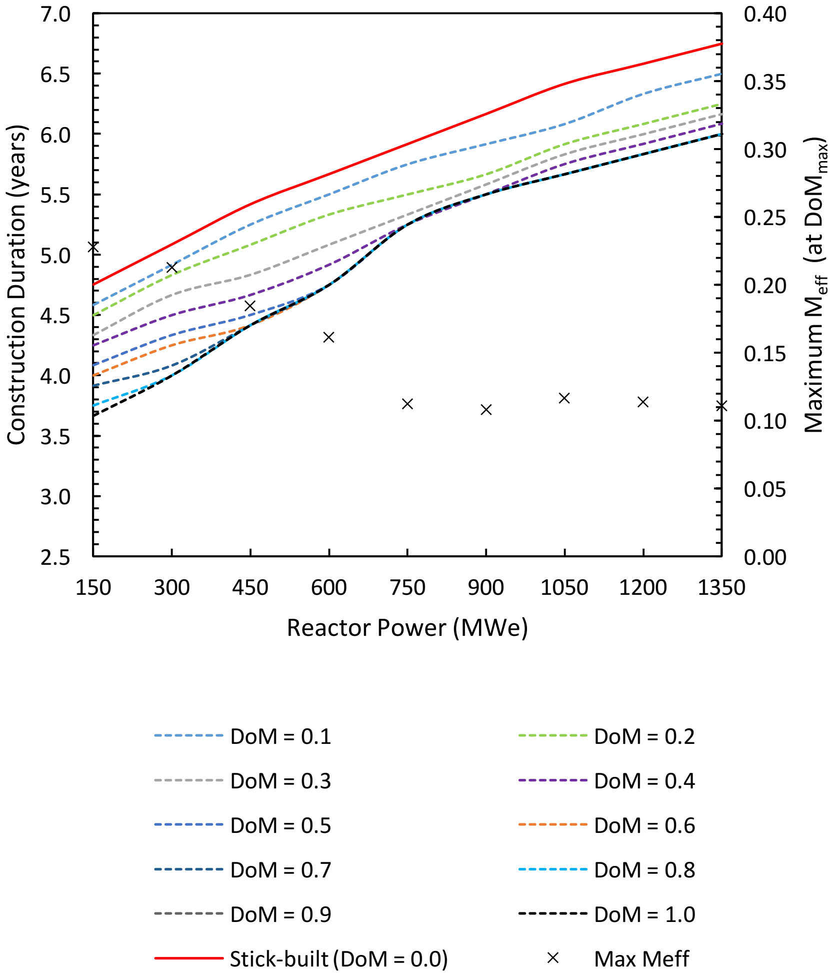

Figure V.11 Construction duration versus reactor power for variable DoM_{input} at **full modularisation**.
Scaling Case I (T = 0.8 and W = 0.0); W unaffected by modularisation.

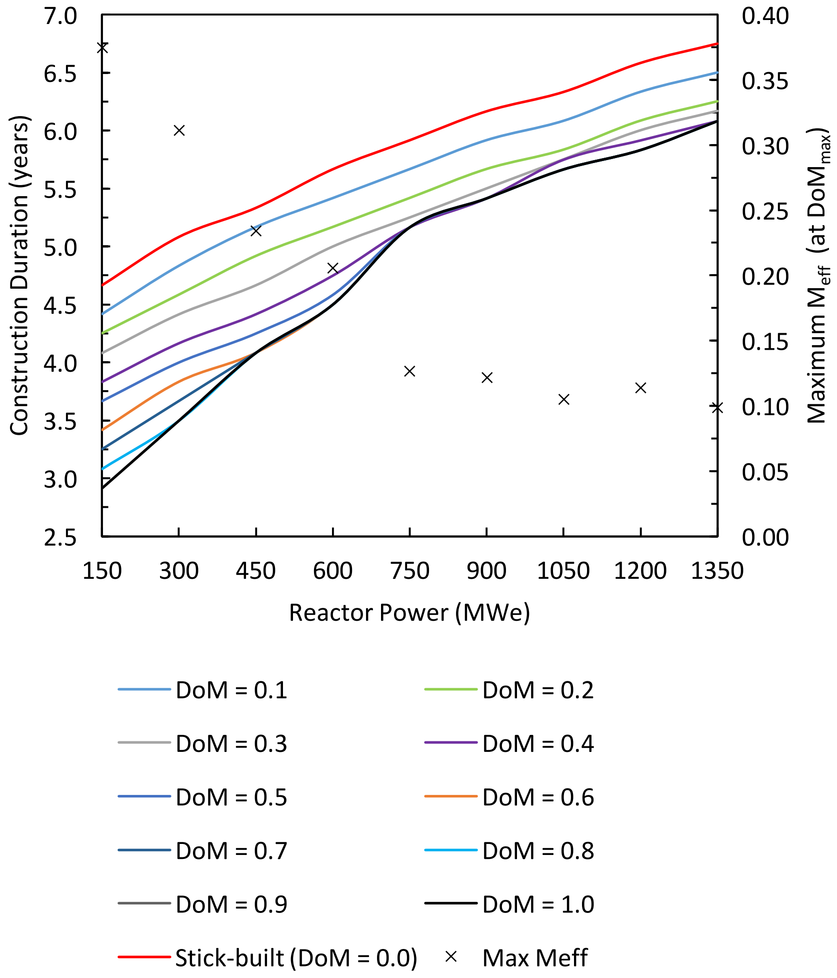

Figure V.12. Construction duration versus reactor power for variable DoM_{input} at **full modularisation**.
Scaling Case II (T = W = 0.4); W unaffected by modularisation.

V.3.3. Module Factory Considerations

This project focusses on how the *in-situ* build time changes in direct response to variations in modularity, but it does not model how the off-site component of build time might affect on-site durations. In general, there are three types of construction location: *in-situ*, an on-site shop, and an off-site factory, each of which has different productivities. These are captured by the 1-3-8 rule of thumb from the shipbuilding industry and approximate the relative reduction in build times *in-situ*, in an on-site shop, and in an off-site factory, respectively [22]. This rule of thumb is applied to nuclear construction, as found in work by Barry [51] and Maronati [32].

V.4. Build Schedule Analysis & Discussion

The results presented in Section V.3 show how total NPP construction duration depends on reactor size as well as on the extent of modularisation and DoM. While some inferences can be made from these overall trends about the importance of different types of on-site activities, it is also useful to examine the effect of modularisation on the specific tasks in a reactor's build sequence.

This section presents some construction scenarios at a detailed Gantt chart level. The different scenarios are chosen because they provide interesting comparisons across a range of modular construction scenarios, offering a better understanding of the overall behaviour of NPP build schedule in response to implementing modular construction. They are not intended to determine the 'best' construction option for SMR build and are not a comprehensive prediction or study of a full range of SMR construction scenarios.

Four specific comparisons are presented in the following sub-sections and a Gantt chart is plotted for each example, with a direct comparison of the modular schedule versus the stick-built baseline schedule (if relevant). Scaling Case II ($T = W = 0.4$) is used to generate all SMR build programmes in this section because closer investigation shows that the critical path generated using Scaling Case II is very similar to the critical path from the reference stick-built LR data (discussed in Sections V.4.1 and

V.4.3). Task times are modularised but wait times are unaffected by modularisation, regardless of their type (enforced, inspection-based, or inefficient) or connectivity (S-S or F-S). There is a point at which increasing the modularity of the NPP provides little to no additional reduction in build time. This arises as a direct result of the increasing difficulty of transport logistics of larger reactors. The 'break points', or the reactor sizes at which these optimal DoM values occur (or change), are summarised in Table V.2 below and are used in setting the conditions for the four comparison scenarios. It is interesting to note that the location of the 'break points' in Table V.2 do not change if scaling Case I is adopted instead of Case II.

Section V.4.1. 1200 MWe stick-built large reactor compared with
300 MWe stick-built SMR
Section V.4.2. 1200 MWe stick-built large reactor compared with
'full' modular LR (DoM = 0.4)
Section V.4.3 300 MWe stick-built SMR is compared with
'low' modular SMR (DoM = 0.60)
'full' modular SMR (DoM = 0.80)
Section V.4.4. Scaling Case I and Scaling Case II compared for a
stick-built 300 MWe SMR

Table V.2. Optimum DoM and 'break points' as they relate to reactor size and extent of modularisation.

		Optimal Input DoM	
Reactor Size	**Power Output**	**Low Modularisation**	**Full Modularisation**
Small Reactor	≤ 450 MWe	0.60	0.80
Medium Reactor	450 MWe-900 MWe	0.60	0.40-0.60
Large Reactor	≥ 900 MWe	0.60	0.40

V.4.1. Stick-built Reactor Comparison

First, the detailed schedule of a stick-built 1200 MWe LR is compared with that of a stick-built 300 MWe SMR as summarised in Table V.3. As expected, scaling has the effect of reducing the net duration of the SMR construction tasks so they are shorter than the corresponding LR tasks. The critical path of the LR and SMR are very similar, with one slight difference. The turbine room finishing activities (task 62) are non-critical in the LR schedule but become critical in the SMR schedule. Instead, some of the M&E installation work for the turbine room (task 70) is on the critical path for a LR and not for a SMR. In the stick-built LR schedule, these two tasks end within a few days of each other and the critical path shift likely arises as a result of the different scaling exponents that are applied to each task's predecessors. The overall similarity of the critical path between the stick-built LR and SMR cases increases confidence in the representativeness and suitability of using the Case II scaling model.

Table V.3. Key figures and values for stick-built LR and SMR schedule comparison.

	1200 MWe LR Appendix V.1	**300 MWe SMR** Appendix V.2
Build Method	Stick-Built	Stick-Built
Build Duration	79 months (6.6 yr)	61 months (5.1 yr)
Number of critical tasks	24	24

In general, structural elements have a large influence on the critical path of a stick-built NPP. The final stages of constructing the structural elements of the Control Building all fall on the critical path in a block (tasks 103-108). A second, similar, case occurs with the structure of the Primary Auxiliary Building + Tunnels, where most of the structural tasks are critical and the fabrication and installation of the M&E systems is dependent on the structure being complete (tasks 75, 79, 81). If any of these structural tasks were delayed, the net schedule would be unable to absorb the over-run and the whole project critical path would be lengthened. These blocks of critical tasks are of concern, since they play a large role in determining the length of the overall project schedule.

The other tasks on the critical path of a stick-built NPP are 'completion' type tasks, such as plant installation and/or finishing activities for the final auxiliary buildings[6]. This is as expected and their criticality is not of concern because these completion activities all occur towards the end of the project and end at approximately the same time. Other one-off critical tasks include finishing the refuelling pond (task 21),

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[6] Waste process (task 216), fuel storage (task 217), administrative (task 218b) buildings, and pipe tunnels (218k).

finishing the containment building dome (task 26 and task 36), and installation of the TGs (task 58). Modularising these tasks will either directly shorten the overall schedule, or else the task will become non-critical and the critical path will shift to a new set of tasks.

V.4.2. 1200 MWe LR Baseline & Modularisation

To compare the impact of modularisation on LR build time, the project schedule of a stick-built 1200 MWe large reactor (Appendix V.1) is compared with that of a fully modularised 1200 MWe reactor at an input DoM of 0.4 (Appendix V.3). 'Full' modularisation includes M&E, piping, equipment, liners and structures; overall results are shown in Table V.4.

Table V.4. Key figures and values for stick-built and modular 1200 MWe LR scheduling comparison.

	1200 MWe LR Appendix V.3	
Build Method	Stick-Built	Modular
Extent of Modularisation	N/A	Full
Input DoM	N/A	0.40
Build Duration	79 months (6.6 yr)	71 months (5.9 yr)
M_{eff} (relative to stick-built 1200 MWe LR)	N/A	0.10
Number of critical tasks	24	5

The result of 'full' modularisation is to move a number of previously critical tasks off-site, forming a new critical path for the modular NPP. This particularly impacts blocks of critical tasks such as the auxiliary building structures (tasks 75, 79, 81) and the control room/diesel-generator building structure with M&E (tasks 103-107 inclusive). In the modularised schedule, these tasks are moved off the critical path and the total number of critical tasks is greatly reduced.

Even when 'full' modularisation is applied to the LR, a number of task durations are still not noticeably shortened in the LR schedule. In most cases this is because transport logistics constrain how modular the elements can be, particularly in the case of structural items, and the actual modularisation of these tasks is much lower than the optimum DoM value that is applied. This is reflected in the difference between

M_{eff} and the input DoM in Table V.4. While the location of the critical path is primarily determined by the extent of modularisation, the duration of each task (and therefore the duration of the overall project) is governed by the achievable input DoM.

V.4.3. 300 MWe SMR Baseline & Modularisation

Two comparisons will be made for modular SMRs, with overall parameters and results for both summarised in Table V.5. The first comparison is between a stick-built SMR and a 'low' modularised 300 MWe SMR at an input DoM of 0.6 (Appendix V.4). The second comparison is between a stick-built SMR and a 'full' modularised 300 MWe SMR at an input DoM of 0.8 (Appendix V.5). In an ideal modular construction strategy, on-site work would simply consist of a series of assembly activities, with only the final stages of construction remaining on the critical path.

Table V.5. Key figures and values for 300 MWe SMR scheduling comparisons.

	300 MWe SMR Appendix V.4 & Appendix V.5		
Build Method	Stick-Built	Modular	
Extent of Modularisation	N/A	Low	Full
Input DoM	N/A	0.60	0.80
Build Duration	61 months (5.1 yr)	56 months (4.7 yr)	42 months (3.5 yr)
M_{eff} (relative to stick-built 300 MWe SMR)	N/A	0.082	0.31
Number of critical tasks	24	19	16

V.4.3.1. Stick-built SMR & low modularisation

Adding a 'low' extent of modularisation to the project (Appendix V.4) removes a number of plant installation tasks off the stick-built SMR critical path. This affects the critical path of both the waste process building and the pipe tunnels. The final structural and M&E tasks of the control room and diesel-generator building are also removed from the critical path. This is particularly advantageous because it removes a block of sequential critical tasks, leaving only the final construction stages as critical. Any M&E systems and/or plant installation tasks that remain on the critical path are affected by modularisation and the entire project duration is reduced accordingly[7].

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[7] Turbine generator 2 (task 58), auxiliary building M&E (task 83), control building M&E (task 103).

The early structural tasks that were critical remain so, as they are not included in the 'low' modularisation extent.

There are two main problem areas in this scenario. The first is with the sequential connectivity of the primary auxiliary building structural elements (tasks 75, 79, 81, 83). The dependency of these tasks on one another means that the ability of subsequent tasks to absorb schedule overruns is low and there is a risk that early construction delays will lengthen the whole project critical path. The other area of concern is the civil work for pipe tunnels (Task 110). Here, because the M&E elements are modularised, the critical path has reverted to the structural elements. Since this task is of particularly long duration, any overrun in this single task will potentially have a significant affect on the overall project build time.

V.4.3.2. Stick-built SMR & full modularisation

The 'full' extent of modularisation case (Appendix V.5) achieves a high input DoM, the on-site tasks become essentially site assembly work, consisting mainly of module joining. The early critical tasks are the same as the stick-built and low modularisation SMR cases described above, although their duration has been compressed. However, the critical path of the later construction activities has shifted. The structural tasks for the auxiliary building and control room/diesel-generator building (tasks 75, 79, 81, and 101, 103, 105 respectively) have been significantly shortened and are no longer on the critical path. This means these tasks are no longer crucial for the timeliness of the project and other task items can absorb delays within the overall structural build.

It is interesting to observe how the number of critical tasks reduces with increasing extent of modularisation. LRs see a much greater reduction in the number of critical tasks when modularised (24 → 5) than SMRs (24 → 16). This is because LRs have much longer task durations, on average, than SMRs. Longer tasks, coupled with the fact that LRs achieve a lower degree of modularisation, means that the schedule compression from modularisation is absorbed and doesn't produce a large reduction in net schedule, as shown by the relatively low M_{eff} values. When tasks in a LR are modularised, the net effect is small but is sufficient to compress the tasks so they are no longer critical. The critical path is therefore distributed across a few tasks that are of long duration. When tasks in a SMR are modularised, however, the resulting compression is large. The shorter task durations for a SMR (in general), coupled with high modularisation potential, means that the modularisation efforts have a significant impact on shortening the overall build time and the critical path remains distributed across a greater number of significantly shorter tasks.

V.4.4. 300 MWe SMR Scaling Case Comparison

Here the two scaling cases are compared for a 300 MWe stick-built SMR to see how the critical path differs between the models. Key results are summarised in Table V.6 and the schedule for each is shown in Appendix V.6, where the 'baseline' is Case II.

Table V.6. Key figures and values for Scaling Case I and Scaling Case II scheduling comparison for a stick-built 300 MWe SMR.

	300 MWe SMR Appendix V.6	
	Scaling Case I (T = 0.8, W = 0.0)	**Scaling Case II** (T = W = 0.4)
Build Method	Stick-Built	Stick-Built
Build Duration	61 months (5.1 yr)	61 months (5.1 yr)
Number of critical tasks	16	24

The critical path is quite different between the two models. This can be attributed to the fact that, since the wait time doesn't scale at all in the Case I model, it is able to provide more buffer time to absorb task criticality. The scaling Case I model has 16 critical tasks, whereas the Case II model has 24 critical tasks, the same as the stick-built LR schedule. The Case I model also doesn't have the same critical blocks of structural element construction on the critical path; this too is a result of high task time scaling. The schedule generated using scaling Case II is much more similar to the reference LR stick-built schedule than the schedule generated using Case I. This comparison helps increase confidence in using the scaling Case II model to generate the SMR build programme estimates.

V.5. Conclusions on Build Schedule

The work presented in this Chapter is based on a 120-task reference build schedule taken from available data from the construction of Sizewell B power station, an 1198 MWe PWR in the UK [47] and is one of the most detailed NPP scheduling models available in current literature. The modelling presented in this Chapter uses top-down methods to estimate the duration of NPP construction tasks by linking the size of a generic reactor to its build duration. Work is moved off the construction site through modularisation which is captured in two ways: first, through the different **types** of construction tasks that are affected (extent of modularisation); and second, through the **quantity** of work that is moved off-site (degree of modularisation).

The smaller size of SMRs means that they take less time to build overall and this, combined with their greater modularisation potential, means that they can achieve much shorter build times than LRs. A comparison between large and small reactors helps identify which individual tasks are significantly impacted by modularisation. The tasks that have the highest *in-situ* build time reduction for SMRs are the mechanical annexe structures (tasks 59-65), turbine hall structures (tasks 48 & 49), turbine hall electrical work (tasks 50 & 52), and control building structures (tasks 93, 95, 97, 99, 101, 103, 105, 107). The *in-situ* duration of each of these tasks is reduced by 95% for a 'full' modularised 300 MWe SMR, relative to the stick-built SMR, and contributes significantly to the overall build schedule reduction of a modular SMR. By contrast, the control building structures in a 'full' modular 1200 MWe LR have, at the most, a 35% reduction in time *in-situ*. 'Full' LR modularisation reduces the *in-situ* time of all other structural tasks is reduced by only 20%-25% relative to a stick-built 1200 MWe LR. Modularisation of M&E systems is more important for LR build programmes; for example, 'full' modularisation reduces the task time for turbine hall crane construction and turbine generator installation by 55% and the RPV build time is reduced by 45%. This highlights the importance of modularising structural elements and explains why, in a 'best-case' scenario, SMRs are able to achieve much higher fractions of time moved off-site ($M_{eff} = 0.31$) relative to LRs ($M_{eff} = 0.10$).

The drawback to significant levels of SMR modularisation is that, since all the task durations become compressed, highly modular projects still have a large number of critical tasks. The risk that a single-task delay will impact the whole project duration is high. The logistics of managing SMR construction projects, as well as ensuring just-in-time module and component supply, will need to be carefully planned before the project is begun. This is, however, typical of manufacturing industries and represents another area in which a production-oriented, DfMA mind-set must be adopted for SMR modularisation to be successful.

The methods presented in this Chapter can be used to inform the design process for modular SMRs, both in terms of the quantity and scope of construction work that should be moved into an off-site factory. The findings in this thesis can be used to guide further studies on module manufacture and/or component procurement and may assist with design of the SMR module production facility, supply chain strategy, or other aspects of SMR development and production that have not been directly addressed in this dissertation.

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CHAPTER VI
MODULARISATION & CONSTRUCTION COST

VI.1. Introduction

Usually off-site build is employed to bring a product to market quicker, to reduce lead times, to improve product customisability, to improve product constructability or safety, or to make the product easier to finance. Ultimately, modularisation is implemented to improve the economic feasibility of a product, whether by reducing manufacturing costs or improving competitiveness, and the effects of modularisation on product cost tend to manifest themselves indirectly. SMRs are no exception to this.

Although productivity improvements and reduced labour costs in the off-site factory reduce the specific cost of a modular SMR, the related standardisation, scheduling, and learning benefits have a much greater impact on SMR construction costs. Modular design and manufacturing strategies underpin these other cost reductions and, while the direct impact of modularisation on construction costs may not be large, SMRs would be unable to realise any of the associated cost benefits without modularisation. This Chapter examines how modularisation influences NPP construction cost and integrates the work from the previous two Chapters on transport and modularisation scheme (Chapter IV) and scheduling (Chapter V) to draw the key findings into a final economic analysis of modularisation and the impact it has on SMR cost.

VI.1.1. Reasons for High NPP Cost

NPPs have high construction costs and low ongoing costs (including fuel, O&M, waste, etc.). High construction costs mean that NPPs require large investment at a point early in the project cycle; this large initial upfront investment, coupled with long build durations, means that NPPs do not begin to generate revenue for 6-10 years. The Interest During Construction (IDC) costs accrued during this time can be significant [1].

The ETI Nuclear Cost Drivers report [15] identifies 8 cost drivers in the civil nuclear sector. 'High' importance cost drivers are the supply chain, labour (which measures efficiency and productivity at the individual level), project governance, and project development. 'Medium' importance cost drivers are construction execution, political and regulatory context, equipment and materials, and vendor plant design. Modularisation – by the fact that it enables higher productivity and standardisation through off-site manufacture – has the potential to benefit 5 of these cost drivers: construction execution, equipment and material usage, supply chain coordination, vendor plant design, and labour productivity. Crucially, the ETI project found that design completion, which is a priority of modularisation best-practice, is a critical factor in managing cost. As Figure VI.1 shows, plants that have a high percentage of design work complete at the beginning of construction can expect to have significantly lower construction costs. A study of US and global nuclear construction cost trends, performed by the Massachusetts Institute of Technology (MIT) [2], echoes the findings reported by the ETI report.

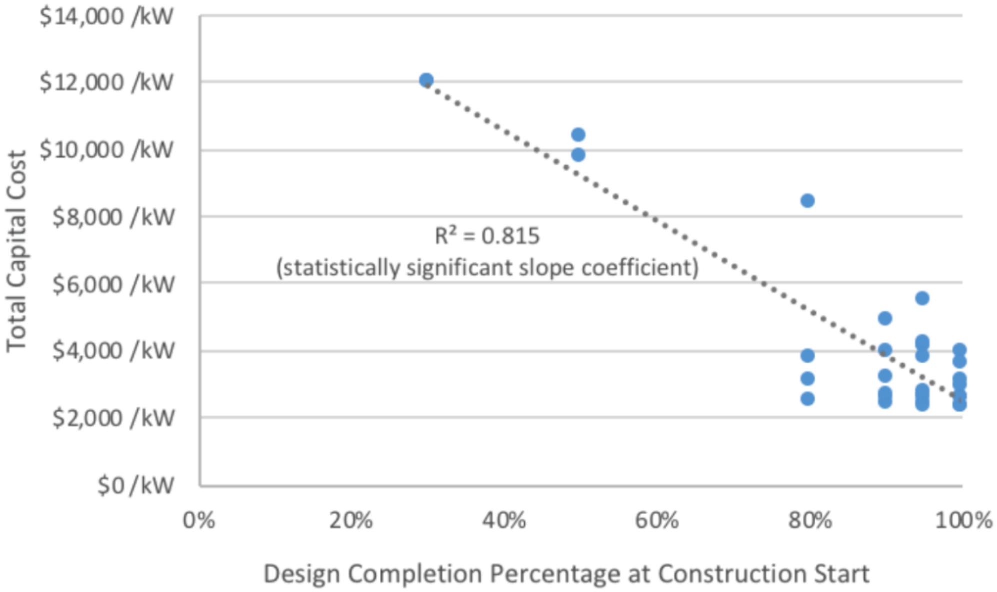


Figure VI.1. Relationship between percent design completion and total capital cost [15].

VI.1.2. Major Areas of High NPP Cost

Section I.2 discusses the context and rational for focussing on NPP construction costs. Capital costs are the largest contributor to total NPP LCOE, with initial NPP construction costs contributing approximately 70% of the total LCOE. The remaining 30% of nuclear LCOE is made up by ongoing expenses through the plant lifetime (O&M, fuel, and decommissioning) [10].

There are a number of different ways to estimate the cost of a nuclear power plant, as Chapter III discusses in more detail. Since this project is specifically concerned with the impact of modularisation on build costs, it makes sense to study TCIC which, according to the IAEA, include all the costs associated with the design, licensing, manufacturing, construction, and commissioning of the nuclear power plant, instead of the LCOE. TCIC also includes the financing costs incurred during the construction period [150]. It is common to divide TCIC into base costs (direct costs), supplementary costs (indirect costs), financial costs, and owner's costs. Costs that are excluded from the work presented here include fuel and fuel processing/disposal costs, O&M costs, and decommissioning costs.

To set these cost calculations in context, Figure VI.7 (in Section VI.3.3) shows how the calculated SMR TCIC costs compare to those of LRs and other energy technologies including renewables, coal, and gas.

VI.1.3. Limitations of Construction Cost Comparisons

In this Chapter, OCC, IDC, and TCIC are compared across different reactor sizes (SMR vs LR) and manufacturing strategy (stick-built, standardised, or modular). Section VI.3.3 shows how NPP costs compare against other energy generation technologies on a specific OCC basis. Civil nuclear power has some advantages that are not directly economic and cost comparisons need to be set in the wider context of energy policy and strategic, long-term thinking. While this type of analysis is outside the scope of this project, more detailed work is available in reports from the ETI [15] and MIT [2]. Some key non-economic factors that are advantageous for nuclear power are highlighted below.

i. Low Carbon

Nuclear power is a low carbon energy source, making it an important component of a nation's energy portfolio and government energy policy. It should be compared with renewables or fossil fuel technologies with Carbon Capture & Storage (CCS) rather than the current market's cheapest energy source, which is typically gas or coal (without CCS). These are not necessarily long-term acceptable energy options and may instead set an unrealistically low threshold for projected energy costs.

ii. Large Installation Capacity Potential

Nuclear can be installed at higher capacity than most renewable sources, giving it an additional strategic and logistical advantage that is not directly captured in an economic comparison based only on construction costs.

iii. Stability & Security of Supply

Nuclear power, unlike most renewable sources, is not intermittent and provides a long-term stable supply of power. This offers policy and strategic advantages in the wider context of a nation's energy portfolio and is not captured in a simple economic comparison of construction costs.

VI.2. Approach to Modelling NPP Construction Costs

Two different methodologies can be used to estimate the construction cost of a NPP, as presented and discussed in Chapter III. The cost estimations that follow in this Chapter use the top-down power scaling method and are, in effect, a culmination of the work presented in the earlier Chapters on NPP modularisation.

The potential for modularisation-related cost reductions depends on how many modules can be feasibly fabricated off-site and transported, via road, to the NPP site. Chapter IV shows how the potential for modularisation generally tends to increase with decreasing reactor size. The DoM_{max}, taken from work in Chapter IV, is used to set the maximum amount of site costs that can be moved off site, by commodity type. While OCC is affected primarily by the fraction of work moved off-site for prefabrication, IDC is affected by the NPP build time. Chapter V shows how NPP build times depend both on the size of the project and the NPP modularity and is key to identifying how TCIC varies with reactor size.

This section explains the methodology by which NPP costs are estimated using power scaling rules. It then shows how modularisation is accounted for across the various elements of NPP construction costs using the modularisation scheme, module transport model, and NPP build schedule model from Chapters IV and V to directly inform the cost modelling and subsequent analysis presented in this Chapter.

VI.2.1. Reference Cost Data

Since no experiential data are available for the construction costs of SMRs, cost estimates are instead derived from data on existing LR construction projects. The reference cost breakdown used in this project is taken from the 1987 EEDB Phase IX Update Report [57], which provides US construction cost data for PWR-12, a generic 1144 MWe PWR. Capital costs from the EEDB Phase IX Update report are for NOAK units and are provided in 1987 US dollars. Costs are inflated in this project to 2017 USD values according to historical CPI values [151] [135] to allow for consistent comparisons with other cost analyses available in current literature (e.g. recent work by MIT [2] and Lazard [152]).

One of the EEDB programme's objectives was to provide current technical and cost information on NPPs to the US Department of Energy (DoE) for planning and decision-making purposes. The EEDB data set covers a 23-year span of studies performed by United Engineers & Constructors Inc. Update reports were published annually between 1976 and 1987.

Advantages: EEDB Cost Breakdown

i. Detailed Cost Breakdown

The EEDB report provides the best available cost information in a complete and comprehensive construction cost data set broken down by direct costs, indirect costs, owner's costs, and contingency.

Summary cost estimates at a 3-digit COA level are used and are based on an abbreviation of a 9-digit cost breakdown (both are available from the EEDB). These costs are based on 50 years of power plant construction experience and current power plant designs and are checked against real field data. The cost breakdowns are based on a detailed technical data model that describes over 50 major structure/systems and up to 400 subsystems and includes design descriptions, engineering drawings, milestone schedules, and a detailed equipment list.

ii. Consistent Data Structure

The EEDB data follows the 3-digit COA system, which is used through this project to provide a standard and consistent categorisation of modules, their build times, and their cost. Using data that adheres to this format simplifies and standardises the cost calculations and analysis.

iii. Generic NPP Siting

Any site-dependent factors are based on a common hypothetical 'Middletown' site with known geological and environmental characteristics. The EEDB report provides further detail on how to adjust the cost data to account for actual sites.

iv. Contemporary with Module & Schedule Reference Data

The EEDB Phase IX update report is approximately the same age as the modularisation scheme (S&W report) and the schedule data (Sizewell B). This means the baseline modularisation, scheduling, and cost models are contemporaries and can be integrated with one another while maintaining consistency across the three models in this project.

EEDB Cost Breakdown: Disadvantages

i. Age of Cost Breakdown

Technological developments in NPP design, improvements in construction methods, and changes in material and labour costs may affect how representative the EEDB data are of current NPP construction experience. This may, in part, be resolved by this project's use of the PWR-12 Median Experience (ME) cost breakdown from the EEDB report instead of the Better Experience (BE) breakdown. ME costs are derived from median NPP cost experience in the EEDB programme since 1978 and are considered to be more representative of actual NPP construction experience than the BE estimates, which are derived for a small group of units at the low end of the cost range [57].

ii. Construction Cost Increases & Inflation

Average inflation rates may not accurately represent the increase in construction costs over time. The EEDB reports that, over the period of data collection, base construction costs increased at a rate 2.5 times that of average material and labour costs and, within these categories, the breakdown of direct/indirect materials and different types of skilled labour costs, increase at different rates and not necessarily in line with inflation. Investigating this effect is outside the scope of this project, but the EEDB discusses their observed construction cost trends in detail (pp. 3-4 to 3-9 [57]) and Ganda *et al.* [135] present a more recent quantitative analysis of historical cost increases in the US and the underlying reasons for rising NPP project costs over time.

This project uses average inflation rates to inflate the EEDB base construction cost data from 1987 USD, as reported, to 2017 US dollars. Inflation rates are taken from [151] and inflates the OCC of the baseline 1144 MWe PWR-12 LR from the original $2,797/kWe (in 1987 USD) to $6,108/kWe (in 2017 USD). This total OCC value is in agreement with the analysis on historical US construction costs found in Ganda *et al.* [135], who uses the same EEDB reference data, and is also in line with current nominal NPP construction costs in the US [2].

VI.2.2. Methodology: Modelling Overnight Capital Cost

The objective of this Chapter is to examine how OCC, TCIC, and IDC vary with different modular build scenarios and as a function of reactor size. The extent of modularisation and DoM can both be varied to develop a realistic modularisation construction strategy based on work presented earlier Chapters.

- **Transport Model (Chapter IV):** modules proposed by the S&W scheme are subdivided up to a maximum of three times (MDF = 3) and an additional 20% of modules, by weight, are allowed in Transport Envelope 3.

- **Schedule Model (Chapter V):** equal fractions of task and wait time scale (T = W = 0.4) and task time is affected by modularisation (wait time is not).

VI.2.2.1. Cost-Power Scaling

Power scaling is widely used for estimating the costs of power project, both in the nuclear industry as per the OECD [9] and for conventional power generation [130]. In the context of NPP costs, work by Bowers *et al.* [132] derives power-cost scaling exponents based on NEDB historical experience and Carelli *et al.* extend the use of these exponents for SMR cost estimations [12]. The derivation, applicability, and suitability of the cost-power scaling method is discussed in Chapter III.

To generate a cost breakdown for any NPP size, cost-power scaling is applied to the reference EEDB LR data according to Equation VI.1, correlating specific reactor cost with reactor power through an exponential factor that depends on the particular commodity type. In Equation VI.1. *Specific Cost* is in 2017 \$/kWe and *Power* is the rated power output of the reactor, in MWe. The subscript *i* refers to the reactor that is under consideration and *EEDB* refers to the baseline cost data from [57]. The commodity-specific exponents, *n*, are from Table III.1 in Chapter III as per work by Bowers *et al.* [153]. As *n* approaches 1, the scaling effect diminishes and the SMR and reference LR specific costs become increasingly similar.

$$Specific\ Cost_i = Specific\ Cost_{EEDB}\left(\frac{Power_i}{Power_{EEDB}}\right)^{(n-1)}$$

Equation VI.1. Specific cost-power scaling.

VI.2.2.2. Application of Modularisation

Modularisation moves *in-situ* construction costs to an off-site location that has higher productivity. Direct site costs, both labour and material, are affected by modularisation in two ways: first through the Degree of Modularisation (DoM), which varies the amount of site costs that are moved to the off-site facility; and second through the Extent of Modularisation, which varies what systems and structures are included in the modularisation scheme. Direct factory equipment costs are unaffected by DoM and/or the extent of modularisation since this account consists of already prefabricated components. Indirect costs, which include home office engineering, supervision labour, and service costs, are reduced depending on whether the work included in the particular indirect cost category is affected by modularisation, schedule reduction, or standardisation.

Direct Costs & Degree of Modularisation

Modularisation affects direct construction costs by moving site work into a factory. The factory work has the potential to be more efficient in terms of material usage, by adopting lean manufacturing techniques and reducing rework. The factory also reduces labour hours by providing a controlled and/or automated construction environment. The cost of labour is also reduced because hourly factory wages are significantly lower than site wages [64].

The benefits that arise from modularisation depend on what cost accounts are being dealt with, where the construction work is taking place, and whether the costs are labour or material. Multiplicative cost factors are used to capture the modularisation-related savings. These are based on guidelines from the EMWG (Chapter 11: Estimating Factory-Produced Modular Units) [64] and are derived from modular construction experience for the purpose of developing consistent and credible cost estimates for NPPs. Table VI.1 shows how the factors are applied to direct site costs to account for modularisation.

Table VI.1. Multiplicative modularisation cost adjustment factors, from [64]. Cost factors are applied to direct site costs only but may be added back to either direct or indirect cost accounts in a modular NPP, as specified.

	Cost Multiplication Factors	
	Remaining site cost	Off-site cost
Site Materials		
Account 21 Materials	(1 – DoM)	DoM × 1.05
All other materials accounts	(1 – DoM)	DoM × 0.90
Site Labour		
Nuclear Island	(1 – DoM)	$\text{DoM} \times 0.31 \times \left(\frac{\text{factory wage} = \$12/\text{h}}{\text{site wage} = \$34/\text{h}}\right)$
Balance of Plant	(1 – DoM)	$\text{DoM} \times 0.25 \times \left(\frac{\text{factory wage} = \$12/\text{h}}{\text{site wage} = \$34/\text{h}}\right)$
Other		
Freight & Transport	2% of each module's material + labour cost is added to Account 915 (indirect)	
Installation	5% of each module's direct labour costs are added to direct site labour costs	
Overheads	200% of each module's direct labour costs are added to total indirect costs *	

* This is to cover the factory costs for each module; see Chapter I, Section I.3.2 for further discussion

The distribution of direct costs for both a stick-built and fully modular SMR and LR is shown in Figure VI.2. The SMR and LR examples from Figure VI.2 shows that just over half the direct costs of a stick-built NPP are incurred *in-situ* (57% for an SMR and 55% for a LR). The slight difference between the cost distribution of an SMR and an LR is because the 3-digit COA entries have different scaling exponents. Modularisation greatly reduces the fraction of SMR direct costs that are on-site but has little effect on moving LR costs: a fully modular SMR has only 22% of the direct costs on-site, whereas this is 43% for a fully modular LR. It is also apparent from Figure VI.2 that some cost accounts have greater scope for modularisation than others. For example, there is a significantly higher proportion of site work in the structures & improvements category (Account 21; solid yellow) than in the reactor plant & equipment category (Account 22; solid purple), which consists mostly of factory-built equipment, even in a stick-built plant. This, coupled with the higher DoM_{max} of small reactors, means that SMRs have significantly greater potential to move site material and labour costs into an off-site production facility and can realise, to a greater extent than LRs, the productivity and efficiency improvements associated with off-site manufacture, illustrated by a comparison of the total shaded and total solid proportions of the bars.

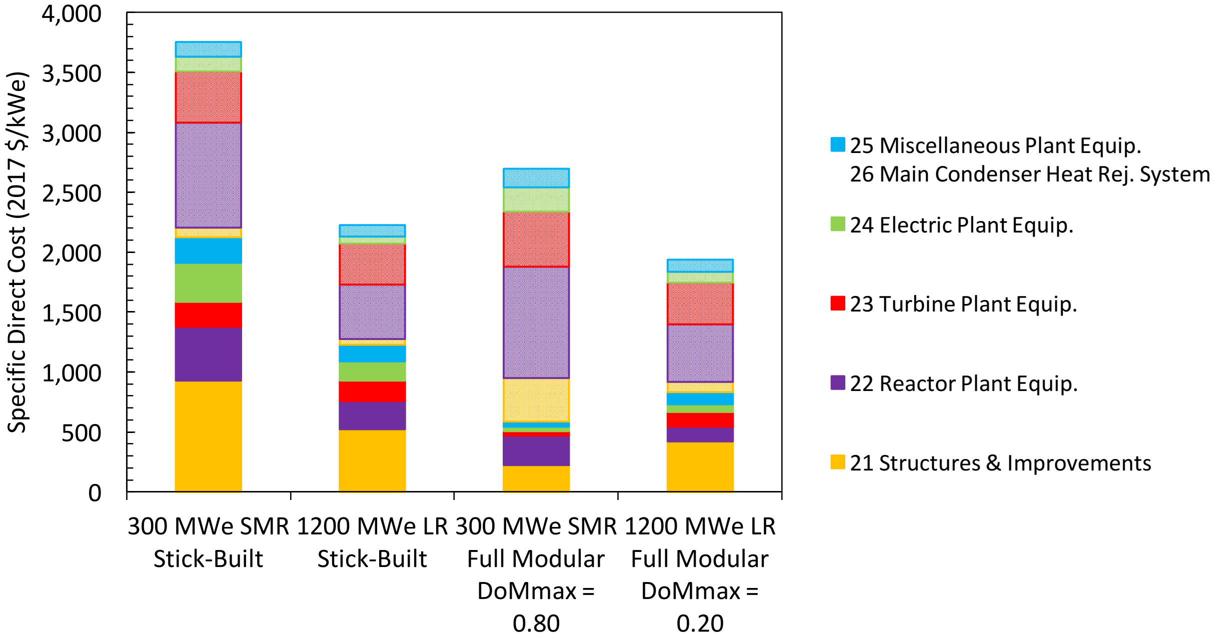


Figure VI.2. Distribution of specific direct construction costs for a stick-built and a fully modular SMR and LR at their respective DoM_{max}. Solid bars correspond to site based costs (material + labour) and shaded bars correspond to factory based costs.

Indirect Costs & Degree of Modularisation

There are three types of indirect costs. The first group includes time-based indirect costs that depend on the duration of the project; for example, the services that are necessary for support at the construction site. The second group relates to indirect costs that are related to the volume of site work; these are affected by any improvements to site productivity and/or site costs and will be affected by modularisation. The third group includes those indirect costs that are affected by standardisation and the one-off removal of repeat work.

A method for capturing the effect of modularisation and standardisation on indirect costs is presented below and was developed in collaboration with Robbie Lyons [16]. Equation VI.2 and Equation VI.3 show how time-based and modularisation-based cost reductions are calculated, respectively. While indirect costs are not directly reduced by modularisation, the DoM has an implicit effect on indirect costs through shortening either the net build duration or the direct labour costs. Parameters that are a function of DoM are noted in Equation VI.2 and Equation VI.3.

i. Time-Based Reductions

Indirect cost work items that depend on the NPP construction duration are called ‘time based’. These costs are reduced in proportion to the schedule reduction that occurs as a result of modularisation using Equation VI.2.

Time-based cost reductions are applied to: Temporary Construction Facilities (911); Permits, Insurance, & Local Taxes (914); Home Office QA (922); Home Office Construction Management (923); Field Office Expenses (931); Field QA (933); Plant Startup & Test (934).

$$(\%\ Cost\ Reduction_{time-based})_{@\ DoM} = \left(1 - \frac{(Construction\ Duration_{modular})_{@\ DoM}}{Construction\ Duration_{stick-built}}\right) \times 100\%$$

Equation VI.2. Time-based percent cost reduction for a modular NPP.

ii. Modularisation-Based Reductions

Some indirect costs depend on the degree of modularisation that is incorporated into the NPP. These indirect cost accounts are reduced proportional to the site labour hour savings that arise as a result of modularisation, according to Equation VI.3 below. Site labour hours provide a better reflection of the impact of modularity on the plant than overall costs, which includes equipment that is factory-built even in a stick-built NPP. Note that the variable $Site\ Hours_{modular}$ includes module construction and assembly/installation.

Modularisation-based cost reductions are applied to: Construction Tools & Equipment (912); Payroll Insurance & Taxes (913); Field Job Supervisions (932).

$$(\%\ Cost\ Reduction_{module-based})_{@\ DoM} = \left(1 - \frac{(Site\ Hours_{modular})_{@\ DoM}}{Site\ Hours_{stick-built}}\right) \times 100\%$$

Equation VI.3. Modularisation-based percent cost reduction for a modular NPP.

iii. Standardisation-Based Reductions

If the NPP design is standardised and re-used, it will remain largely unchanged between projects except for site-specific features (ground work, heat rejection system, and so on). This removes the need for a large amount of repeat design work, reducing the project design services.

It is assumed that 80% of the design work in the Home Office Services account (921) is not required for repeat projects, regardless of NPP modularity or size. This is based on the EEDB definition of standardisation which assumes that 70%-90% of engineering work is complete by the start of construction in a standardised NPP design (p. 6-16 [57]).

VI.2.3. Modelling Interest During Construction

The methodology described thus far is used to estimate a NPP OCC and the impact different modularisation scenarios have on the direct and indirect construction costs. The next step is to consider the interest costs that are incurred during the construction period to estimate IDC and TCIC costs. Including financing costs in the cost modelling is key to capturing one of the significant, indirect effects of build schedule reduction on net NPP construction economics. The interest rate that is used throughout these estimates is 7.86%, based on the interest rate used in the MIT NPP economic study and similar to interest rates used elsewhere in NPP literature on economic modelling and analysis (BEIS uses 10% [10]; Lazards uses 8% [152]).

VI.2.4. Modelling Production Learning

Finally, it is important to realise that, if manufacturing construction methods are employed according to current industry best-practice, NPP construction costs would be expected to decrease over the course of a GWe-scale installation programme through production learning. In the energy industry, the unit construction cost of an energy technology tends to decrease over time and with successive build projects, as experience is gained by the manufacturer. This project only models a simple production learning case; more detailed analysis of the learning effect on NPP projects is available from Robbie Lyons [16].

Experience is accumulated within an industry by repeating tasks, reducing the cost of each subsequent unit produced. The learning curve is obtained by plotting unit cost against total production quantity according to Equation VI.4, which is based on the Wright learning equation [33]. The Wright learning curve originated from production data in the aircraft industry but the principle of learning has been observed in many other industries. In Equation VI.4, y refers to the learning rate and b is the number of times the production volume doubles. The subscript 0 refers to the original reference design and i refers to the target design. The parameter b is calculated using Equation VI.5, where n is the number of units installed. Note that the specific cost calculated by Equation VI.4 is an average over all n units and does not give the specific cost of the n^{th} unit.

$$\frac{Specific\ Cost_{\ i}}{Specific\ Cost_{\ 0}} = (1-y)^{b}$$

Equation VI.4. Wright learning equation.

$$b = \frac{\ln(n)}{\ln(2)}$$

Equation VI.5. Number of doublings.

McDonald & Schrattenholzer [34] present a comprehensive study of learning within different energy technologies including nuclear, coal, and gas turbine combined cycle power plants, as well as gas pipelines, gas turbines, and solar PV modules. They estimate the aggregate learning rate based on current construction practices for NPPs is 5.8%, well below the learning rates typical of other industries, which fall between 18 and 25% [34]. Work by the University of Chicago [154] also indicates NPP site learning is between 0%-5%. Module construction, on the other hand, is expected to be similar to other heavy industries that produce large factory built components, achieving learning rates between 10% -20% [34]. Increasing the factory-built content of an NPP means a greater proportion of the site costs can access the higher factory learning rate, resulting in lower costs than are achievable through site-learning alone. Learning rates also depend on the frequency with which units are produced. This is important for SMRs, where a higher volume of units is required to provide the same generation capacity and suggests that they can benefit from production learning effects: first through their higher modular, factory-built content (and therefore their higher learning potential); and second through their higher production volumes (allowing learning to continue over a greater number of doublings).

This Chapter looks at a single, moderate production learning case to illustrate the potential contribution of learning to cost reductions. Typical moderate programme conditions are listed below, although further scenarios are discussed in detail by Lyons [16].

- Direct costs are reduced by learning over the whole programme
  Site learning rate of 2% as per Delene & Hudson [58].
  Factory learning rate of 15% as per McDonald & Schrattenholzer [34].
- 10 GWe power installed over the course of 10 years
  This is a moderately sized programme; the ETI identifies a potential UK market of 7 GWe for SMRs [15]; the US could accommodate significantly more.
- 1 off-site factory is used for manufacturing modules

VI.3. Results & Discussion

There are three general cases of interest that are presented on each chart in this section. The NPP construction strategy for each case is described below and numerical results are presented for a 1200 MWe LR (Table VI.2) and a 300 MWe SMR (Table VI.3).

i. Stick-built (Conventional) Construction

This represents current NPP construction practice with no modularisation or standardisation. Estimates are based on cost-power scaling, which only accounts for different NPP sizes. IDC costs are estimated using the stick-built NPP schedules from Chapter V.

ii. Standardised Programme

There is some commitment to a standardised, sequential build programme but the NPP is not modularised. Standardisation reduces Home Office Engineering costs by 80% but there is no modularisation (DoM = 0 and the Extent of Modularisation is 'none'). The IDC for this 'standardised programme' case is calculated using the build duration of a stick-built reactor, as per the results presented in Chapter V.

iii. Modular (Off-Site) Manufacture

This scenario includes modularisation and standardisation. An efficient off-site factory or supply chain produces modules as part of a larger programme for building a series of standardised NPPs. Costs are reduced through varying the DoM and the extent of modularisation, in addition to standardisation. The cost estimates between the 'medium' and 'full' extent of modularisation are not significantly different; therefore, only the 'low' and 'full' modularisation scenarios are shown here. IDC cost estimates use the modular construction durations determined in Chapter V.

Table VI.2. Key parameter values and results for a 1200 MWe LR with different construction scenarios.

	Stick-Built	Standardised	Modular	
Build Duration	6.6 yr	6.6 yr	6.3 yr	5.8 yr
Extent of Modularisation	N/A	N/A	Low	Full
Optimal DoM	N/A	N/A	0.20	0.30
M_{eff} (relative to stick-built LR)	N/A	0.15	0.22	0.28
OCC (2017 \$/kWe) (incl. contingency & owner's)	6,007	5,126	4,712	4,315
IDC (2017 \$/kWe)	2,735	2,334	1,966	1,611
TCIC (2017 \$/kWe)	8,742	7,460	6,678	5,926

Table VI.3. Key parameter values and results for a 300 MWe SMR with different construction scenarios.

	Stick-Built	Standardised	Modular	
Build Duration	5.1 yr	5.1 yr	4.7 yr	3.5 yr
Extent of Modularisation	N/A	N/A	Low	Full
Optimal DoM	N/A	N/A	0.60	0.80
M_{eff} (relative to stick-built SMR)	N/A	0.16	0.28	0.45
OCC (2017 \$/kWe) (incl. contingency & owner's)	9,884	8,350	7,088	5,468
IDC (2017 \$/kWe)	2,993	2,528	1,898	998
TCIC (2017 \$/kWe)	12,877	10,878	8,986	6,466

Comparing Table VI.2 and Table VI.3 offers some insight into relative SMR and LR construction costs across different programmes. Stick-built SMRs are not economically feasible, as they cost significantly more than LRs on the basis of both OCC and TCIC. While standardisation does not reduce build schedule or move work off-site, it can still reduce OCC and TCIC by approximately 15% for both LRs and SMRs. Fully modularising a series-produced standard plant has a significant effect on both OCC and TCIC: full modularisation reduces OCC by 30% for LRs and 45% for SMRs. TCIC is reduced by 33% for LRs and 50% for SMRs, with IDC reductions arising from shorter build schedules playing a large role in this.

Modularisation is key for SMR economic success, provided shorter build schedules can be achieved. Even a 'low' modular standardised SMR series can compete with a stick-built LR and has a similar TCIC (\$8,986/kWe) to that of the LR (\$8,742/kWe) despite the fact that the SMR still has a relatively long build time. This finding differs from existing literature work by Carelli *et al.* [12] which claims that SMRs, on a first of a series basis, will be more expensive than conventional LRs. The issue with existing work is that it does not rigorously integrate the effects of standardisation, modularisation, and shorter build times into the cost estimate. Additionally, SMRs have much better scope than LRs for further production-learning cost reductions, both because more of their cost is factory-based and also because SMRs need to be produced in greater numbers to fulfil a set capacity requirement.

VI.3.1. Overnight Capital Cost (OCC)

To show the effect of modularisation and standardisation on SMR construction cost, OCC results are plotted for both a 'low' and 'full' modularisation (Figure VI.3 and VI.4 respectively) over a range of NPP sizes and varying DoM. Standardisation alone reduces the OCC by approximately 15%, regardless of reactor size. Comparing Figure VI.3 and Figure VI.4 shows that modularising the structural NPP elements, in addition to the M&E and piping systems, is key to achieving the full potential of off-site build. The OCC in the 'full' extent of modularisation is significantly less than the 'low' modularisation OCC scenario; particularly for reactors smaller than 750 MWe. This is because diseconomies of scale tend to predominate when the extent of modularisation is 'low'. When a SMR is fully modularised, however, SMRs can achieve significant cost reductions as off-site manufacture begins to offset the diseconomies of scale.

M_{eff} is plotted on the secondary axes in both Figure VI.3 and Figure VI.4 and is useful for comparing the net amount of site costs moved into a factory for the whole plant. M_{eff} clearly illustrates that 'full' modularisation moves a significantly larger fraction of costs off-site for SMRs. The M_{eff} value is very different from the DoM_{max} value because DoM_{max} is distributed differently across the 3-digit accounts depending on how transportable a certain module commodity type is. For example, M&E accounts tend to have higher DoM_{max} than structural elements and liners. The difference in DoM_{max} distribution, coupled with the different modularisation productivity factors from Table VI.1 (Section VI.2.2.2), skews what amount of site costs are actually moved off-site depending on which account they fall under. Thus, M_{eff} is an important indicator of the fraction of stick-built plant OCC that is actually moved off-site in a 'full' modular NPP of the same size.

M_{eff} also shows how important it is to fully modularise the plant. The 'low' modularisation scenario limits the net economic benefit to 30% or less for LRs. Increasing the extent of modularisation improves the economic case, although this is strongly correlated with NPP size. The sharp decrease in M_{eff} is mirrored by a kink in the bounding curve that occurs between 500 MWe and 700 MWe (both in Figures VI.3 and VI.4) and is a direct consequence of a drop off in module transportability because of increasing module size.

The modularisation cost reductions are provided in diminishing returns, thereby creating an optimal DoM at which point further modularisation efforts are not attended by significant additional cost reductions. There are two 'break points', dependent on both NPP size and the extent of modularisation, at which the optimal DoM changes. These OCC break points are listed in Table VI.4 and are mirrored by the trend in OCC M_{eff}.

Table VI.4. OCC Break Points and associated optimal DoM values

		Optimal Input DoM	
Reactor Size	**Power Output**	**Low Modularisation**	**Full Modularisation**
Small Reactor	≤ 300 MWe	0.60	0.80
Medium Reactor	300 MWe-750 MWe	0.40	0.40-0.60
Large Reactor	≥ 750 MWe	0.40	0.40

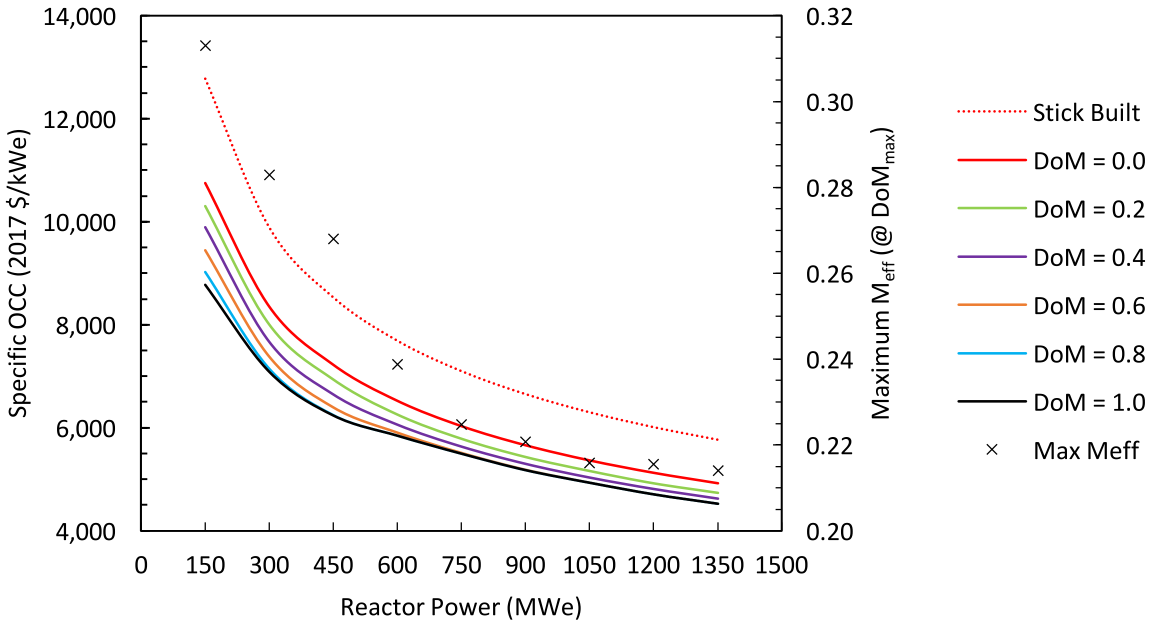


Figure VI.3. Specific OCC at a **low extent** of modularisation for a range of NPP sizes and over a range of input DoM values. Maximum M_{eff} compares modular cost at DoM_{max} against stick-built cost, and is plotted on the secondary axis.

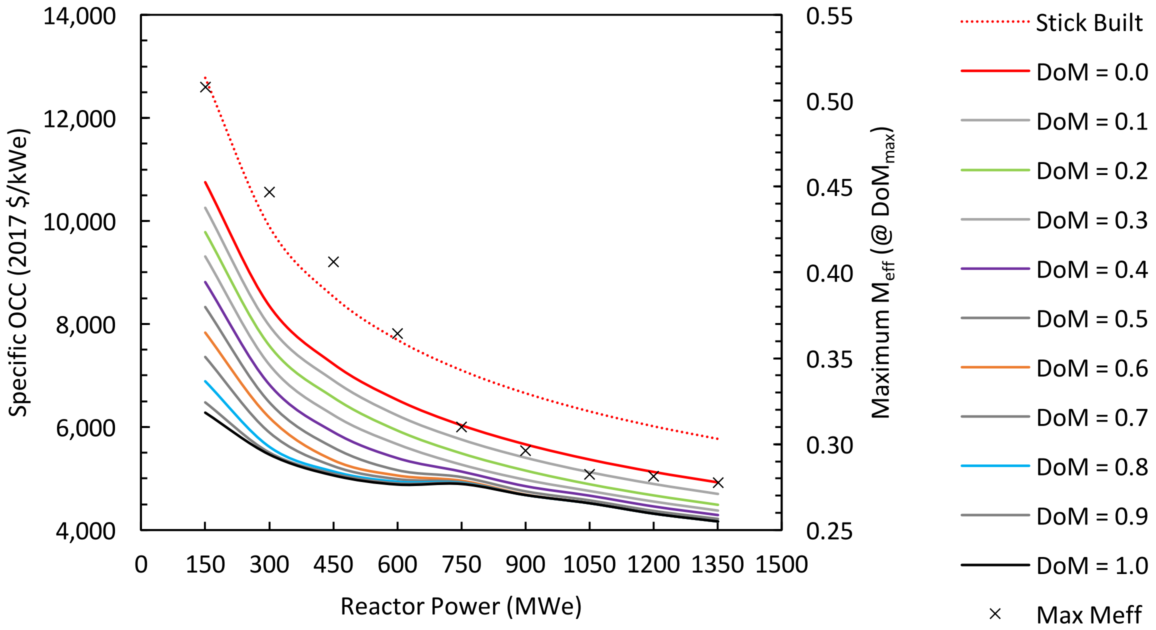


Figure VI.4. Specific OCC at a **full extent** of modularisation for a range of NPP sizes and over a range of input DoM values. Maximum M_{eff} compares modular cost at DoM_{max} against stick-built cost, and is plotted on the secondary axis.

VI.3.2. Total Capital Investment Cost (TCIC & IDC)

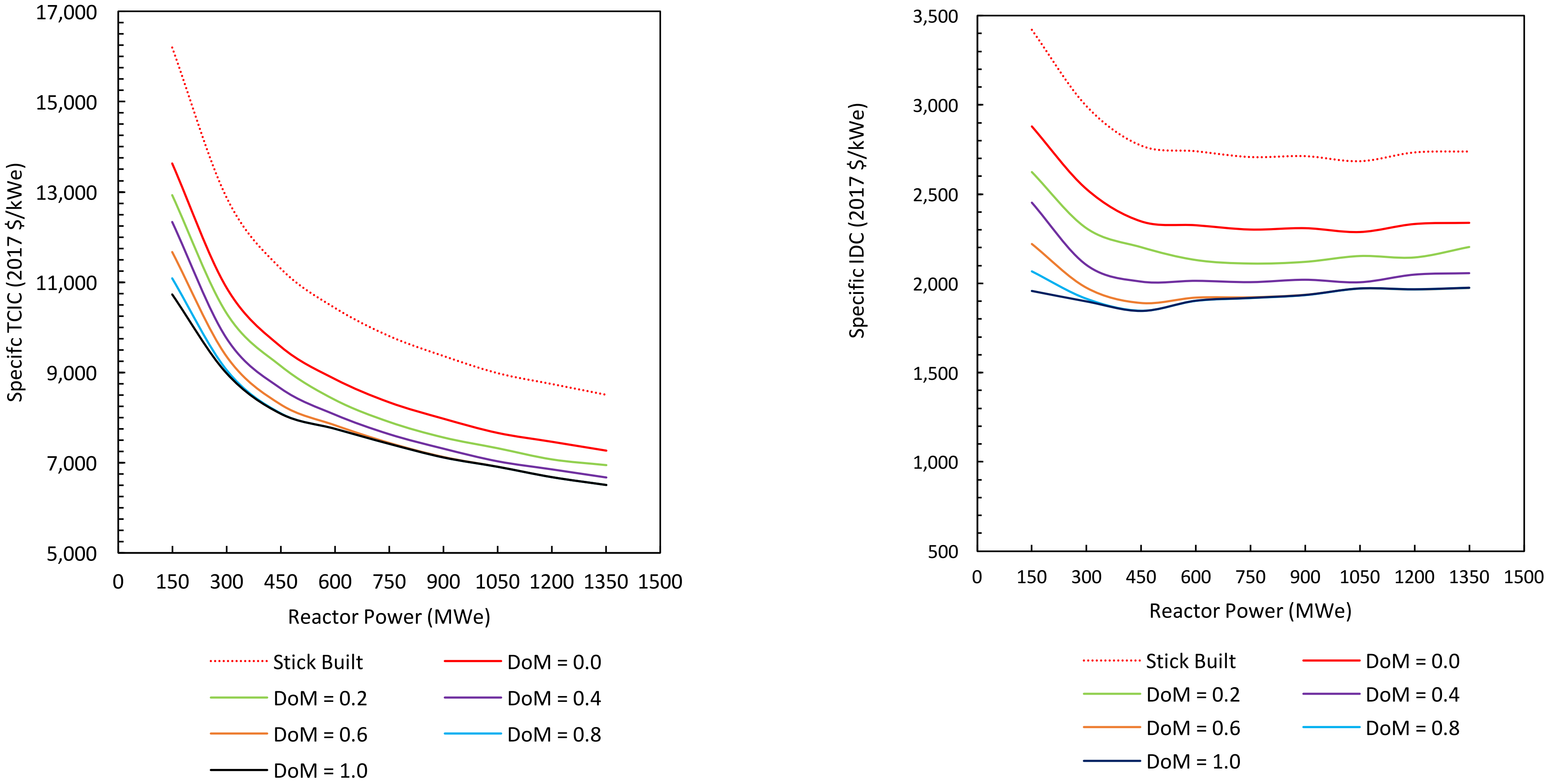
Reducing NPP build times not only reduces indirect costs, as per Section VI.2.2.2, but also has the effect of reducing investment costs during the construction period. This section examines how TCIC and IDC vary with reactor power for the given conditions.

- NPP build times, for each DoM, are taken from Chapter V. Task and wait times scale equally (T = W = 0.4); only task time is affected by modularisation.
- Interest rate in all cases is 7.86% [2]; assuming the project is partly funded by the state and partly by private investment.

Similar to the OCC estimates, standardisation reduces the TCIC (and IDC) costs by approximately 15% from the stick-built case, regardless of reactor size. The optimal DoM break points occur at the same reactor sizes. A comparison of the TCIC curves in Figure VI.5 (i) and Figure VI.6 (i) for 'low' and 'full' modularisation, respectively, takes the same general shape as the OCC curves in Figures VI.3 and VI.4.

The IDC results in Figure VI.5 (ii) and Figure VI.6 (ii) illustrate the trade-off between shorter schedules, achieved through smaller and/or more modular projects, versus the higher specific cost of SMRs. At 'low' modularisation, in Figure VI.5, small reactors (450 MWe and less) have high IDC costs because their build schedules are not reduced enough to offset their higher OCC caused by diseconomies of scale. When DoM_{max} is reached, the SMR build schedule reductions compensate for the effect of higher initial OCC. In the best case scenario, IDC is roughly constant at $2,000/kWe, regardless of reactor size. Therefore, when the extent of modularisation is low and if the DoM is also low, SMRs incur higher specific IDC costs than LRs.

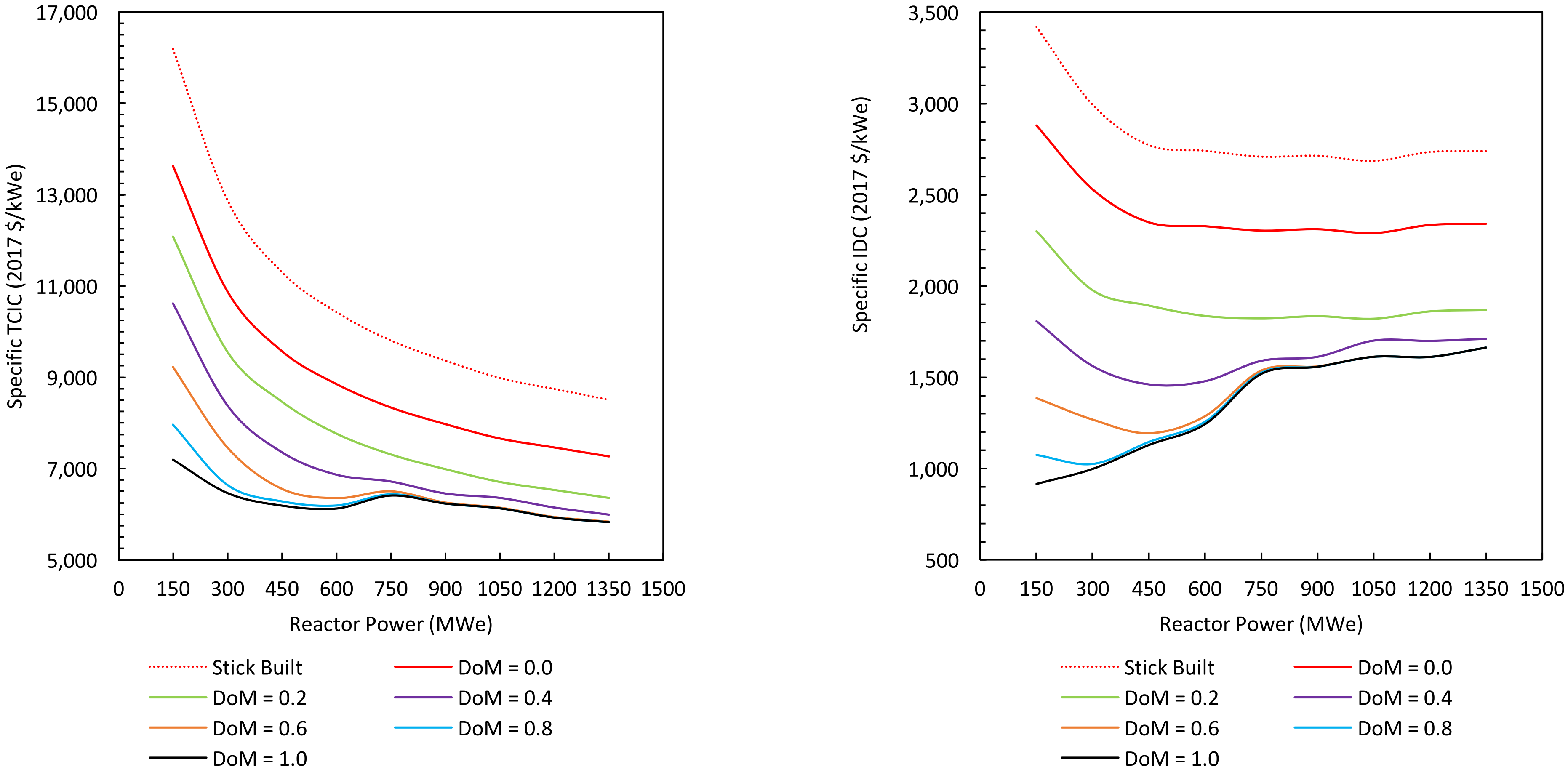
For a 'full' extent of modularisation, as in Figure VI.6, SMRs have significantly greater potential to benefit from schedule reductions. IDC is much lower for smaller reactors at high DoM and with 'full' modularisation; this effect is most significant when the DoM is higher than 0.20-0.40. By contrast, LRs bigger than 750 MWe have roughly constant IDC costs, even when fully modularised. As a reactor's modularity increases, both through DoM and extent of modularisation, build times decrease, enabling SMRs to begin compensating for their higher OCC, a consequence of their diseconomies of scale.



(i) TCIC at low modularisation with an interest rate of 7.86% pa.

(ii) IDC at low modularisation with an interest rate of 7.86% pa.

Figure VI.5. Specific TCIC and IDC (2017 $/kWe) at **low modularisation** for a range of NPP sizes and input DoM values. Build times from Chapter V.



(i) TCIC at full modularisation with an interest rate of 7.86% pa.

(ii) IDC at full modularisation with an interest rate of 7.86% pa.

Figure VI.6. Specific TCIC and IDC (2017 $/kWe) at **full modularisation** for a range of NPP sizes and input DoM values. Build times from Chapter V.

VI.3.3. Production Learning

SMRs have a number of learning-related advantages over LRs. For a given size of nuclear programme, smaller reactors have a greater number of doublings and therefore higher potential for learning cost reductions. Their higher potential for modularisation also means a greater proportion of SMRs costs can occur in a factory, achieving better learning rates and more significant cost reductions. This section uses a single moderately sized nuclear programme to illustrate potential learning-based cost reductions in addition to one-off modularisation and standardisation reductions.

- Site learning = 2% as per Delene & Hudson [58]
- Factory learning = 15% as per McDonald & Schrattenholzer [34]
- 10 GWe power installed over the course of 10 years [16]
- 1 off-site factory is used for manufacturing modules [16]

The effect of including learning in an NPP build programme is shown in the lines plotted in Figure VI.7. The solid bars show current TCIC estimates for different energy technologies from [2]. Stick-built SMRs are not competitive, on the basis of TCIC, with other energy technologies unless they are part of a series. Even then, they are only just competitive with the 'high' LR scenario, as shown by the red dotted line. A build programme of standardised SMRs, however – even without modularisation (solid red line) – has the potential to be competitive with the 'nominal' LR construction cost case. Once the SMR is more extensively modularised, costs decrease to the point where a fully modular SMR is competitive with the 'low' LR scenario and even begins to reach the competitive energy benchmark TCIC of $4,400/kWe, corresponding to an LCOE of about $80/MWh [1].

A number of parameters can affect what learning rates are achievable, including the factory design, production rate, and the supply chain characteristics. Supply chain organisation is essential for efficient knowledge transfer and will affect what learning rates are possible. This may offer a further advantage to SMRs, which could achieve a more coordinated supply chain since a wider range of suppliers might be available to produce the smaller-sized components and/or modules for a SMR. Work by Lyons [16] offers a much more detailed study on how SMRs can achieve better learning rates.

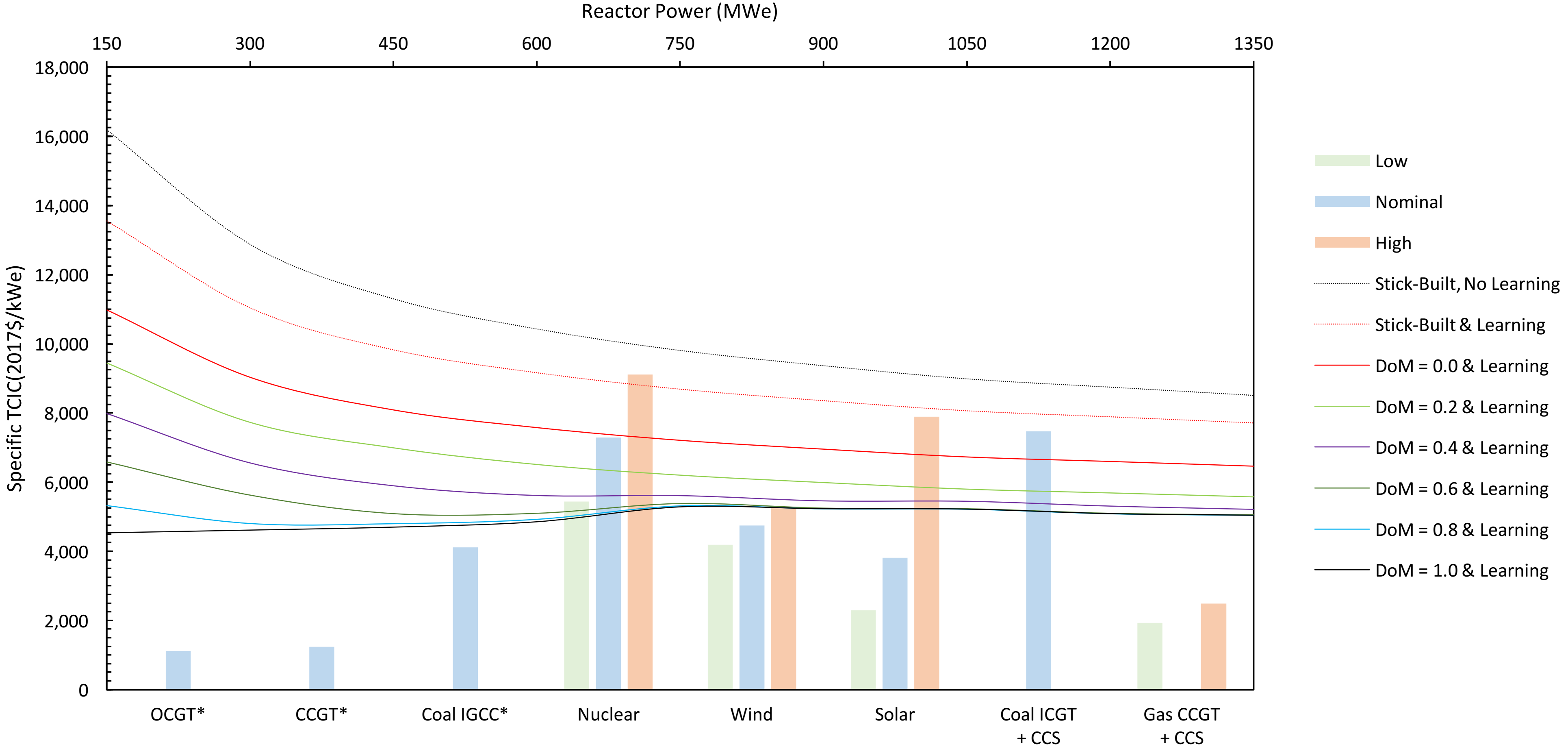


Figure VI.7. Comparison of NPP specific TCIC costs in 2017 $/kWe with learning over a range of DoM values and for **full modularisation**. Learning rates are 2% at the site and 15% in the factory, and the programme is moderate (10 GWe installed over 10 years).
Bars show a comparison with TCIC costs for other energy generation technologies, also in 2017 $/kWe based on US data (Table A.1 [2]). Energy sources marked (*) do not include carbon costs. The capacity factors for wind and solar energy are assumed to be 34% and 25%, respectively, as per [2]; note that capacity factors depend on the location and type of site (e.g. onshore vs. offshore wind) and may be different than those stated here, depending on the specific scenario..

VI.4. Conclusions on Construction Cost

VI.4.1. Summary

This Chapter estimates OCC in order to show how one-off productivity benefits resulting from modularisation can be expected to benefit NPP construction cost. The findings in Section VI.3.1 are consistent with the results from the scheduling work presented in Chapter V and highlight the fact that modularising the structural elements is key to fully realising schedule and cost reductions. Modelling IDC is a useful addition to the analysis because it adds an economic argument to the benefits of reduced build times. The TCIC and IDC analysis in Section VI.3.2 shows not only that SMRs need to be fully modularised, but also that a moderate to high fraction of site work must be moved off site before the lower IDC cost benefits can be leveraged. A fully modular 300 MWe SMR has a TCIC of $4,700/kWe, similar in magnitude to the competitive energy benchmark of $4,400/kWe (roughly equivalent to an LCOE of $80/MWh) [1]. SMRs have the potential to compete economically with LRs, particularly if other indirect financing, logistical, and scheduling benefits of SMRs are taken into consideration.

The cost benefits of standardised, series build are not one-off productivity benefits alone. The production learning results in Section VI.3.3 show that, even with a moderate amount of learning and relatively small total installation programme, modular SMRs can quickly become competitive with ‘best case’ OCC predictions for LR technologies. By further improving the achievable learning rates through optimising factory production and supply chain coordination, and by committing to a sufficiently large programme, fully modular SMRs should be able to compete economically with renewables and/or gas with CCS.

VI.4.2. Future Work

Some topics related to SMR costs and their economic feasibility are worth more investigation; these are highlighted in the following points.

i. Ongoing & Decommissioning Costs

Variable and fixed O&M, fuel, waste, and decommissioning costs are excluded from this analysis because they are small relative to the upfront capital cost of construction. Moreover, modularisation is assumed to have little impact on these costs. In practice, however, standardised modular build has effectively simplified parts replacement in the shipbuilding industry, reducing maintenance time and cost. The ability to design and install modular combat systems independently of the ship hull design and construction process is the primary advantage of the Blohm & Voss MEKO warship design [69].

ii. Off-Site Costs: Factory & Transport

The off-site module factory is assumed to be a 'black-box' facility that produces the set of required modules as needed. In this project, the additional cost of modularisation is estimated according to the EMWG guidelines: the factory costs are 200% of the module's construction cost and road transport costs are 2% of the module's cost as per [64]. The uncertainty analysis in Chapter VII finds that variation in these parameters has little effect on the net OCC estimates; however, a coupled analysis of factory and transport costs would help inform decisions on both the capability and capacity of the module factory. These issues could also indicate which components or modules can be outsourced and which are critical to NPP production.

iii. Impact of Learning on Build Duration

If production learning reduces construction cost over a build series, there may also be the potential for learning and knowledge transfer to progressively reduce build times. Whether or not this is a real effect of series production and learning is not investigated in the current NPP construction literature. Modularisation might also allow improvement in the conditions for site learning by: ensuring that the same people perform the same tasks, repeating tasks between different areas/components of the plant (e.g. using a single type of join between precast concrete modules), and building multiple units at a single site (co-siting benefits). Whether or not production learning has the effect of reducing build times over a series of NPP projects and, if so, what conditions facilitate learning, is well worth further investigation.

iv. Financing Issues

Reduced construction costs and alternative options for financing SMRs can further improve their feasibility. NPP projects that take less time to build and that require less capital upfront are lower risk projects, return revenue earlier in the project cycle, and are easier to finance. NPPs with shorter build times may also be able to borrow money at lower interest rates because of their lower risk than long construction projects. These strategic financing issues may offer yet another area in which modular SMRs have an advantage over traditional LR build and, while some of these topics are addressed by Lyons [16] and Carelli *et al.* [12], would be worth further investigation.

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CHAPTER VII

UNCERTAINTY ANALYSIS

This Chapter develops an uncertainty analysis around the assumed parameters that are used in this project for each of the three models: transport, schedule, and cost. The effects of uncertainty on each model are assessed and discussed independently for the purpose of providing an indication of how sensitive – and therefore how useable – the results in this dissertation are.

VII.1. Approach to Uncertainty Analysis

VII.1.1. Monte Carlo Methods

In general, Monte Carlo methods are defined as "resampling approximation techniques" [155] whereby random values for the input parameters are generated according to their frequency distribution and are fed into a model or algorithm which then calculates the model's output, or deterministic, parameters [156]. When a large number of these trials are run, the mean, standard deviation, confidence interval, etc. of the resulting set of deterministic parameters can be calculated. This gives an indication of the magnitude of the model's response to uncertainty in the input values and reveals the input parameters to which the model is particularly sensitive.

Monte Carlo methods are applied to the models in this thesis according to Section VII.1.3. Deterministic parameters (Table VII.1) are calculated based on random numbers generated for each 'assumed' parameter specified in Table VII.2. The mean and 95% confidence interval for each set of results are calculated according to Equation VII.1, where μ is the sample mean as in Equation VII.2, σ is the population standard deviation as in Equation VII.3, n is the sample size, and z* is the corresponding z-value. Normal distributions are assumed in all instances.

$$\mu \pm z^* \frac{\sigma}{\sqrt{n}}$$

Equation VII.1. Confidence interval calculation. At 95% confidence, z* = 1.96 (normal distribution assumed).

$$\mu = \frac{\sum_{i=1}^{n} \mu_i}{n}$$

Equation VII.2. Calculation of a sample mean (normal distribution assumed).

$$\sigma = \sqrt{\frac{\sum_{i=1}^{\square} (\mu_i - \mu)^2}{(n-1)}}$$

Equation VII.3. Calculation of the population standard deviation (normal distribution assumed).

VII.1.2. Types of Parameters

VII.1.2.1. Deterministic Parameters

The three deterministic parameters, or outputs, that are calculated by the models presented in the earlier chapters of this thesis are listed in Table VII.1 below.

Table VII.1. List of deterministic parameters in this thesis with the related model and Chapter number.

	Deterministic Parameter
Transport Model *Chapter IV*	*DoM*$_{max}$
Schedule Model *Chapter V*	*Build Duration (in years)*
Cost Model *Chapter VI*	*Specific OCC (2017 \$/kWe)* *[Specific TCIC (2017 \$/kWe)] – semi-deterministic because of dependency on funding structure and government support; not included in Monte Carlo simulations but dealt with separately in Section VII.2.3.*

VII.1.2.2. Input Parameters

There are four types of input parameters in this project: each is described below with an example. Appendix VII.1 provides full detailed tables for all input parameters.

i. Assumed

These parameters are based on general derivations and/or best-practice guidelines and their values are subject to variability. Scaling exponents are an example of assumed parameters. This uncertainty analysis examines the variability of only the assumed parameters.

ii. Base Data

This type of parameter is set by the reference data source and, since it is based on historical experience or empirical evidence, is not subject to variability. The task durations from the Sizewell B schedule are an example of base data.

iii. Constraint

These parameters are a result of regulation or other type of constraint and are not subject to variability. The only constrained parameters in this project are the Transport Envelope sizes which constrain module weights and dimensions and come directly from the UK's C&U and STGO road regulations.

iv. Solution Space

These parameters typically arise as a result of a design decision and can be related to which construction strategy is being used. The prior Chapters vary the solution space parameters investigating different construction scenarios. Solution space parameters include the extent of modularisation applied to the NPP and the DoM that the NPP designer decides to implement.

VII.1.3. Application of Monte Carlo Methods

Monte Carlo methods were used to perform an uncertainty analysis on each set of assumed parameters over 1,000 trials. The error bars in each case correspond to a 95% confidence interval. The transport, schedule and cost models, and their response to stochastic variability, are assessed separately to avoid confounding effects.

Power scaling is an assumed parameter used extensively throughout this thesis. It occurs in all three models and, although Bowers *et al.* [153] provide the most comprehensive work on NPP cost scaling, other sources also derive overall scaling exponents. These are used to determine a mean scaling exponent $n_{\mu} = 0.61$, as per Appendix VII.2. A normal distribution is assumed. During each simulation, a random overall scaling exponent is selected (n_i) and each 2-digit scaling exponent from the set provided by n_{Bowers} is varied according to the relative difference between the current random overall scaling exponent and the mean (n_i/n_μ). The results for each model are then recalculated.

The remaining assumed parameters are taken from a single source or single best-practice guideline. This is assumed to be each parameter's mean and a percentage of each parameter's value is taken to be one standard deviation about this mean, as per Table VII.2. These choices are based on an accuracy range appropriate for estimates that are performed at the concept screening and/or feasibility study level, as per American Association of Cost Engineers criteria in Table VII.3 (Class 4 and Class 5).

Finally, the interest rate is a semi-deterministic parameter and depends on the project funding structure, the extent and nature of government support, and other programmatic features. Realistic upper and lower bounds are set based on whether there is low government support (10% interest rate) or high support (5% interest rate), respectively, and are consistent with high/low interest rate scenarios in literature [10] [152] [157].

Table VII.2. Lower and upper uncertainty bounds on assumed parameters in all three models.

	Lower Bound **$\mu - \sigma$**	**Model Value** **μ**	**Upper Bound** **$\mu + \sigma$**
Transport, Schedule, Cost Model			
Scaling Exponent, n	$n_{\mu-\sigma} = 0.42$	$n_\mu = 0.61$ $n_{Bowers} = 0.64$	$n_{\mu+\sigma} = 0.79$
Schedule Model			
Assembly Time Expressed as % of direct labour hours for module	2.5%	5%	7.5%
Cost Model			
Module Cost Factors See Appendix VII.3	+ 25% productivity to each cost factor	as per EMWG[8]	- 25% productivity from each cost factor
Standardisation	85%	80%	75%
Interest rate (semi-deterministic)	5%	7.86%	10%

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[8] Module cost factors are taken from EMWG guidelines and include factory and site labour rates, site productivity factors, and material input quantities.

Table VII.3. Estimate classification matrix for process industries, from the American Association of Cost Engineers [158].

	Primary Characteristic	**Secondary Characteristic**		
Estimate Class	**Maturity Level of Project Definition Deliverables** Expressed as % of complete definition	**End Usage** Typical purpose of estimate	**Methodology** Typical estimating method	**Expected Accuracy Range** Typical variation in low and high ranges at an 80% confidence interval
Class 5	0% to 2%	Concept screening	Capacity factored parametric models, judgment, or analogy	L: –20% to –50% H: +30% to+ 100%
Class 4	1% to 15%	Study or feasibility	Equipment factored or parametric models	L: –15% to –30% H: +20% to +50%
Class 3	10% to 40%	Budget authorisation	Semi-detailed unit costs	L: –10% to –20% H: +10% to +30%
Class 2	30% to 75%	Control or bid/tender	Detailed unit cost with forced detailed take-off	L: –5% to –15% H: +5% to +20%
Class 1	65% to 100%	Check estimate or bid/tender	Detailed unit cost with detailed take-off	L: –3% to –10% H: +3% to +15%

VII.2. Uncertainty Results and Discussion

This section presents the Monte Carlo simulation results and discusses implications for the level of confidence that can be placed in the models developed in this dissertation.

VII.2.1. Transport Model

The only assumed parameters in the transportation and modularisation scheme modelling are the scaling exponents. All other variables are either based on data (module weights and dimensions), are design decisions, or are constraints (road transport regulations). The full set of parameters is summarised in Appendix VII.1, Table A.VII.1.

Figure VII.1 shows how the output from the transportation model, DoM_{max}, varies with perturbations in scaling exponent about the mean and one standard deviation ($n_{\mu} = 0.61 \pm \sigma = 0.18$). The results from using Bower's scaling exponents at the 3-digit COA level (n_{Bowers}) align well with those calculated using n_{μ} and it is reasonable to expect that the results presented in Chapter VI are representative of the mean experience. The variability in DoM_{max} is within ±1% for all reactor sizes, at a 95% confidence interval, indicating that the results from the transport and modularisation scheme model do not vary substantially with perturbations in the scaling exponents.

Table VII.4 compares the DoM_{max} from Chapter IV at n_{Bowers} with the mean DoM_{max}, and the value of one standard deviation about the mean, for a range of reactor sizes. This shows that the standard deviation about the mean DoM falls within ±5% of the DoM_{max} for reactors larger than 900 MWe. Since the S&W reference NPP is a 950 MWe reactor, NPPs close to this in size are expected to have lower variability because module weights are not scaled by much. The standard deviation for small reactors (150 MWe) is also low, at ±10% of their DoM_{max}. Although the impact of scaling on module weight is large, SMR modules are small enough to easily fit within transportable limits and variations caused by scaling the module sizes up or down doesn't impact overall transportability. By contrast, medium sized NPP's have modules that are much closer to the feasibly transportable limits and small changes in size can have a large impact on whether these modules are transportable or not. This explains why reactors in the 300 MWe to 750 MWe range (inclusive) are more sensitive to changes in scaling exponent and their DoM_{max} can vary by ±15% to ±20% across one standard deviation. This sensitivity to module size for medium-sized reactors highlights how important it is to ensure modules can be feasibly transported. The key conclusion from Chapter IV is reiterated: transport is crucial to maximising NPP modularity and ensuring sufficient amounts of work can be moved to the off-site factory.

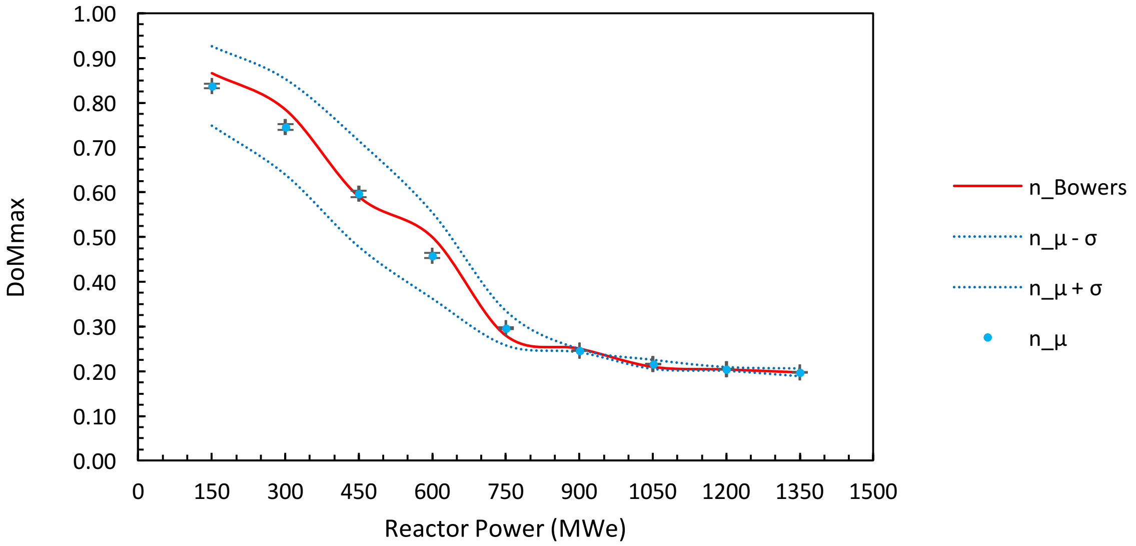

Figure VII.1. Effect of uncertainty in scaling exponents on DoM_{max}. Error bars correspond to a 95% confidence interval on $n_\mu = 0.61$. Chapter IV model results are plotted for comparison at $n_{Bowers} = 0.64$.

Table VII.4. DoM_{max} at n_{Bowers} compared with mean DoM_{max} and one standard deviation.

Reactor Power (MWe)	DoM_{max} at n_{Bowers}	Mean DoM_{max} at n_{μ}	Standard Deviation in DoM_{max}
150	0.87	0.84	0.089
300	0.78	0.75	0.107
450	0.59	0.60	0.119
600	0.50	0.46	0.096
750	0.28	0.30	0.039
900	0.25	0.25	0.004
1050	0.21	0.22	0.011
1200	0.20	0.21	0.004
1350	0.20	0.20	0.009

VII.2.2. Schedule Model

The full set of parameters used in the scheduling model are summarised in Appendix VII.1, Table A.VII.2. The two assumed parameters are the scaling exponents (again) as well as the amount of time required for module assembly. The upper and lower bounds on the uncertainty of these parameters are as per Table VII.2. Note that the conditions for the fully modular results use equal scaling for task and wait times (Scaling Case II; T = W = 0.4) and a 'full' extent of modularisation at DoM_{max}.

The effect of scaling exponent uncertainty on overall build duration for both stick-built and modular NPPs is shown in Figure VII.2. Scaling has a greater effect on small reactors and less on LRs. Stick-built reactors have a slightly greater response to scaling exponent uncertainties than modular reactors, although this effect is very small. Scaling exponent uncertainty results in a variability of ±0.75 months for stick-built SMRs smaller than 450 MWe; modular SMR variation is only ±0.50 months. Reactors larger than 900 MWe are the least sensitive to scaling exponent uncertainty; their build durations vary negligibly (±0.15 months at most). This behaviour is as expected: the farther an NPP is from the reference 1198 MWe LR, the more important the scaling exponent is to calculating the construction duration.

Figure VII.3 shows that uncertainty in assembly time has a negligible effect on the overall NPP build time. A ±50% variation in site assembly time results in, at most, a

±0.1 month variation in build time regardless of reactor size. *In-situ* assembly requires only a small fraction of total on-site time and can be absorbed by other, longer site tasks, meaning that variations in module assembly have little impact on build schedule. The overall build schedule is well able to respond to slight perturbations in on-site time because other non-critical tasks absorb the slack/excess. Variations in assembly time may, however, change which tasks fall on the critical path. Assembly time increases task times unequally, depending on what proportion of each task is modular, but does not affect wait times. Since most of the additional assembly work is absorbed by longer *in-situ* tasks, only the change in duration of critical tasks contributes to the overall build duration. This explains why, in some cases, the mean case (n_{μ}) isn't centred on the error bars, as it is dependent on how the critical path is affected and whether it is changed or not.

Figure VII.4 shows how NPP build times respond to combined uncertainty in scaling exponents and assembly time. This is, as expected, governed by scaling variability. SMRs and medium sized reactors (any size up to and including 750 MWe) respond to the combined uncertainty by up to ±0.55 months on the build schedule. For LRs larger than 750 MWe this combined uncertainty decreases to ±0.25 months, at the most.

Finally, and in all instances, the build schedule results from using n_{Bowers} are very similar to the mean build durations calculated using $n_{\mu} = 0.61$. This indicates that the 3-digit scaling exponents are representative of the mean experience. The resilience of the scheduling model to uncertainty in the assumed parameters increases confidence in the Chapter V modelling, since uncertainty in the assumed parameters has little consequence for overall on-site time.

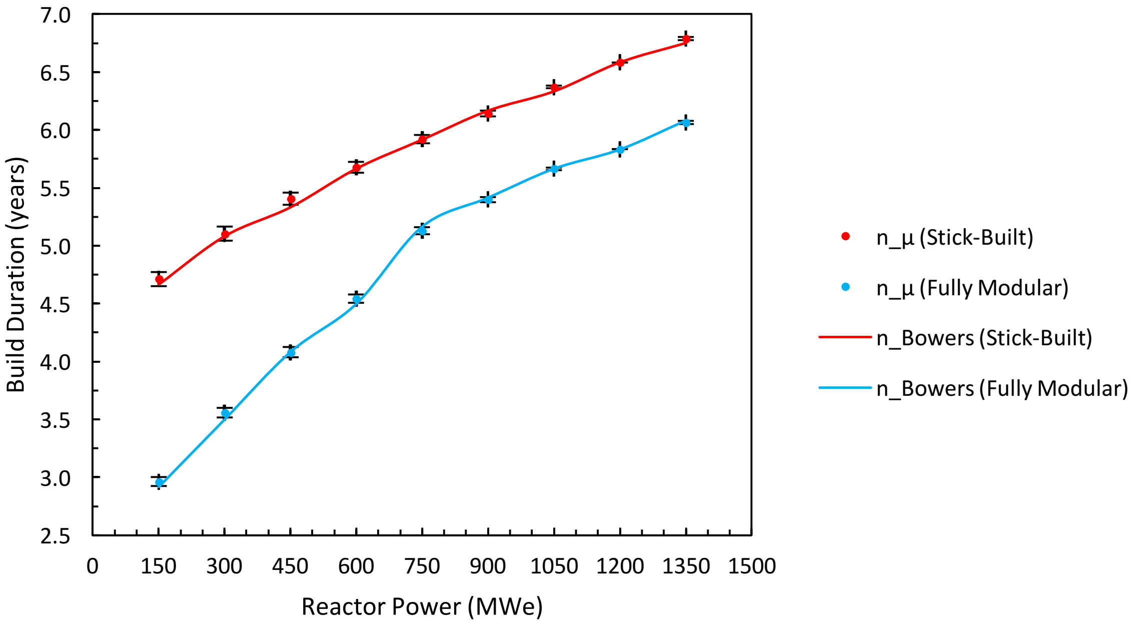

Figure VII.2. Effect of scaling exponent uncertainty on build duration for stick-built and fully modular NPPs. Error bars correspond to a 95% confidence interval on $n_{\mu} = 0.61$. Chapter V model results are plotted for comparison at $n_{Bowers} = 0.64$. Assembly time is 5% of module build time in all cases.

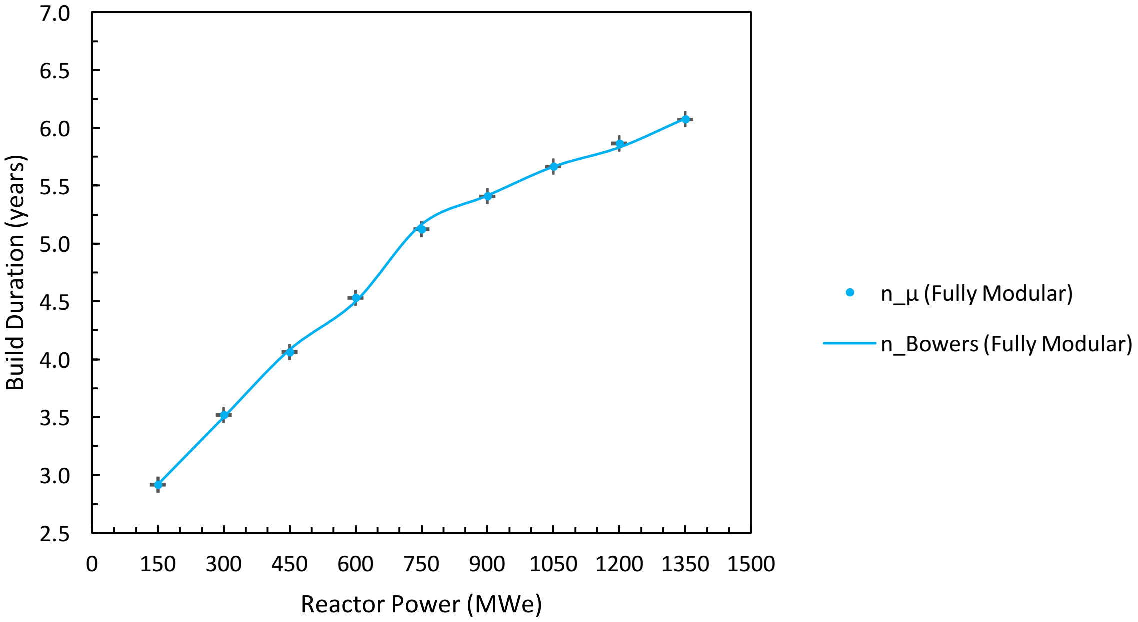

Figure VII.3. Effect of module assembly time variability on build duration for a fully modular NPP. Error bars correspond to a 95% confidence interval on mean assembly time (this is 5% of module build time). Scaling exponent is $n_{\mu} = 0.61$ in all cases. Chapter V results are plotted to compare with $n_{Bowers} = 0.64$.

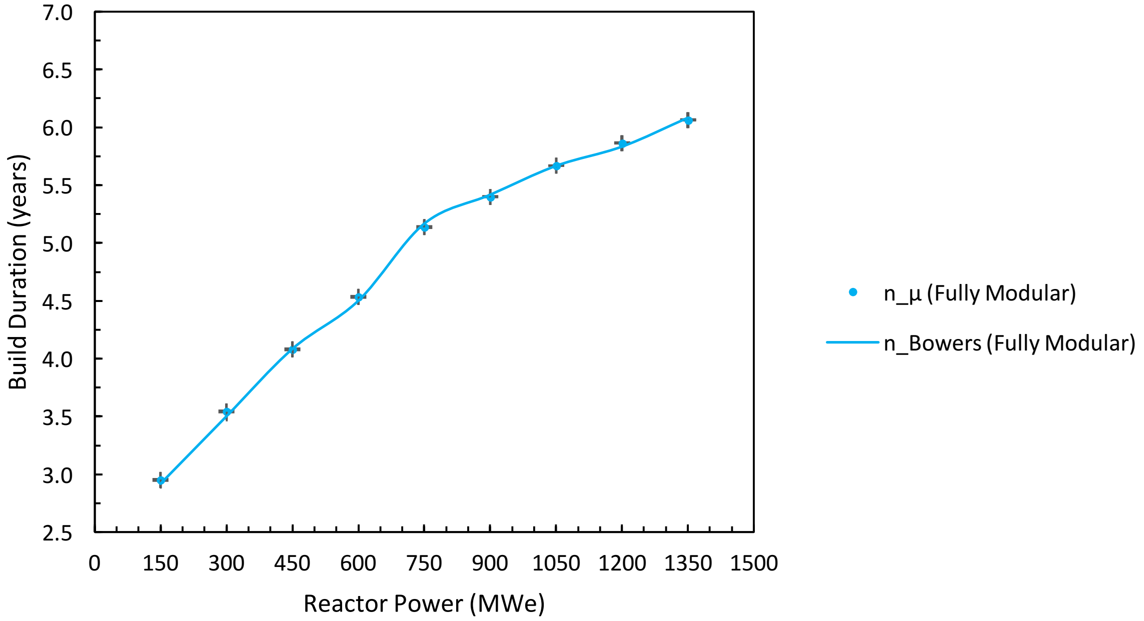

Figure VII.4. Effect of combined assembly time uncertainty and scaling exponent uncertainty on overall build duration for a fully modular NPP. Error bars correspond to a 95% confidence interval on n_{μ} = 0.61 and mean assembly time, which is 5% of module build time. Chapter V results are plotted with n_{Bowers} = 0.64.

VII.2.3. Cost Model

The full set of parameters used in the cost model are summarised in Appendix VII.1, Table A.VII.3. Assumed parameters include the scaling exponents as well as the set of modular cost and productivity factors from the EMWG guidelines. The upper and lower bounds on the uncertainty of these parameters are as per Table VII.2 and are listed in full in Appendix VII.3. Note that the conditions for the modular construction scenario use 'full' modularisation at DoM_{max}.

Overnight Capital Cost (OCC)

The cost model is slightly more sensitive to scaling than either the transport model or the scheduling model. This is as expected; both the transport and schedule models are set up to give weight to other factors besides scaling. Using Bower's scaling exponents at the 3-digit level slightly underestimates the OCC in all instances; this is because n_{Bowers} is larger than n_{μ} and results in a lower scaling effect. Note also that n_{μ} is not centred on the error bars because the contingency and owner's costs are a direct percentage of the base cost and are not scaled.

Figure VII.5 shows the response of the cost model to uncertainty in the scaling exponents. As NPP size gets farther from that of the reference LR, the scaling exponent takes more effect and OCC uncertainty increases. Both modular and stick-built NPPs have a similar percentage OCC variation in response to scaling exponent uncertainty. The OCC of a 150 MWe SMR varies by ±8.2% (at 95% confidence interval); by contrast, the OCC of LRs bigger than 750 MWe vary by ±1.0% or less for the same confidence.

The impact of uncertainty in modularisation cost and productivity factors is shown in Figure VII.6, where factors are determined as per Appendix VII.3. Uncertainty in modular cost factors has less of an impact on OCC than scaling because only the modularised cost fraction is affected and also because not all cost elements are impacted equally. OCC varies negligibly in response to uncertainty in modular productivity factors; at the most this is ±1.5% for a 95% confidence interval. The OCC of smaller reactors has a slightly greater response to modular cost factor uncertainty since a greater fraction of small reactor costs are modularised, a direct consequence of their higher $\mathrm{DoM}_{\mathrm{max}}$ values.

Figure VII.7 shows the combined effect of uncertainty in both the scaling exponent and the modularisation productivity cost factors. OCC uncertainty is governed by scaling effects. The smallest reactors have the largest response to uncertainty; their OCC can vary by as much as ±8.0% at a 95% confidence level. LRs greater than 750 MWe are still not highly affected by uncertainty and their OCC varies by less than ±1.0%. The findings from this analysis suggest that a high degree of confidence can be placed in the OCC estimates and results from Chapter VI.

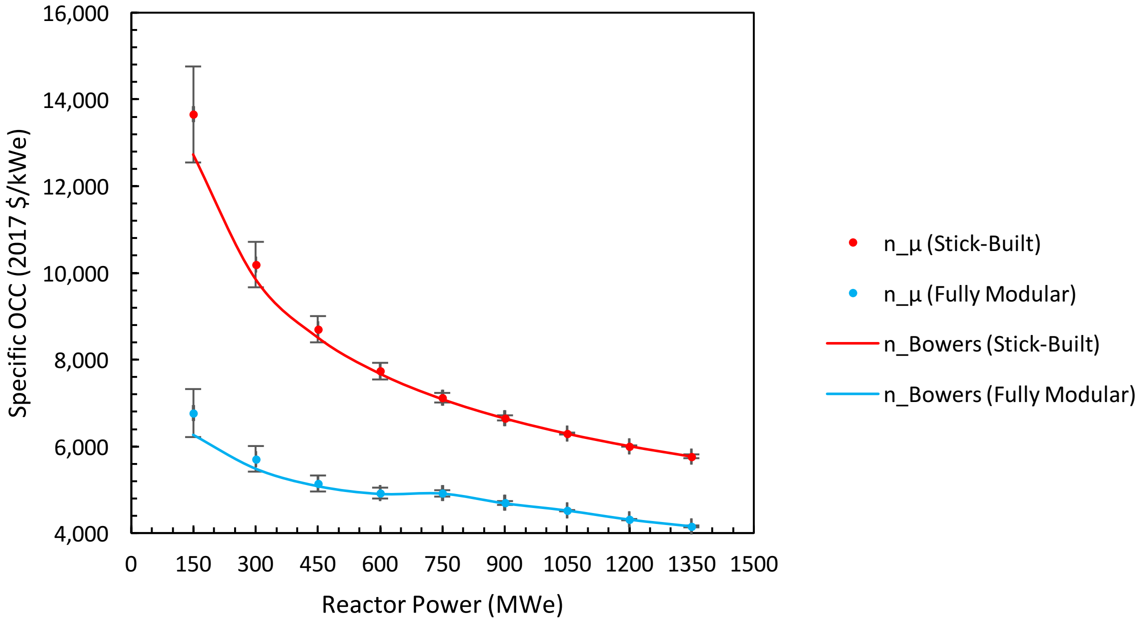

Figure VII.5. Effect of scaling exponent variability on specific OCC for stick-built and fully modular NPPs. Uncertainty bounds are set by ±σ = 0.18 for n_{μ} = 0.61. Chapter VI results are plotted for comparison at n_{Bowers} = 0.64. EMWG modular cost factors are used in all instances (see Appendix VII.3 for values).

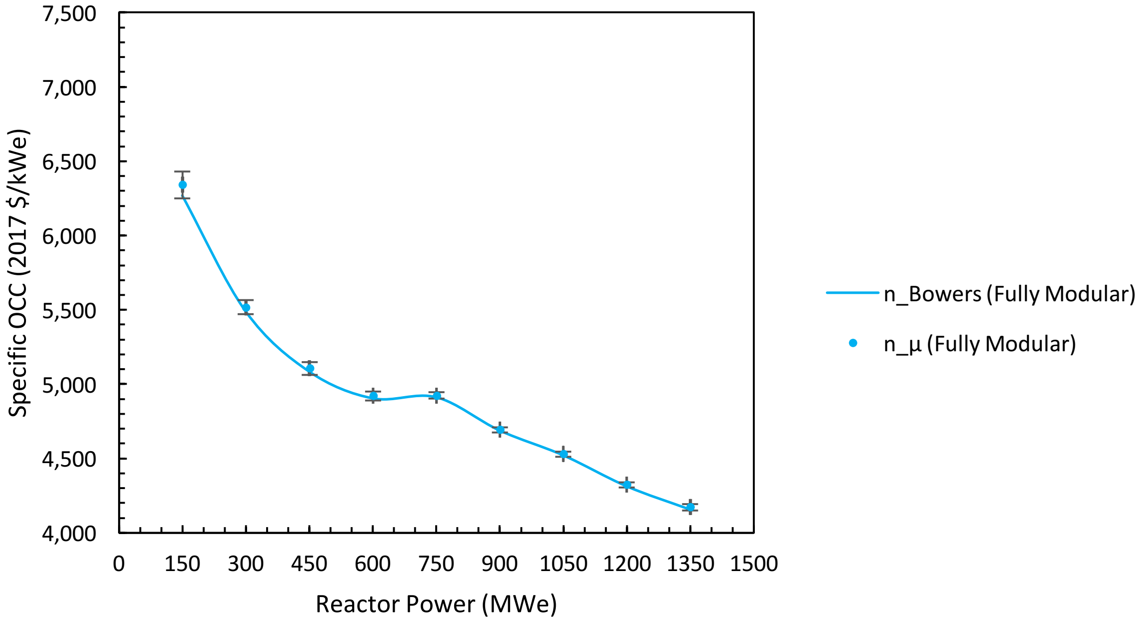

Figure VII.6. Effect of uncertainty in modular cost factors on specific OCC for a fully modular NPP. Uncertainty bounds are ±25% of each modular cost factor at n_{μ} = 0.61 (see Appendix VII.3 for values). Chapter VI results are plotted for comparison at n_{Bowers} = 0.64.

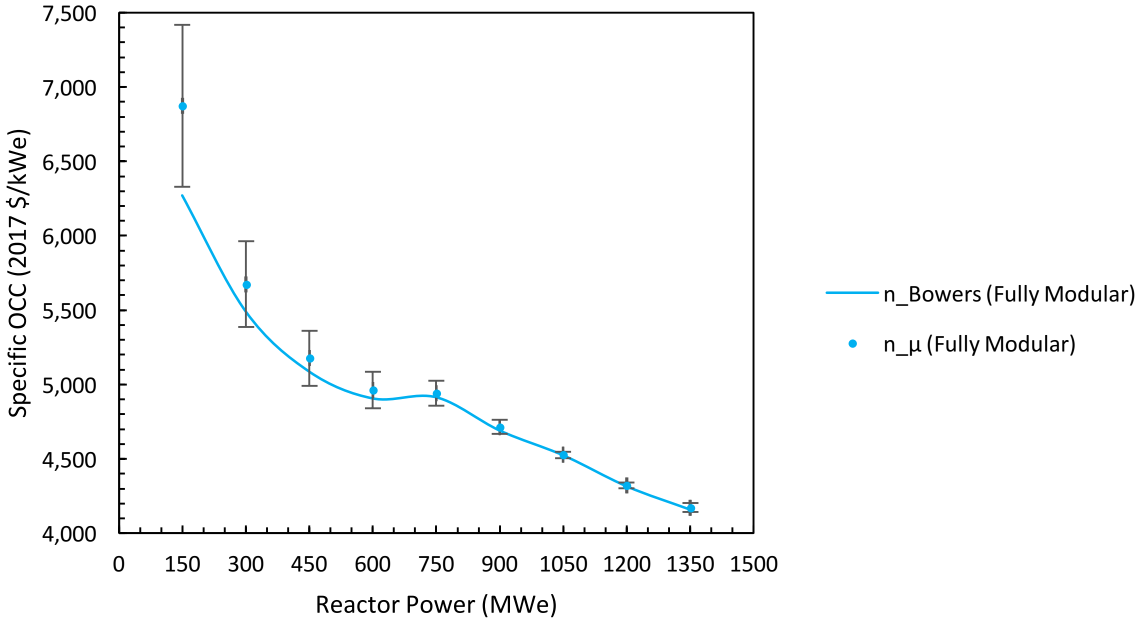

Figure VII.7. Effect of combined uncertainty in modular cost factors (±25% of each factor) and scaling exponents ($n_\mu = 0.61 \pm \sigma = 0.18$) on specific OCC for a fully modular NPP. Exact upper and lower bounds are in Appendix VII.3. Chapter VI results are plotted for comparison at $n_{Bowers} = 0.64$.

Total Capital Investment Cost (TCIC)

TCIC variations in response to changes in project interest rate are shown in Figure VII.8. Interest rate, unlike the other 'assumed' parameters, is a semi-deterministic variable that is, in part, set by the funding structure and level of government support available for the project. Low support corresponds to a high interest rate ($r_{max} = 10\%$) and high support corresponds to low interest ($r_{min} = 5\%$) as per Table VII.2. The central case is determined using n_{Bowers} and a 7.86% interest rate.

The effect of interest rate uncertainty on TCIC increases as the NPP build schedule increases. This means that uncertainty increases with reactor size, as LRs have longer build times than SMRs regardless of whether the reactor is stick-built or modular. Uncertainty also tends to increase as modularity decreases, because stick-built NPPs take more time to build than modular ones, regardless of reactor size. The TCIC of a fully modular SMR will vary by only ±5%, compared with a ±10% variation if the same SMR is stick-built. A stick-built LR, by comparison, will have TCIC varying by as much as ±20%.

The uncertainty analysis in Figure VII.8 emphasises the importance of ensuring that the build schedule reductions are achieved. Build time has a significant impact on the overall NPP economic case because it not only impacts the amount of IDC costs incurred but also impacts the magnitude of the uncertainty in that IDC estimation. Modular SMRs could experience a double benefit from schedule reduction, since their shorter build time means they not only incur lower net IDC costs but they may also be more easily able to obtain government support and funding than longer projects, accessing lower interest rates. Additionally, some SMR funding mechanisms propose co-siting multiple SMRs that are constructed following a staggered build sequence. The revenue generated from the power produced by the first unit is used to fund the subsequent SMR units. This is a further financing benefit that could serve to reduce the interest rates of SMR projects.

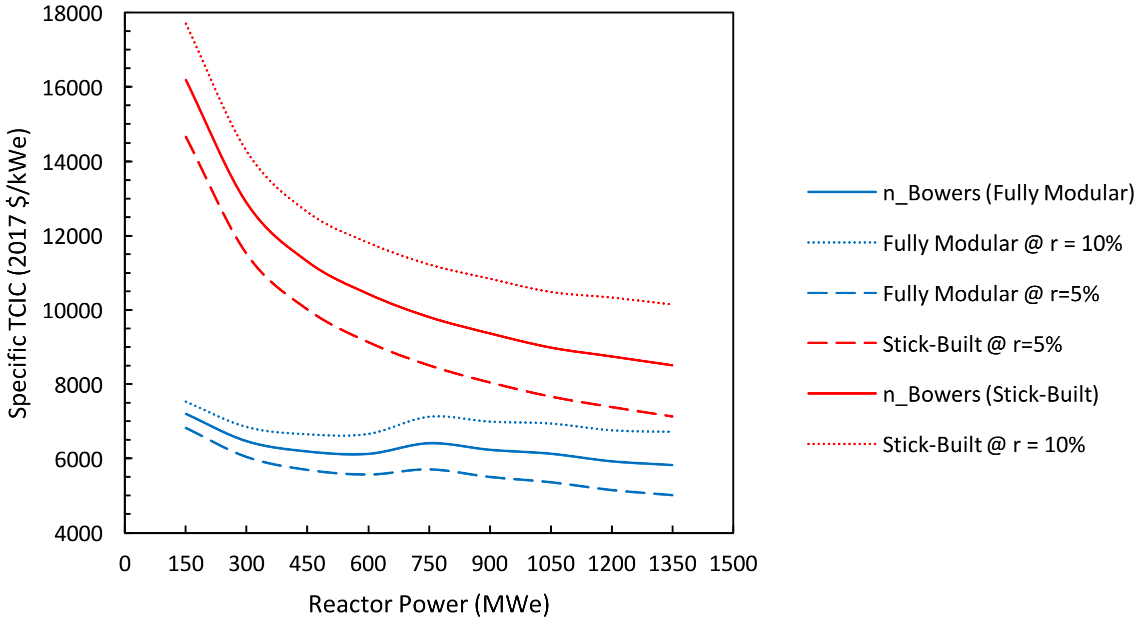

Figure VII.8. Impact of interest rate variation on specific TCIC costs for a stick-built and fully modular NPPs, for the central case from Chapter VI (n_{Bowers} = 0.64). Upper and lower limits are set by r_{max} = 10% and r_{min} = 5%, respectively.

VII.3. Conclusion

This uncertainty analysis shows that the results from the transport, schedule, and cost models developed in this dissertation are indeed useable and are not highly sensitive to variability in the uncertain parameters. Given that this project is conducted at the level of a feasibility study, confidence can be placed in the representativeness of the estimates provided in this report and the models developed in this dissertation are appropriate for projects in the concept development stages.

The principle of power scaling is typically applied only to construction costs, and the extension of scaling to NPP modules weights and build programme is a novel component of this project. The ability of the module scheme and scheduling model to absorb variability in the scaling exponents is significant and is a positive result from this work. Since scaling uncertainties tend to govern the overall level of uncertainty in the schedule and cost models, future work should focus on generating an accurate project schedule and construction cost breakdown before taking a modular SMR concept forward.

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CHAPTER VIII

CONCLUSIONS

VIII.1. Research Contributions

This dissertation assesses the feasibility of constructing small nuclear power plants using modular design and manufacturing methods. One of the novel contributions of this dissertation is an analysis of modularisation as a function of NPP size, subject to transport constraints. This project also develops a new theoretical framework to assess the scope for applying modularisation to nuclear reactors, capturing the impact of modular manufacture on NPP build time and construction cost. Finally, this dissertation shows how SMRs can improve the economic competitiveness of nuclear by leveraging a new, modular, build approach to reduce *in-situ* construction work. This section demonstrates how this thesis achieves its original objectives by directly addressing the research question from Chapter I.

Research Question

What are effective modularisation principles and practices, how can they be applied to SMR construction, and what are the implications for build time and capital cost?

i. Can modularisation be feasibly applied to NPPs, whether small or large?

Yes. The review of modularisation provided in this thesis presents evidence that design for modular build and construction works in other, related, industries and is now common practice. Modularisation is already attempted in the nuclear sector for LRs but the benefits have been limited. Hitachi uses an on-site shop for modularisation to allow parallel construction, resulting in build time reductions of approximately 1 year. Westinghouse employs a similar on-site modularisation strategy, but has not observed build time or cost savings because module transport issues were not comprehensively addressed and the necessary supply chain capabilities were not developed.

The conceptual S&W modularisation scheme used in this dissertation considered the economics and practicality of using modular build for a 950 MWe reactor design and proposed a scheme consisting of 1,419 structural, M&E, and electrical modules in both the NI and BoP buildings. This scheme can be applied as-is or modified to both small and large nuclear power plants. The feasibility of this is supported by current practice in other modular industries, which already use various structural and M&E modules and other solutions to potential issues with module interfaces, joints, and assembly techniques.

ii. What are the limits to modularisation for a particular size of reactor?

The main constraints for modularisation are available transportation methods as well the practicality and economics of the design of smaller modules. This dissertation shows that transport-limited modularisation is a function of reactor size, conditional on the S&W modularisation scheme being scalable on a weight-power basis across the range of reactor sizes and subdivision of the S&W modules by a maximum factor of 3 being feasible. Road is the preferred method of transport, with the restriction extended to include, at most, 20% of modules in STGO Category 3.

The maximum Degree of Modularisation (DoM_{max}) is shown in Table VIII.1 below. DoM_{max} decreases with increasing reactor size from a high of 0.86 (150 MWe reactor) to a low of 0.20 (1350 MWe reactor). As Chapters V and VI show, the benefits of modularisation to schedule and cost are maximised when the NPP is fully modularised and the DoM is larger than 0.60, meaning that units smaller than 600 MWe can achieve the greatest modularisation-related benefits.

iii. Can modularisation cut the build schedule?

SMR build times can be reduced by up to 21 months relative to the stick-built schedule (for a 150 MWe reactor), provided a radical modularisation approach is implemented where the DoM_{max} is achieved, the NPP is fully modularised, and the module fabrication and off-site factory work does not affect the *in-situ* construction schedule. Smaller units benefit most from modularisation: the build schedule of a stick-built LR (1200 MWe) is 6.6 years, compared to 2.9 years to build a modular 150 MWe SMR. The net percentage of build schedule reduction from modularisation, relative to a stick-built schedule, is shown in the Effective Modularisation for schedule (Schedule M_{eff}) percentages shown in Table VIII.1.

iv. Can modular SMRs compete with nuclear on overall project costs?

A standardised SMR, where the full productivity and labour benefits are realised in the factory, can reduce OCC by as much as 50% relative to the stick-built OCC (for a 150 MWe reactor). Commitment to a moderate series production of modular SMRs will result in sufficient production learning to enable SMRs to compete with low-cost large nuclear and other energy technologies on a TCIC basis. Smaller units again benefit the most from modularisation: for a given 10 year, 10 GWe, standardised build programme, the TCIC of a stick-built LR (1200 MWe) is $6,005/kWe, whereas a 150 MWe fully modular SMR has a competitive TCIC of $4,535/kWe. The net percentage reduction in OCC from modularisation, relative to the stick-built plant cost, is shown as Effective Modularisation for cost (Cost M_{eff}) percentages in Table VIII.1.

Table VIII.1. Summary of modularisation limits and maximum benefits.

Reactor Size (MWe)	***150***	***300***	***450***	***600***	***750***	***900***	***1050***	***1200***	***1350***
DoM_{max} *Maximum transportable weight fraction of modules*	*0.86*	*0.79*	*0.59*	*0.49*	*0.28*	*0.24*	*0.21*	*0.20*	*0.20*
Build Duration									
Schedule M_{eff} *% build time moved off-site from modularisation; at DoM_{max}*	*38%*	*31%*	*23%*	*21%*	*13%*	*12%*	*11%*	*11%*	*10%*
Modular Build Duration *years required to build a fully modular NPP; at DoM_{max}*	*2.9*	*3.5*	*4.1*	*4.5*	*5.2*	*5.4*	*5.7*	*5.8*	*6.1*
Overnight Construction Cost									
Cost M_{eff} *% OCC moved off-site from standardisation & modularisation; at DoM_{max}*	*51%*	*45%*	*41%*	*36%*	*31%*	*30%*	*28%*	*28%*	*28%*
Modular OCC *$/kWe required to build a fully modular NPP; at DoM_{max}*	*6,284*	*5,468*	*5,061*	*4,883*	*4,894*	*4,678*	*4,518*	*4,315*	*4,163*
Total Capital Investment Cost									
Modular TCIC *$/kWe required to build a fully modular NPP; at DoM_{max}, given learning rate of 2% and 10% at site and factory (respectively) and interest rate = 7.86% pa*	*4,534*	*4,611*	*4,697*	*4,851*	*5,279*	*5,226*	*5,215*	*5,084*	*5,039*

v. Are there key barriers to adopting modular construction in nuclear?

Some of the key barriers that could prevent modular build being used in nuclear construction are listed below.

- Module design feasibility

  One barrier to adopting modular construction is the need to successfully address the module subdivision issues introduced in Chapter IV. The SMR design must be producible from modules sized for economic off-site production and feasible for road transport.
- Module joints and interfaces

  Comprehensive testing and development is required to demonstrate and ensure the module interfaces and joints proposed for nuclear applications meet the required standards of physical and functional integrity and safety.
- Investment in modular design and facilities

  High initial upfront investment may present a barrier to modular construction. Upfront investment is required both to ensure that all the design work on the NPP and modules is complete before construction begins, as well as investing in the necessary facilities to support modularisation, including the module factory, suppliers and supply chain logistics, transport logistics, and so on.
- Ensuring series production

  Commitment to a large enough nuclear programme is required to enable economies of multiples through series production of SMRs, as is commitment to construction of a single SMR design throughout that build programme.
- Regulatory approval

  The need to gain regulatory approval for modular construction of nuclear power plants and the requirement to demonstrate the safety and feasibility of the proposed modular construction methods may present a barrier to the feasibility of implementing modularisation. Additionally, regulators in different countries may wish to make design changes to the SMR design, thereby negating the standardisation on which the modularisation concept is based.

VIII.2. Key Findings

The key findings from this project are centred on the research objectives from Chapter I and emerge from the intersection of the transport, schedule, and cost studies.

Research Objectives

Identify means and constraints of reducing the long build times and high cost of NPP construction by using modularisation and taking advantage of SMR specific features and characteristics.

Highlight particular areas of focus and/or practices that need to change in nuclear construction programmes to make DfMA feasible for SMRs.

Identify any barriers to implementation of these modular principles and practices and, if possible, present strategies for overcoming these barriers.

i. Reducing the long build time and high construction cost of nuclear power is key to ensuring its success in the future.

Nuclear power offers some significant benefits as an energy source, including its capability for providing large supplies of baseload electricity, its stability and security of supply, and its low-carbon appeal. These benefits are largely offset by the long build times and high cost of NPPs that make new nuclear projects too expensive in comparison to alternative energy sources which, although they may be less ideal in terms of their environmental impact and strategic benefits, are more economically feasible.

Modularisation can reduce schedule and build costs even for large reactors from 6.6 years (stick-built 1200 MWe LR) to 5.8 years (fully modular 1200 MWe LR). Though SMRs apparently are more expensive than large reactors due to power scaling, their smaller physical size means they are better able to leverage modular build techniques to cut build times and construction costs. Modularisation could enable SMRs to reduce construction duration and OCC from 5.1 years and $9,885/kWe (stick-built 300 MWe SMR) to 3.5 years and $5,470/kWe (fully modular 300 MWe SMR).

ii. Stick-built SMRs will not be economically feasible.

The findings from this dissertation are consistent with work conducted previously in literature and shows that stick-built SMRs will not be economically feasible with large nuclear, let alone other energy technologies. A stick-built 300 MWe SMR will have an OCC of $9,885/kWe, over 1.5 times that of a stick-built 1200 MWe LR ($6,005/kWe). Even if stick-built SMRs are produced as part of a series build programme in which economies of multiples may be achieved, they will still not compete with LRs. Over the course of a 10 year, 10 GWe programme, the OCC of a stick-built 300 MWe SMR is $8,470/kWe, whereas the stick-built 1200 MWe LR has an OCC of $5,420/kWe.

This agrees with work by both Carelli et al. [12] and Abdulla [159] which shows that approaching SMR build in the same way and using the same methods by which conventional LRs are constructed is not cost effective, instead severely restricting their benefits and therefore the extent to which SMRs are deployed. However, as already stated, the work in this thesis goes beyond existing literature and examines how radical modularisation is effective and can make nuclear more competitive.

iii. Modularisation methods and best-practices from other industries are applicable to NPPS, with smaller units achieving greater benefits.

There are a range of well-developed modular solutions for the M&E, equipment, and piping systems currently used in other modular industries that can be employed in NPP construction for both large and small reactors. Most of the off-site schedule and cost benefits from modular build will not be realised unless both the structural elements and M&E/piping systems of an NPP are modularised. Structural modules tend to be either excessively heavy (precast concrete elements) or large (structural steel elements), making them more difficult to modularise since they often have additional design, construction, and transport challenges. Structural modularisation is where SMRs win out over LRs, since the smaller physical size of the SMR modules offers greater transportability, as shown by the DoM_{max} figures in Table VIII.1.

The best-practices that SMR modularisation can and should leverage are listed in the following points:

- **Standardisation of modules, design, and build process:** removes a large amount of home office engineering work and provide a significant amount of cost and schedule savings.
- **Early design freeze:** the modular design needs to be fixed up front and early in the concept stages, with minimal changes through the project cycle.
- **Facilitate learning:** production learning across a NPP build programme needs to be achieved in order for SMRs to compete with other energy technologies. Learning is facilitated by off-site factory build, supply chain coordination, and standardisation.

iv. Modularisation allows significant reductions in build time and construction cost. Radical modularisation, based on modification of an existing NPP modularisation scheme and the limits of transportation, allows for much shorter build schedules, a reduction in construction costs to levels that are comparable with low LR cost estimates, and an increase in scope for further significant cost reductions. This dissertation shows that SMRs have the scope to lower project costs to levels that are competitive with other energy sources and could cut project timescales from approximately 6.5 years for a stick-built LR to 3.5 years for a fully modular 300 MWe SMR, with significant accompanying reductions in construction financing costs over this period.

SMRs have two opportunities for schedule reduction benefits: first, they have an inherently shorter schedule because they are smaller-scale construction projects; second, their greater scope for modularisation, reflected by their higher DoM_{max}, means a greater proportion of build time can be moved off-site. Reducing the build time has a widespread impact on the entire construction project because net overhead costs are lower, time-dependent indirect costs are reduced, and financing costs are significantly less. Project risks are also reduced because schedule uncertainty is lower in a modular project; this is because only a small amount of the construction work, mainly foundation construction and assembly tasks, are done on site.

v. Ensuring a feasible method of module transport is key.

Road transport is the most flexible transport option, admitting a wide range of siting alternatives and allowing the full potential of off-site manufacture to be realised. This project shows that NPPs with a greater proportion of feasibly road-transportable modules will be able to move more work off-site, thereby benefitting more from off-site benefits. This thesis demonstrates how road-transportable modules can be developed from the reference S&W modularisation scheme with some module design modification. The level of modification is less for SMRs, because they have initially smaller modules, but LRs have large modules that do not fit in road transport limits and would require extensive module redesign.

vi. NPP size is a critical parameter that must be carefully selected.

Deciding on an optimal NPP size depends on the preferred optimisation and trade-off between the various factors that drive NPP and/or module size.

The factors that favour smaller modules and smaller reactors include:

- More **transport** options are available and transport logistics are easier with smaller modules;
- **Off-site factory manufacture** and assembly line production is easier if components and modules are smaller;
- **Series production** provides higher benefits if a large number of components is produced;
- **Build schedules** are shorter for smaller projects.

The factors that favour larger modules and/or reactor sizes include:

- **Economies of scale** drive reactor sizes up because larger reactors have lower specific costs;
- The number of **joints** and **module interfaces** are reduced with fewer, large modules;
- **Current practice** in the nuclear industry and the **lack of experience** with modular construction of small NPPs means there must be a big step change from conventional construction processes.

VIII.3. Future Work

The topics below arise from issues that are tangential to the main body of work conducted in this thesis. While these topics are outside the scope of work presented in this project, they are well worth further study.

i. Specific Module Design

This dissertation takes a high-level, concept design, approach and highlights what elements of modular build are key within the SMR facility as a whole. The criteria for, and feasibility of, individual module design and optimisation may differ depending on the NPP design or module type. Piping modules, for example, are typically optimised to reduce pipe lengths whereas structural modules are often optimised to increase transportable surface area or volume. Further work on the optimisation criteria and design constraints is required before a complete set of modules can be produced for a specific SMR design.

ii. Nature of the Module Production Facility

Modules can be produced in either an on-site shop or an off-site factory. The location of the production facility and the implications for module transport and design constraints need to be investigated in greater detail. Additionally, the manufacturing features of the production facility, including its capabilities and work content, capacity, layout and flow-lines, level of automation, staffing and skills requirements, and so on, are all aspects of the module factory that should be addressed in future work.

iii. Additional Modularisation Benefits

There are some benefits to modularisation that are neither directly economic or schedule related. These additional benefits are not captured in the modelling presented in this thesis. For example, a further advantage of off-site build is better worker safety during construction and results in improved productivity and product quality. Factory build also enables the manufacturer to fabricate elements to a higher specification, tolerance, and quality. This can eliminate rework and simplify testing and inspection, reducing build time and cost. Many-industries that have adopted modular build methods have also observed that modularisation simplifies maintenance and parts replacement tasks, reducing ongoing costs and through-life downtime.

VIII.4. Summary

Modularisation is a well-established build strategy; however, its use in the context of NPP construction for developing modular SMRs is a novel concept for civil nuclear power generation. The findings in this dissertation give substance to the claims surrounding the constructability advantages, lower cost, and reduced build times of modular SMRs. This project shows, for the first time, that SMR diseconomies of scale can be offset by design for modular build and assembly and addresses how the necessary modularisation could be achieved. Smaller units, in the 300-450 MWe range, offer the greatest potential for cost and build schedule reductions and could make nuclear competitive with other energy technologies.

This project establishes a framework for thinking about modularisation in a nuclear context by discussing modularisation principles and best practises, identifying key constraints and optimisation criteria for modules, and estimating the expected cost and schedule benefits from switching to off-site construction. Available LR build experience is used to supply reference baseline data that help to focus the study and give meaning and context to SMR-specific results through comparisons with what is already well-understood. Some of the knowledge gaps pertaining to SMR build time and cost are filled by identifying suitable sources of nuclear construction data and investigating appropriate cost estimation methods for SMRs. The assessment of transportation limitations as a function of reactor size is also new and demonstrates how SMRs can achieve greater modularisation than LRs, thereby increasing the extent of their off-site productivity benefits and cutting build time and construction cost. The detailed characteristics of SMR modules and the manufacturing facility are the next obvious topics requiring further study; the findings from this project can be used to direct and justify more detailed work on the development of modular manufacture and construction strategies SMRs for civil power generation purposes.

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APPENDICES

APPENDIX I

I.1. Worldwide LWR Construction Duration

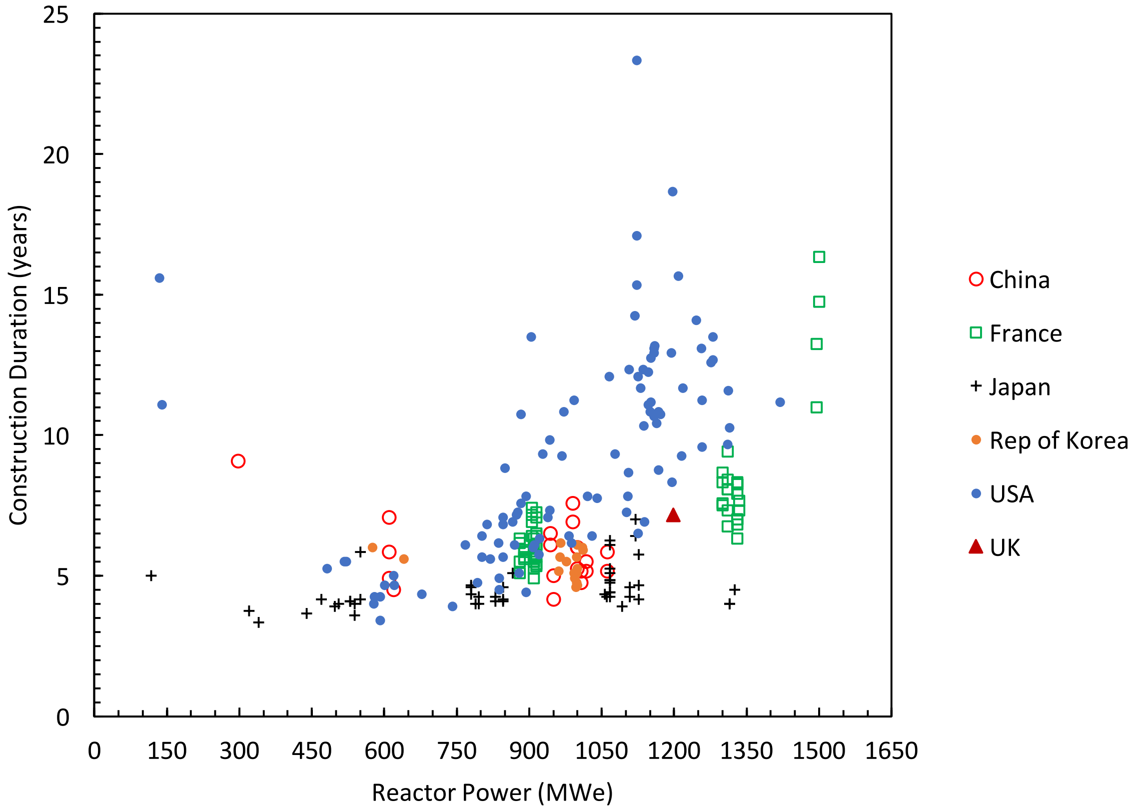


Figure A.I.1. Construction duration wrt reactor power for operational PWRs and BWRs in the world, from IAEA [149]. Construction duration is the time between the reactor's construction start date and the date of commercial power production.

I.2. Reference LR Plans

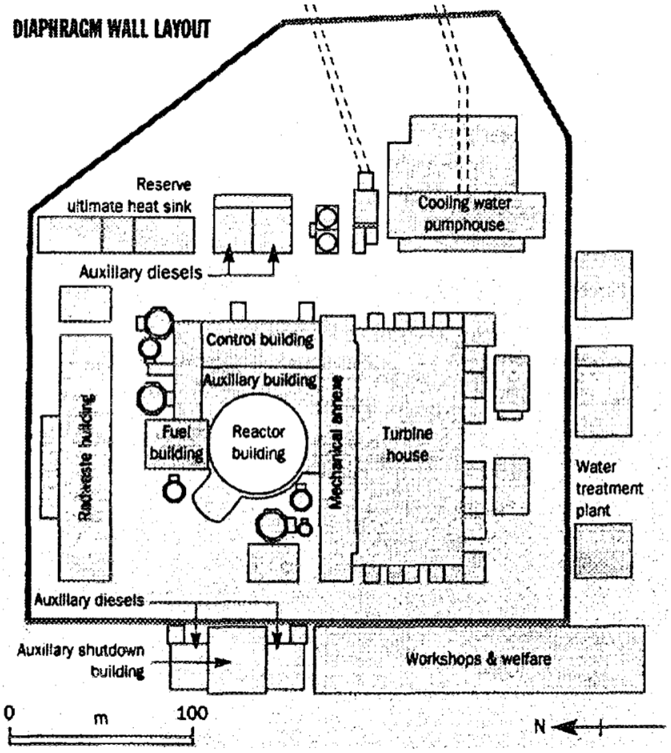


Figure A.I.2. Location of diaphragm wall enclosing the central part of Sizewell B power station (Figure 1 [70]).

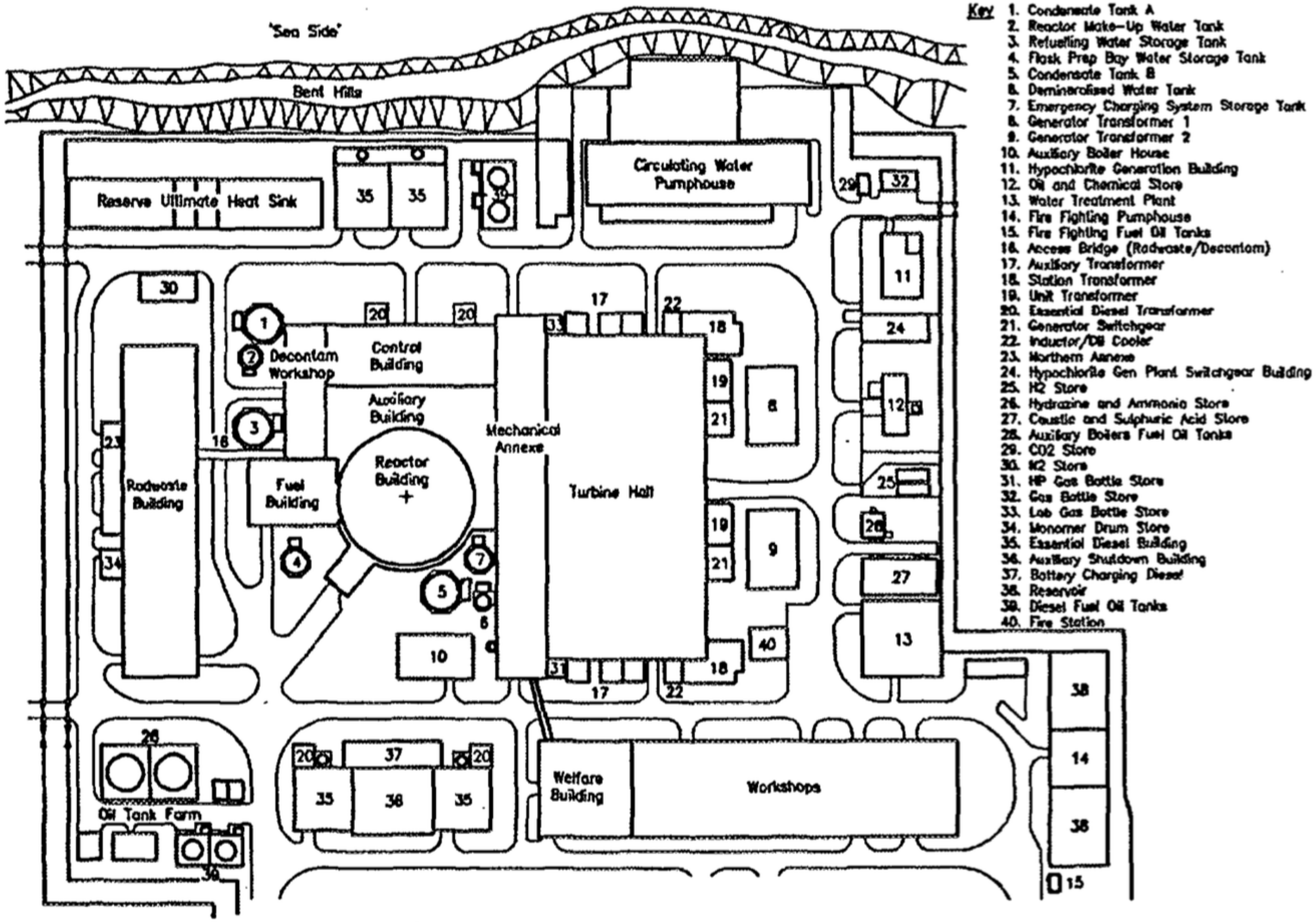
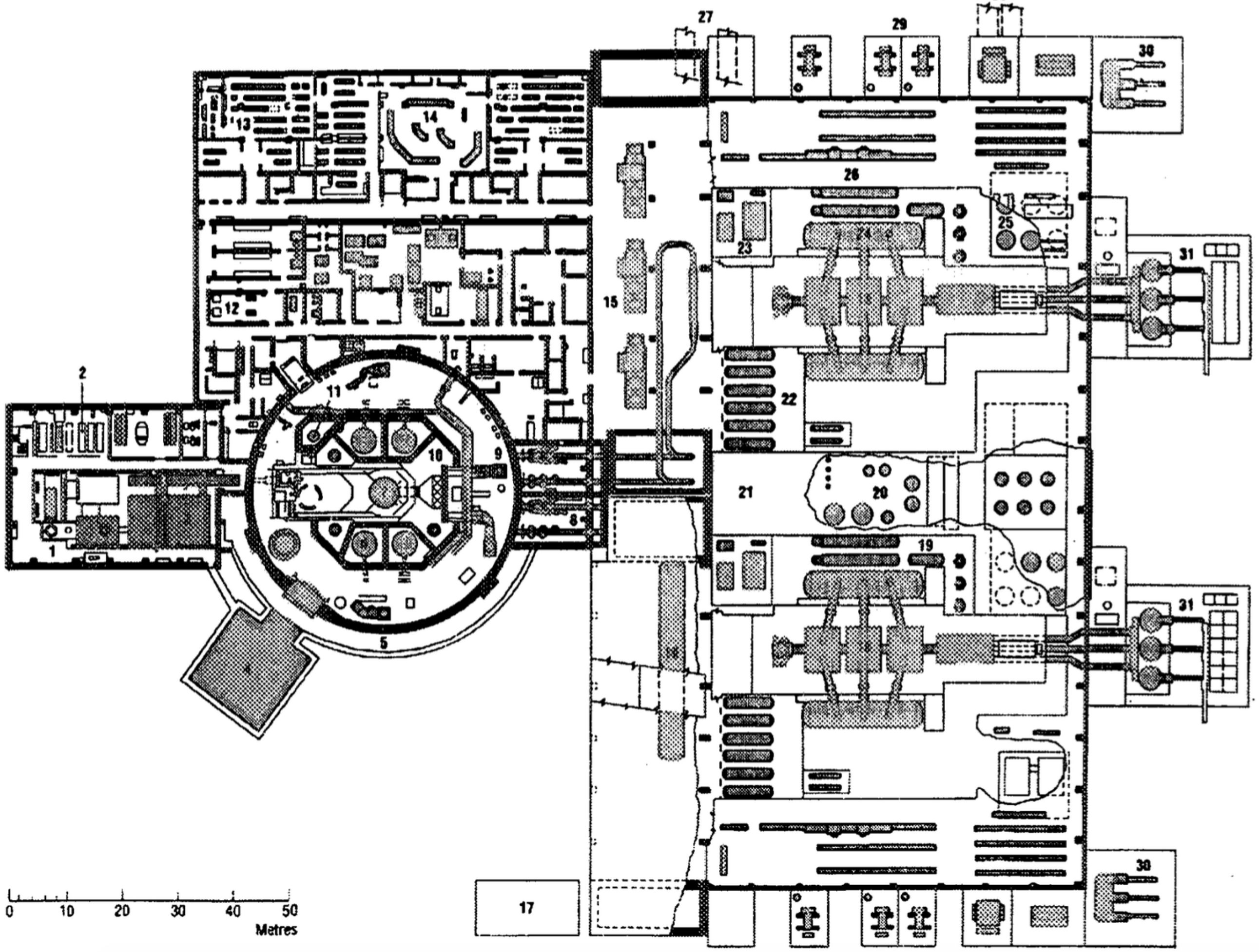


Figure A.I.3. Layout of Sizewell B power station site Suffolk, UK (Figure 2 [70]).



1	Fuel building
2	New fuel
3	Fuel store
4	Plant access hatch
5	Secondary containment
6	Steam generators (four)
7	Reactor pressure vessel
8	Steam mains
9	Ventilating plant
10	Reactor coolant pumps
11	Pressuriser
12	Auxiliary building
13	Control building
14	Main control room
15	Feed pumps (six)
16	Deaerator
17	Auxiliary boiler house
18	Turbo-generator
19	Low pressure heaters
20	Auxiliary plant
21	Loading bay
22	High pressure heaters
23	Lubricating oil plant
24	Reheaters
25	Polishing plant
26	Switchgear
27	Circulating water outlet
28	Circulating water inlet
29	Transformers
30	Station transformers
31	Generator transformer

Figure A.I.4. Sizewell B main plant layout (Figure 3 [70]).

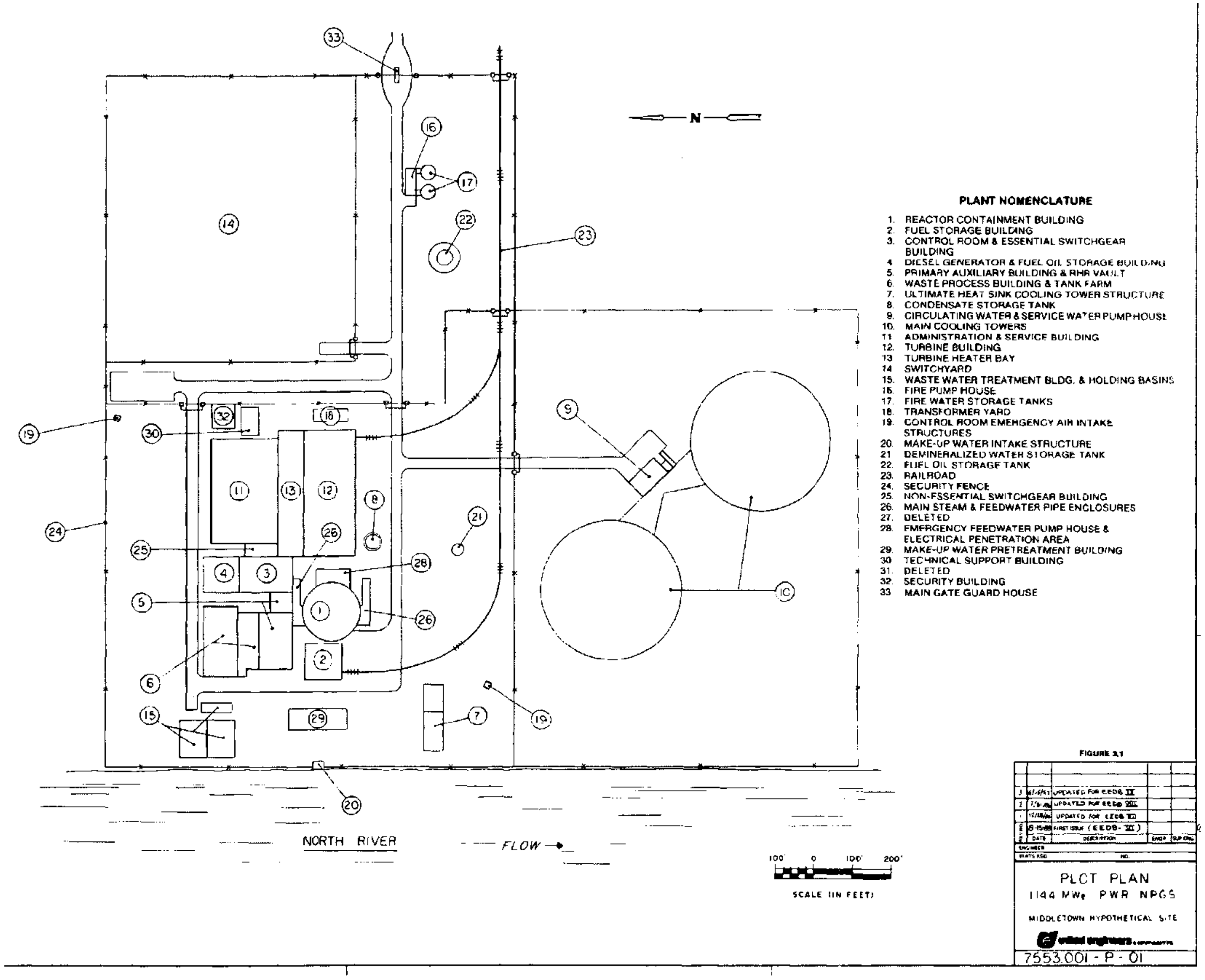


Figure A.I.5. Plot plan for PWR-12 (p. 3-111 [73]).

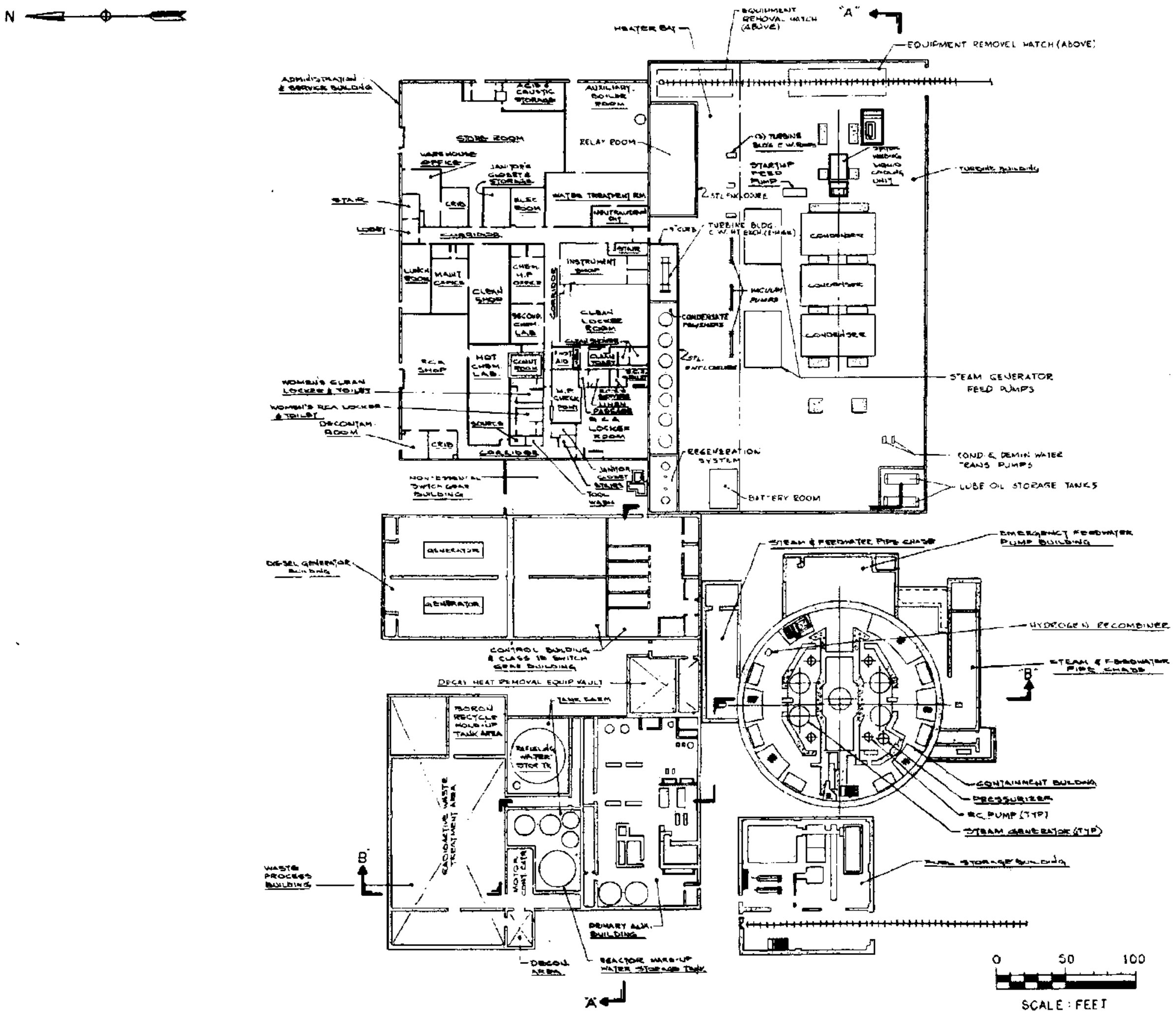


Figure A.I.6. General arrangement plan for PWR12 at ground elevation (p. 3-112 [73]).

I.3. SMR Layout Plans

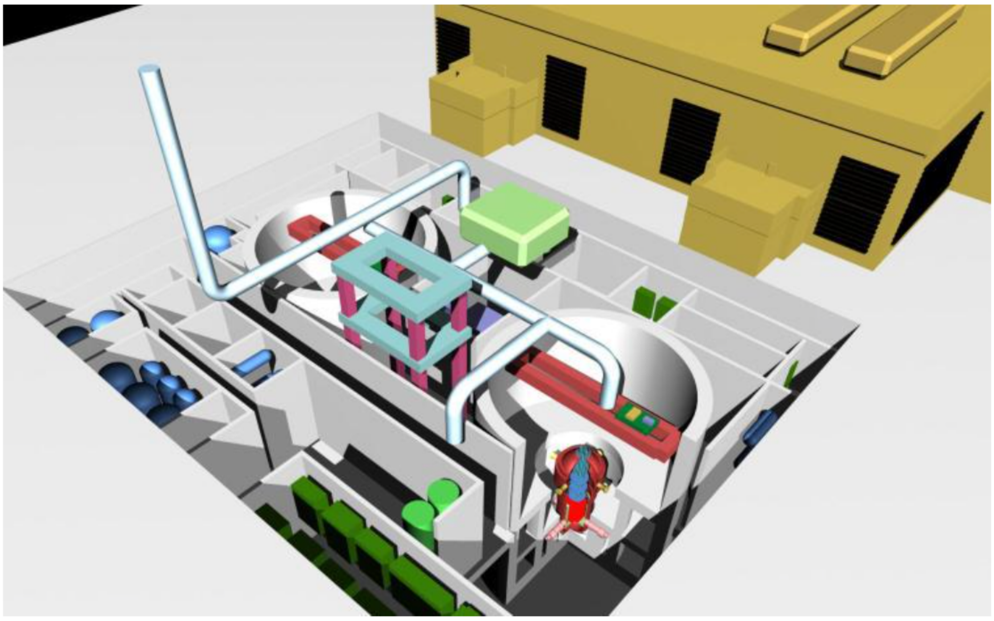


Figure A.I.7. Plan layout of the ACP100 (CNNC, China) twin SMR reactor building [160], with a net power output of 200 MWe (2 × 100 MWe units).

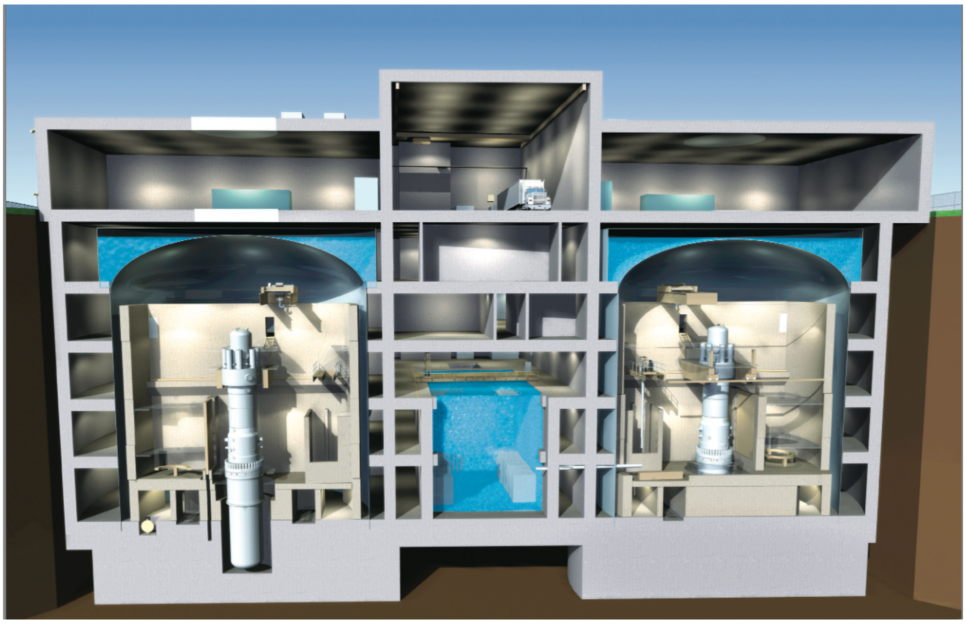


Figure A.I.8. Cross-section of the Generation mPower (B&W, USA) twin SMR reactor building [40] with net power output of nearly 400 MWe (2 × 195 MWe).

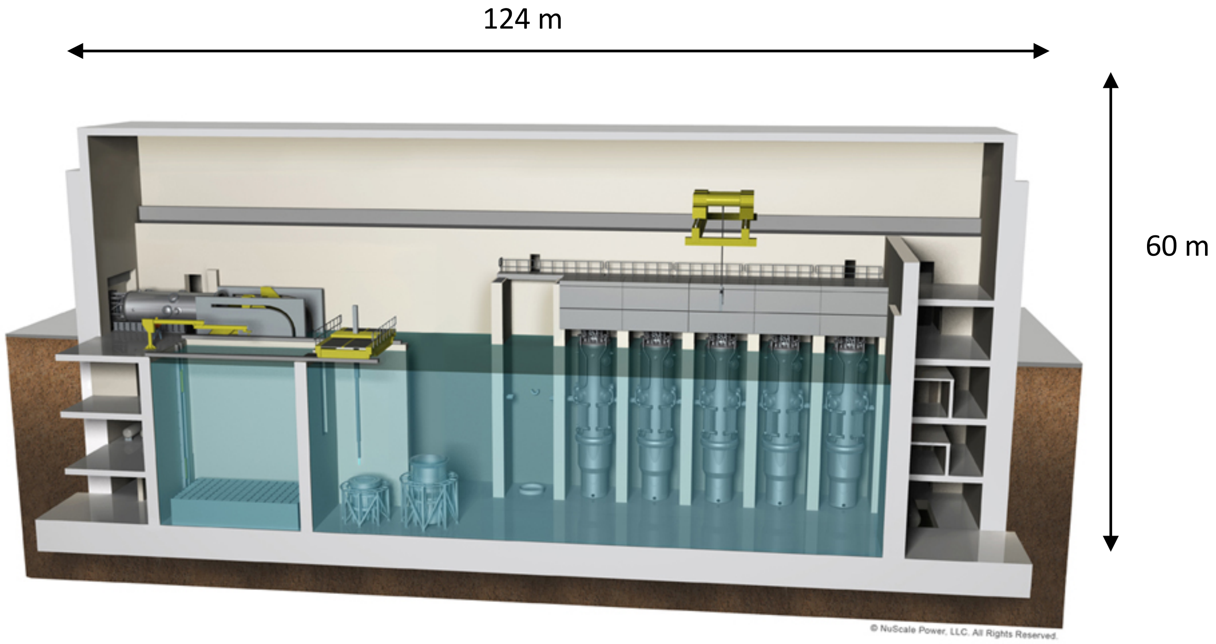


Figure A.I.9. Cross-section of the NuScale (USA) SMR reactor building [41] with a net power output of 540 MWe (12 × 45 MWe units). Dimensions of 124 m length by 48 m width by 44 m height were estimated off given power module dimensions [161] of 75.8 ft (23.1 m) height and 15 ft (4.6 m) maximum outer diameter.

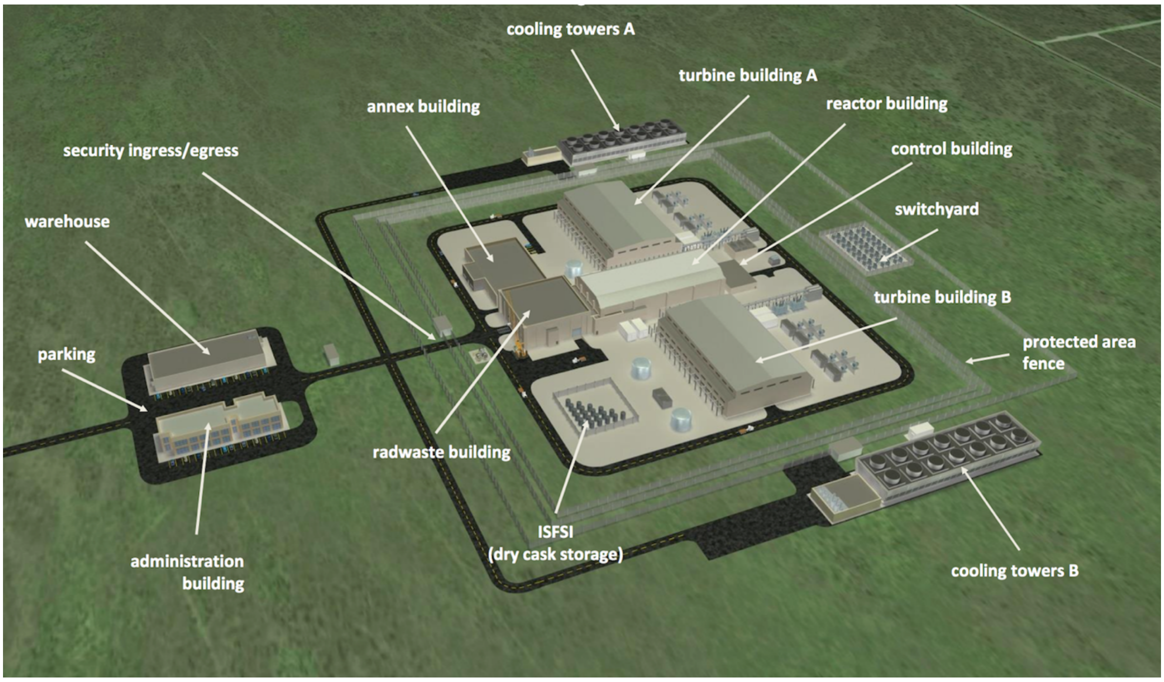


Figure A.I.10. NuScale site plan [41]. Reactor building dimensions are estimated to be 124 m (length) by 48 m (width) from estimates in Figure A.I.9 and all other building dimensions were scaled off that.

Figure A.I.11. Plan view of the SMART (KAERI, Republic of Korea) twin SMR reactor facility [162] with a net power output of 200 MWe (2 × 100 MWe units).

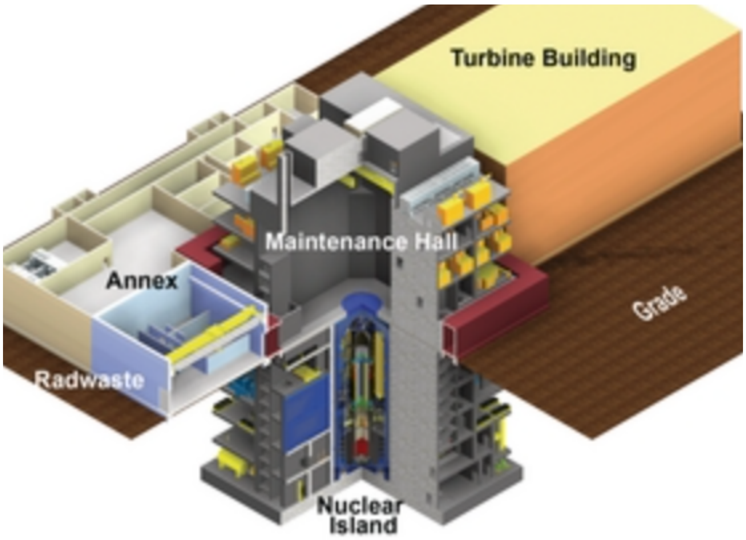


Figure A.I.12. Westinghouse SMR (USA) reactor building [29] with a net power output >225 MWe.

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APPENDIX II

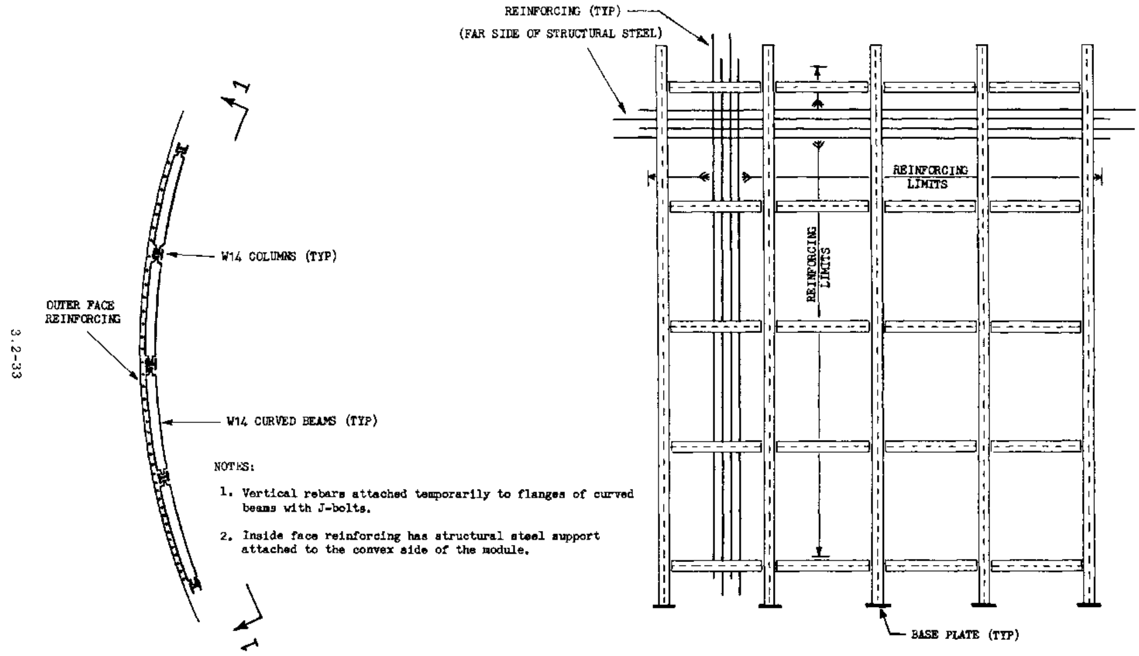
II.1. S&W Structural Modules

i. Reinforcing Steel

Used in: containment, annulus, turbine buildings.

Used for: mats, walls, floor and roof slab modules.

Preassembled rebar steel modular cages are placed and tied in position in an on-site shop; wooden templates used to help control placement of cages and ensure interfaces are accurate. Additional/stronger ties may be required, together with bracing, to prevent racking as module is lifted. There is the option to use reinforcing steel modules instead of precast modules, depending on transportation constraints. An example reinforcing module is shown in Figure II.A.1.i.



NOTES:

1. Vertical rebars attached temporarily to flanges of curved beams with J-bolts.
2. Inside face reinforcing has structural steel support attached to the convex side of the module.

Figure A.II.1. Containment wall reinforcing modules (p. 3.2-34 [60]).

ii. Precast Concrete

Used in: annulus, turbine, diesel-generator, control buildings.

Used for: walls (exterior & interior circumferential, radial & cubicle, shield) and slabs.

Reinforced concrete blocks are precast in a designated area near the batch plant. Placement of precast concrete modules in the annulus building is shown in Figure II.A.1.ii. Structural integrity is obtained by using a cast-in-place closure pour, where reinforcing extends beyond the limits of the precast concrete module and closure pours ties the panels together, as shown in Figure II.A.1.iii. Module weight is limited by crane lifting capacity. Standardisation is achieved through selection of either repetitive areas and/or common sizes of modules.

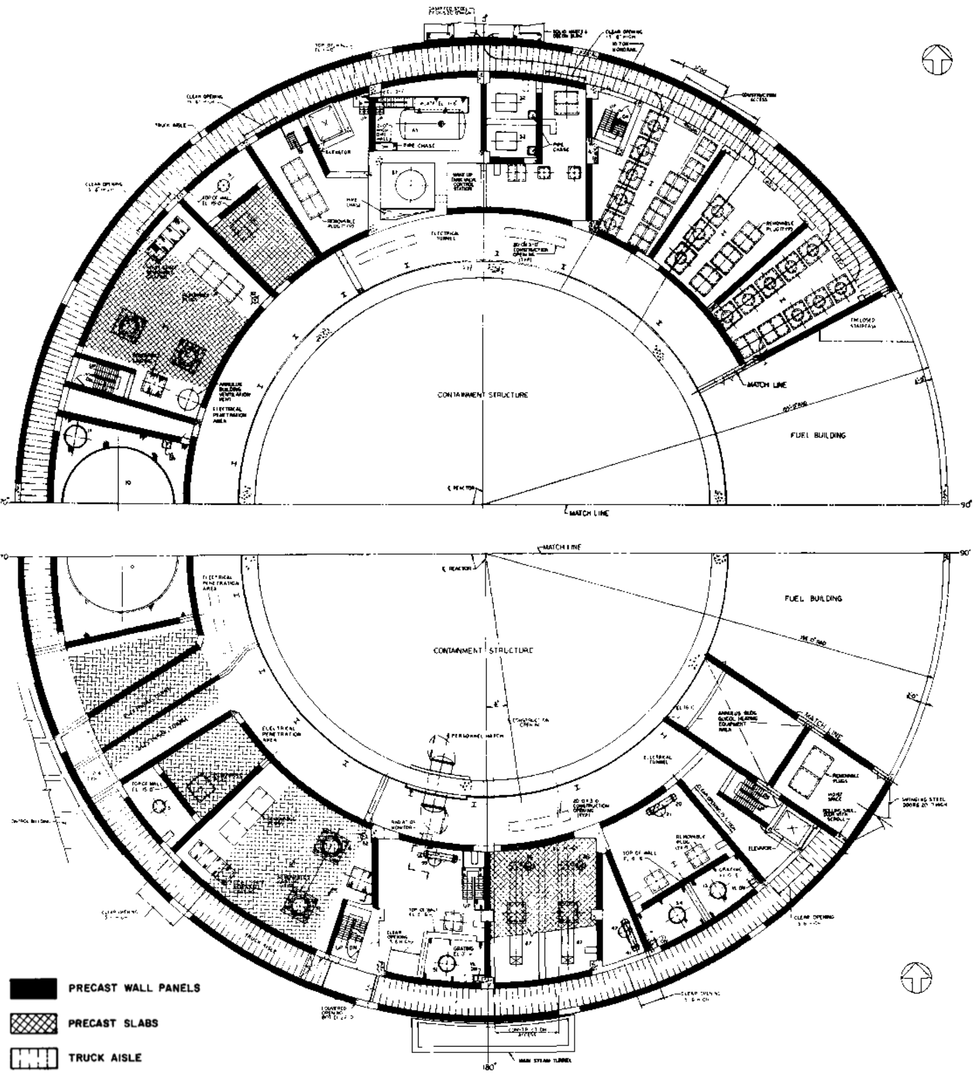


Figure A.II.2. Annulus building precast panels (0’-6’) (pp. 3.2-42 & 43 [60]).

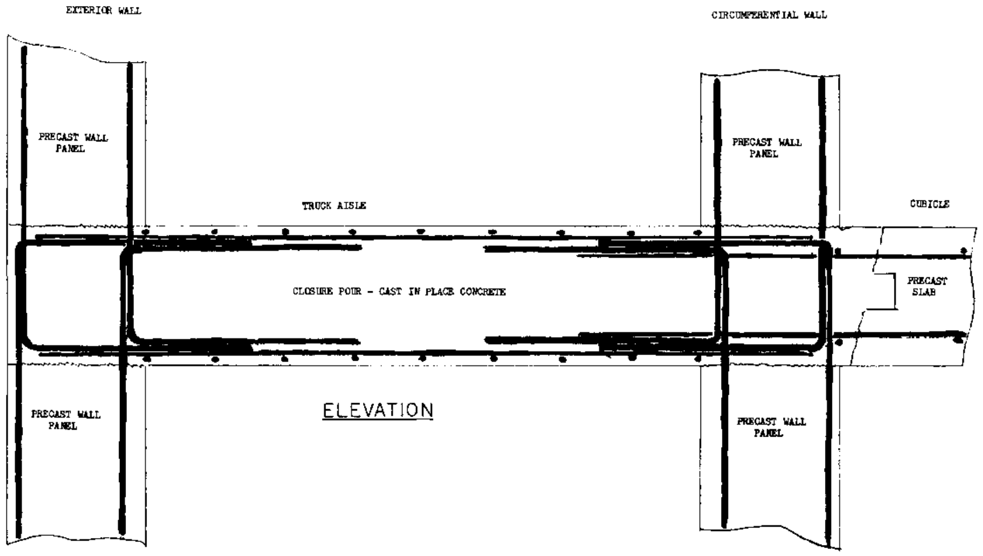


Figure A.II.3. Closure pour for annulus building precast slabs (p. 3.2-50 [60]).

iii. Structural Steel

Used in: annulus, turbine, control buildings.

Used for: floor, roof modules.

Steel beams or columns are welded or bolted together at grade in an on-site shop. The modules are hauled to location using large-capacity flatbed trailer trucks and are placed using cranes.

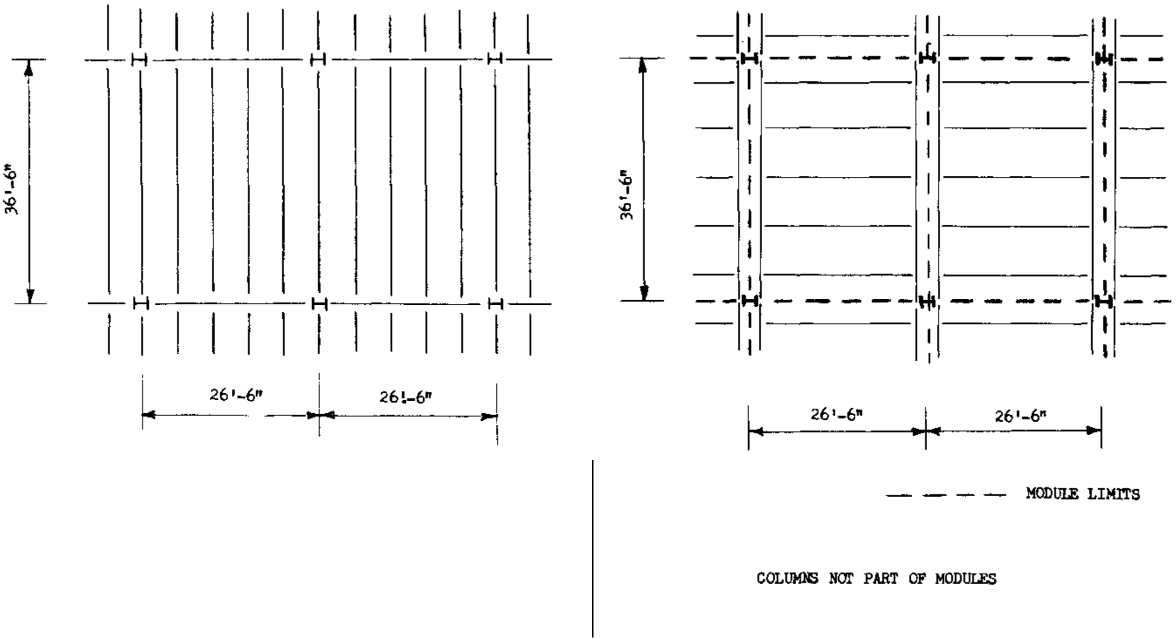


Figure A.II.4. Comparison of conventional (left) and modular (right) steel arrangements for the control building floor (pp. 3.2-60 & 61 respectively [60]).

iv. Liners

Used in: containment, transfer canal, spent fuel pit buildings.

- **Containment Liner Structures**

  Consist of bottom mat liner plates, rolled shell plates, personnel access locks, equipment hatches, penetrations, and base assembly. The modular solution preassembles these liner elements in four cylindrical shell liner assemblies (each of which consists of four rings) complete with spray piping. These are built on an assembly foundation area and are lifted in place by cranes.

- **Other Liner Structures**

  Includes those in the refuelling building. These liner units are modularised and designed to enable rapid assembly *in-situ*, using automatic welding whenever possible. These modules can be assembled and welded into complete pool liners in an on-site shop before being lifted into the nuclear hole. Figure II.A.1.v. shows an example of the spent fuel pit liner pool and Figure II.A.1.vi. shows a specific liner module from the spent fuel pit.

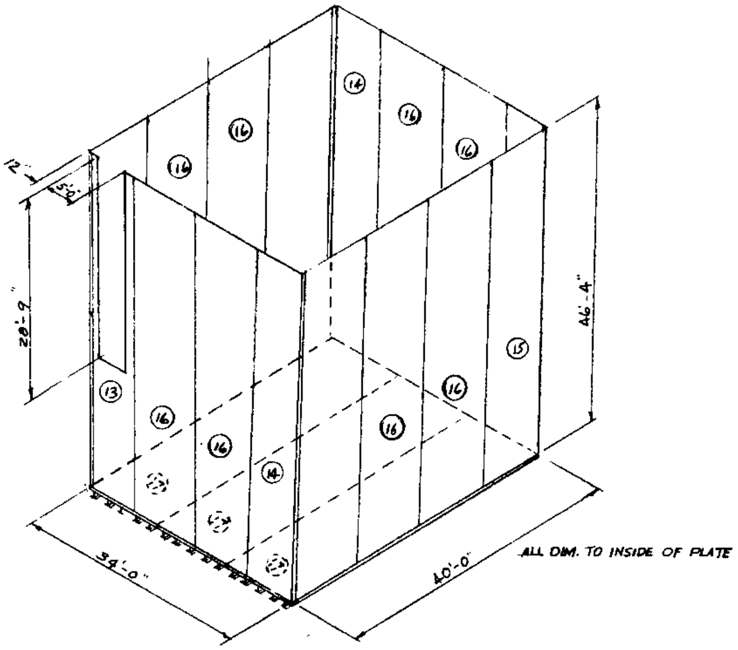


Figure A.II.5. Modularised spent fuel pit liner (p. 3.2-73 [60]).

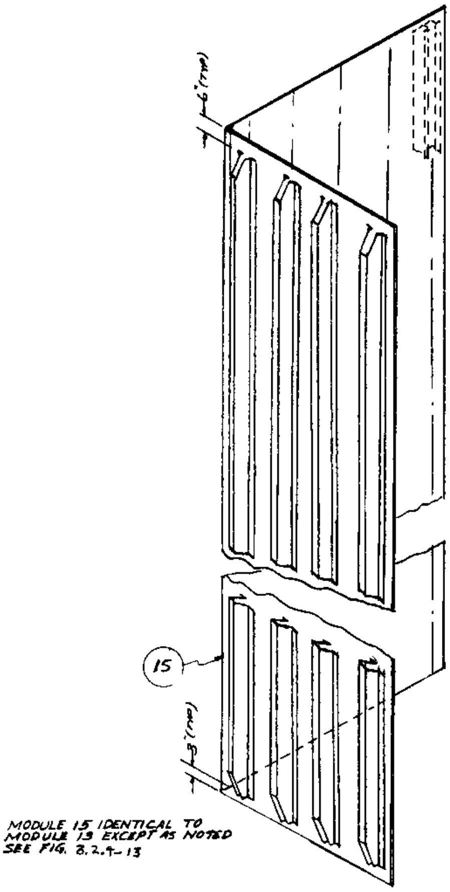


Figure A.II.6. Modular section of spent fuel pit liner (p. 3.2-75 [60]).

v. *Polar Crane Modules*

The polar crane support structures can only be placed after the interior concrete walls of the containment are poured and set. The S&W solution preassembles these structural steel modules into a set of assemblies that can be lifted into place in the containment and are bolted or welded to pre-set baseplates. The main challenge for modular installation of the polar crane modules is the precise alignment required.

II.2. S&W Mechanical Modules

i. Equipment (skid-mounted)

Used in: annulus, fuel, turbine buildings.

Used for: sumps, demineraliser and filter vessels, MSR, feedwater pump and turbine, condensate polishing equipment.

- **Sump Systems**

  The modular system consists of two required pumps, together with the associated piping, arrive on site preassembled and mounted on a standard baseplate.

- **Demineraliser & Filter Vessels**

  The vessels arrive in preassembled and pre-mounted modules, with associated piping included, for crane installation. A diagram of the proposed demineraliser assemblies is shown in Figure A.II.7.

- **MSR Units**

  The unit is mounted on structural steel skid; the reheater drain tank is located above the skid and beneath the MSR, and the moisture separator drain tank is hung below skid. Related piping is supported on the skid structure. A diagram of the proposed modules is in Figure A.II.8.

- **Feedwater Pump & Turbine System**

  The module arrives on site complete with a turbine on a baseplate, high and low pressure stop valves, lubricating oil system, and an instrument console. The wiring and connection tasks need to be completed *in-situ*, after the module is installed.

- **Condensate Polishing Equipment**

  The module consists of preassemblies of tanks, pumps, filters, demineralisers, and blowers. Related piping and valves are placed *in-situ* and any remaining components must be individually installed.

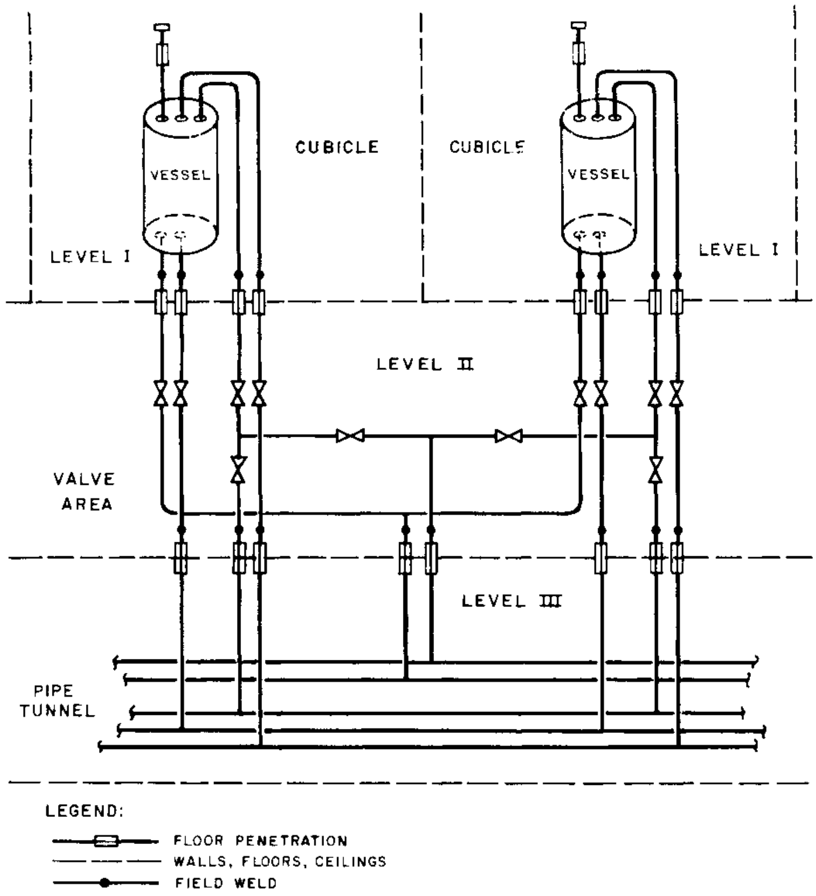


Figure A.II.7. Annulus building demineraliser filter subassemblies (p. 3.3-37 [60]).

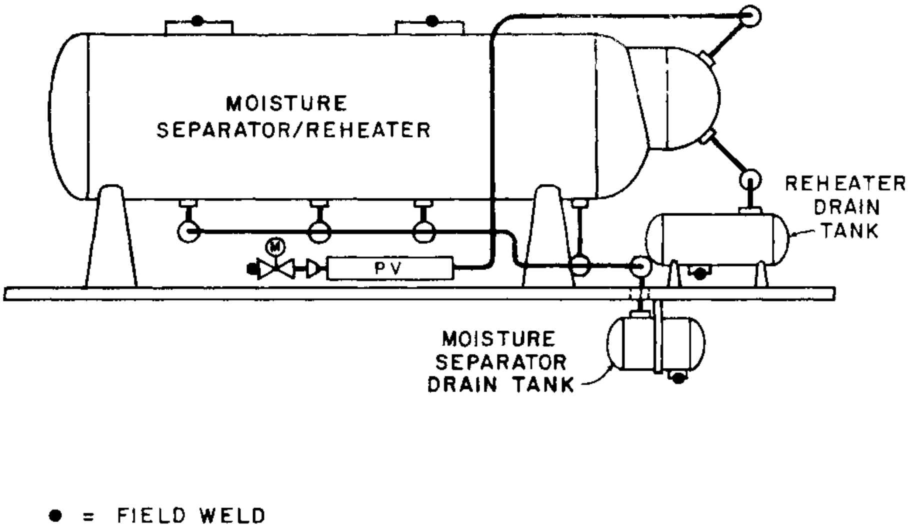


Figure A.II.8. Moisture separator/reheater module (p. 3.2-39 [60]).

ii. Condenser

The condenser consists of a tube bundle, steam inlet assembly, and water boxes. The system is too large to be shipped as a single unit; therefore, S&W subdivide the condenser into pieces that are completely outfitted and tested, and can be installed with minimal *in-situ* fabrication required.

iii. Tanks

Used in: annulus and other miscellaneous locations.

Used for: auxiliary feedwater, refuelling water storage, miscellaneous.

Modular tanks are to be constructed on temporary foundations and then lifting them into place; transportation is the primary constraint on this (tanks larger than 12ft diameter are typically fabricated at the site).

iv. Piping

Used in: annulus and containment buildings.

Used for: main steam, reactor plant service water & component cooling water, decay heat removal, containment spray, primary coolant piping.

An on-site shop area is used to pre-assemble piping modules together with related components, valves, equipment. The modules are then ready to be lifted into place and attached using flanges, bolts, and/or welding. Automatic welding is used as much as possible.

v. Pipe Racks

Modules are fabricated in a designated pipe rack assembly area and contain relevant piping and valves and other components; and example is shown in Figure II.A.2.iii. Automatic welding is used where possible.

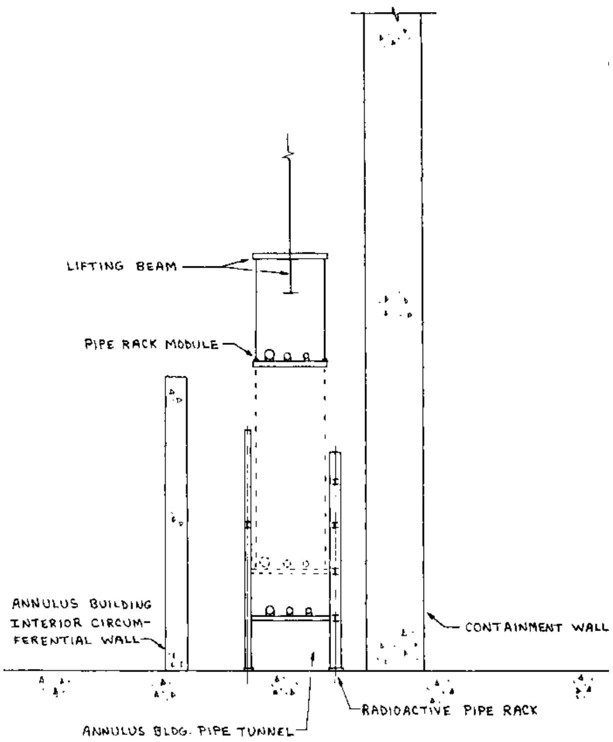


Figure A.II.9. Modularisation of pipe racks with piping (p. 3.3-54 [60]).

II.3. S&W Electrical Modules

These modules require extra analysis before they can be validated for use in NPPs.

i. Non-Seismic Cable Trays

Modules use a factory-fabricated ladder type support as shown in Figure II.A.3.i.

ii. Non-class lE Cable Installation

Currently, separate control cables are assigned for each piece of equipment activated. This separate assignment is applied throughout the electrical design to include interlocks and alarm function. Modules will use a larger number of conductors per cable to reduce the need for large numbers of individual cables.

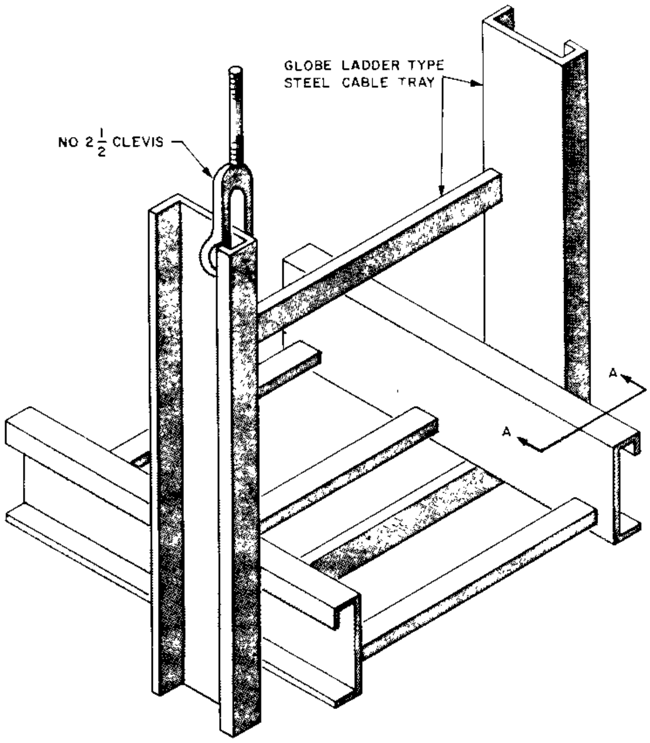


Figure A.II.10. Ladder type cable tray support (p. 3.4-13 [60]).

II.4. S&W Reference Modularisation Scheme Details

Table A.II.1. S&W module details by location/building, module type, quantity, and dimensions (weight, length, width, height) [60].

Preassembly of reinforcing steel

Module Location/Building	Module Type	Qty	Wt (te)	L'th (m)	W'th (m)
Containment	exterior wall	45	88.00	20.7	18.60
	mat	54	131.50	49.4	18.90
	cubicle walls	4	98.00	19.5	15.24
	primary shield wall	2	86.20	15.2	10.36
Annulus	exterior wall	8	129.70	36.6	10.70
	interior wall	132	1.80	7.9	3.70
	floor and roof slabs	110	3.63	9.1	3.70
Turbine	ground floor slabs	179	0.91	9.1	6.10
	spread footings	80	1.36	3.7	3.70
	grade beams	50	1.90	8.96	3.63
Total reinforcing steel modules		**664**	**13667**		

Precast Concrete

Module Location/Building	Module Type	Qty	Wt (te)	L'th (m)	W'th (m)
Annulus	exterior circumferential walls	36	258.50	18.90	9.40
	interior circumferential walls	91	204.10	17.70	7.00
	radial & cubicle walls	113	217.70	20.70	7.00
	cubicle slabs	38	263.10	14.60	13.70
Turbine	shield walls	17	181.40	14.60	8.50
Diesel-Generator	walls	6	195.00	15.80	8.23
	slabs	6	181.40	12.20	10.00
Control	walls	56	154.20	17.10	6.10
	slabs	16	117.90	10.70	7.62
Total precast concrete modules		**379**	**78341**		

Preassembly of Structural Steel

Module Location/Building	Module Type	Qty	Wt (te)	L'th (m)	W'th (m)
Annulus	floors and roof	68	10.90	13.10	8.20
Turbine	mezzanine level	46	42.60	11.00	9.10
	operating level	37	48.10	11.00	9.10
Control	floor & roof (edge)	24	22.70	11.00	7.90
	floor & roof (interior)	10	22.70	11.00	7.90
Total structural steel modules		**185**	**5252**		

Liner Modules

Module Location/Building	Module ID Number	Qty	Wt (te)	L'th (m)	W'th (m)	Ht (m)
Containment	module 1 (base plate)	1	145.15	45.72	45.72	12.19
	module 2	1	145.15	45.72	45.72	0.08

	modules 3,4,5,6	4	145.15	45.72	45.72	4.57
	module 7	1	123.38	45.72	45.72	7.62
	module 8	1	122.47	45.72	45.72	7.62
	module 9	1	120.66	45.72	45.72	7.62
Transfer canal	module 1	1	16.87	15.01	3.66	3.66
	module 2	1	9.12	8.76	3.73	3.66
	module 3	1	16.87	6.40	3.10	1.52
	module 4	1	16.87	8.61	3.05	1.52
	module 5	1	16.87	2.74	1.83	1.52
	module 6	1	16.87	11.86	3.35	1.68
	module 7	1	16.87	12.19	1.52	0.00
	module 8	1	16.87	11.86	2.49	0.00
	module 9	1	16.87	11.86	3.05	0.00
	module 10	1	16.87	11.86	3.05	0.00
	module 11	1	16.87	3.51	3.09	0.00
	module 12	1	3.08	8.61	1.83	1.22
Spent fuel pit	module 13	1	5.90	14.12	2.97	2.24
	module 14	2	7.30	14.12	3.12	2.03
	module 15	1	7.35	14.12	2.97	2.24
	module 16	8	4.17	14.12	3.05	0.00
	module 17	3	32.61	12.19	3.45	0.00
Total liner modules		**36**	**1577**			

Polar Crane Modules					
Module Location/Building	**Module Type**	**Qty**	**Wt (te)**	**L'th (m)**	**W'th (m)**
Containment	support steel	5	123.40	25.90	21.33
	box girder	9	54.42	18.30	8.15
Total polar crane modules		**14**	**1107**		

Mechanical Modules					
Module Location/Building	**Module Type**	**Qty**	**Wt (te)**	**L'th (m)**	**W'th (m)**
Annulus	sump 1	6	0.55	1.22	0.91
	demineraliser – level i	1	1.81	3.05	2.44
	demineralizer – level ii	3	0.91	6.10	3.05
	demineralizer – level iii	5	0.68	14.63	3.05
	filter – level i	2	0.45	2.44	2.13
	filter – level ii	3	0.45	4.60	2.44
	filter – level iii	5	0.45	14.63	2.44
	sump 2	2	0.55	1.22	0.91
	sump 3	1	0.54	1.22	0.91
Fuel	demineralizer – level i	1	1.81	2.44	2.44
	demineralizer – level ii	4	0.91	6.10	4.60
	filter – level i	2	0.45	2.44	2.13
	filter – level ii	4	0.91	2.44	2.13
	sump	1	0.55	1.22	0.91

	demineralizer – level i	1	1.81	2.44	2.44
	demineralizer – level ii	4	0.91	6.10	4.60
	filter – level i	2	0.45	2.44	2.13
	filter – level ii	4	0.91	2.44	2.13
	sump	3	0.55	1.22	0.91
Turbine	moisture separator/reheater	4	181.44	19.80	7.62
	feedwater pump & turbine	3	45.36	9.14	3.81
	condensate polishing module 1	1	9.53	2.87	2.77
	module 2	1	6.35	2.10	2.03
	module 3	1	8.62	2.72	2.44
	module 4	1	1.18	2.64	1.52
	module 5	1	1.41	3.56	1.52
	module 6	1	2.27	2.57	1.02
	module 7	1	1.63	2.36	2.34
	module 8	1	1.45	3.05	1.52
	module 9	1	1.34	1.83	1.83
Main Condenser Heat Rejection	condenser tube bundle	2	27.21	18.30	4.90
	condenser steam inlet assembly	1	27.21	18.30	9.75
	condenser water boxes	4	27.21	3.70	2.74
Miscellaneous Equipment	miscellaneous tanks	10	27.20	9.14	9.14
Annulus	tanks – auxiliary feedwater	1	45.40	10.70	10.70
	tanks – refuelling water storage	1	99.80	11.30	11.30
	main steam piping (151)	1	22.00	9.34	2.44
	reactor plant service water piping (254)	1	4.78	9.81	2.97
	reactor plant component cooling water piping (258)	1	5.42	9.20	5.60
	reactor plant component cooling water piping (262)	1	15.10	8.00	7.42
	decay heat removal piping (264)	1	6.44	5.49	2.70
	containment spray piping (294)	1	1.59	13.35	10.30
	decay heat removal piping (342)	1	10.90	16.72	8.69
	reactor plant component cooling water piping (390 A)	1	1.84	5.28	3.07
	reactor plant component cooling water piping (390 B)	1	1.78	16.94	9.57
	reactor plant component cooling water piping (390 C)	1	1.16	16.50	5.28
	reactor coolant pipe (391)	1	7.60	5.33	3.66
	pipe racks	39	31.75	27.40	3.39
Containment	primary coolant piping (370)	1	47.26	21.58	7.09
	main steam piping (410)	1	24.40	9.72	3.84
Total mechanical modules		**141**	**2931**		

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APPENDIX III

III.1. EMWG COA Structure

Direct Cost Account # and Account Name		
21		**Structures + Improvements**
	211	Yardwork
	212	Reactor Containment Building
	213	Turbine Room + Heater Bay
	214	Security Building
	215	Primary Auxiliary Building + Tunnels
	216	Waste Process Building
	217	Fuel Storage Building
	218a	Control Room/Diesel-Generator Building
	218b	Administration + Service Building
	218d	Fire Pump House (including Foundations)
	218e	Emergency Feed Pump Building
	218f	Manway Tunnels
	218g	Electrical Tunnels
	218h	Non-Essential Switchgear Building
	218j	Main Steam + Feedwater Pipe Enclosure
	218k	Pipe Tunnels
	218l	Technical Support Centre
	218p	Contain EQ Hatch Missile Shield
	218s	Waste Water Treatment
	218t	Ultimate Heat Sink Structure
	218v	Control Room Emerg Air Intake Structure
22		**Reactor Plant Equipment**
	220a	Nuclear Steam Supply (NSSS)
	220b	NSSS Options
	221	Reactor Equipment
	222	Main Heat Transfer Export System
	223	Safeguards System
	224	Radwaste Processing
	225	Fuel Handling + Storage
	226	Other Reactor Plant Equipment
	227	Reactor Instrumentation + Control
	228	Reactor Plant Miscellaneous Items
23		**Turbine Plant Equipment**
	231	Turbine Generator
	233	Condensing Systems
	234	Feed Heating System
	235	Other Turbine Plant Equip
	236	Instrumentation + Control
	237	Turbine Plant Miscellaneous Items
24		**Electric Plant Equipment**
	241	Switchgear
	242	Station Service Equipment
	243	Switchboards
	244	Protective Equipment
	245	Electrical Structures + Wiring
	246	Power & Control Wiring
25		**Miscellaneous Plant Equipment**
	251	Transportation & Lift Equipment
	252	Air, Water + Steam Service Systems
	253	Communications Equipment
	254	Furnishings + Fixtures
	255	Wastewater Treatment Equip
26		**Main Condenser Heat Rejection Syste**
	261	Structures
	262	Mechanical Equipment
Indirect Cost Account # and Account Name		
91		**Construction Services**
	911	Temporary Construction Facilities
	912	Construction Tools & Equipment
	913	Payroll Insurance & Taxes
	914	Permits, Insurance, & Local Taxes
	915	Transportation
92		**Home Office Engineering & Service**
	921	Home Office Services
	922	Home Office Q/A
	923	Home Office Construction Management
93		**Field Office Engineering & Service**
	931	Field Office Expenses
	932	Field Job Supervisions
	933	Field QA
	934	Plant Startup & Test

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APPENDIX IV

IV.1. Road Transport Limitations

Since all regulatory road limits are gross weights and dimensions, a reference lorry is defined to obtain the maximum module weight and geometry. A 6-axle articulated reference vehicle is assumed, since the restrictions on articulated truck and trailers are slightly more conservative than for road train configurations.

Vehicle tare weight: 15.9 te

Trailer length: 13.6 m, with 2.9 m allowed for the cab [163]

Table A.IV.1. C&U road transport limitations [164]. Falls within STGO Category 1 limits.

Weight	Maximum vehicle weight = 44 te (gross)*
Length	Individual truck length = 12m Articulated truck and trailer length = 16.5m Road trains = 18.75m (maximum)
Width	Maximum width = 2.55m
Height	No limit, but if vehicle height exceeds 3 m a sign should be displayed in the vehicle windscreen Height is practically limited to 4.95m by most bridges in the UK

* In the EU maximum gross vehicle weight is 40 te

Table A.IV.2. STGO and Special Order limitations for AILs and non-C&U loads [165]

Weight

STGO Category 2 Gross weight exceeds C&U up to 80 te	2 days notice to RBA
STGO Category 3 Gross weight between 80 te – 150 te	2 days notice to Police; 5 days notice to RBA
Special Order Gross weight > 150 tons	8 weeks notice to HE; 5 days notice to Police & RBA

Width

STGO Category 2 Net width between 3.0 m – 5.0 m	2 days notice to Police
STGO Category 3 Net width between 5.0 m – 6.1 m	2 days notice to Police; HE Form VR1
Special Order Net width > 6.1 m	8 weeks notice to HE; 5 days notice to Police & RBA

Length

STGO Category 2 Net length > 18.75 m (up to 30.0 m)	2 days notice to Police
STGO Category 3 Net length of 2 vehicle-combo > 25.9 m (up to 30.0 m)	2 days notice to Police
Special Order Net length > 30.0 m	8 weeks notice to HE; 5 days notice to Police and RBA

IV.2. Impact of MDF on Module Numbers

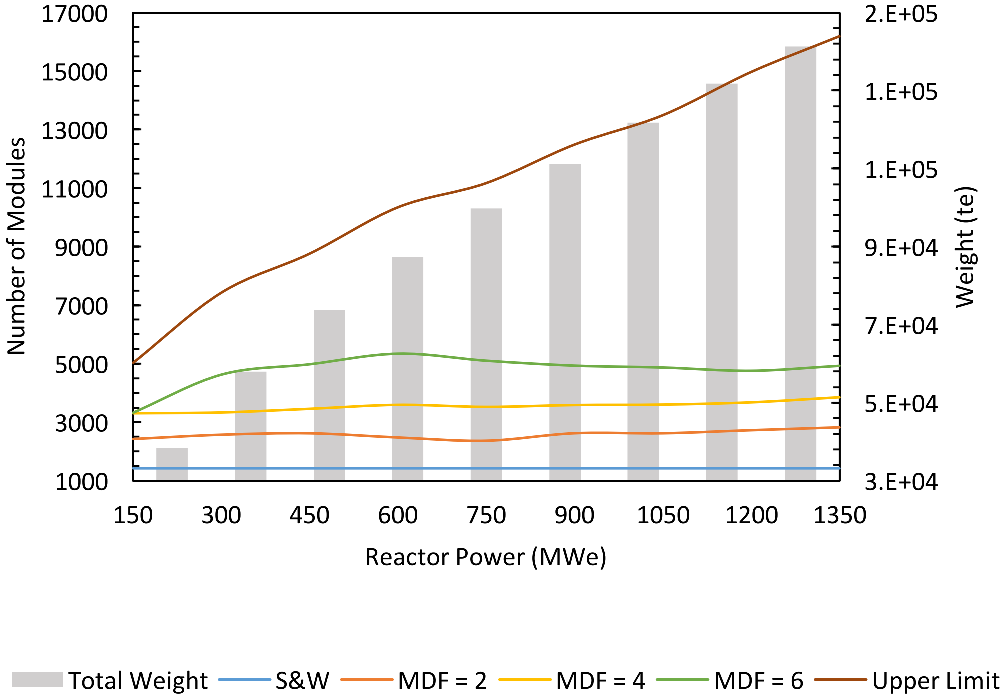

Figure A.IV.1. Total number of modules vs reactor power for varying MDF (shown on the primary vertical axis). The total weight of modules is shown in shaded bars and varies with reactor power but not MDF (shown on the secondary vertical axis).

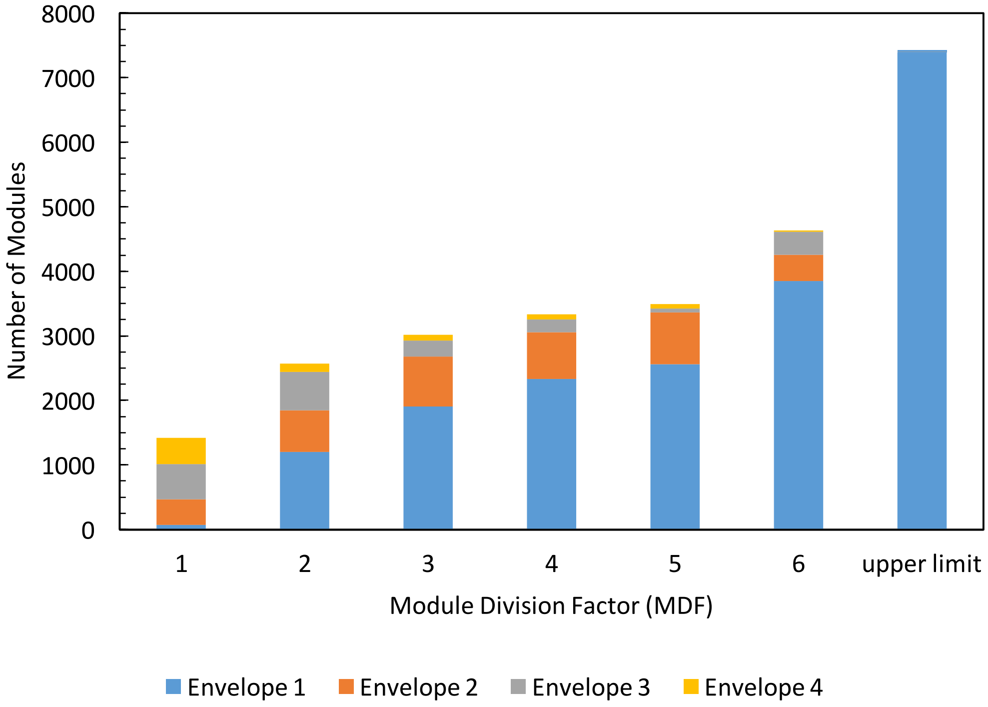

Figure A.IV.2. Number of modules in each Transport Envelope vs MDF for a 300 MWe SMR.

IV.3. Maximum Degree of Modularisation

Table A.IV.3. DoM$_{max}$ on a module location basis, with subdivision (MDF = 3) and extended transport (x = 0.2) as used in Chapters V and VI.

Reactor Power Module Location	150 MWe	300 MWe	450 MWe	600 MWe	750 MWe	900 MWe	1050 MWe	1200 MWe	1350 MWe
Containment Building	0.09	0.08	0.07	0.07	0.01	0.01	0.01	0.01	0.01
Annulus (Annex) Building	0.98	0.86	0.44	0.21	0.21	0.21	0.20	0.20	0.20
Turbine Building	0.96	0.95	0.94	0.81	0.49	0.22	0.22	0.22	0.22
Diesel Generator Building	1.00	1.00	1.00	0.61	0.61	0.20	0.20	0.20	0.20
Control Building	1.00	1.00	1.00	0.39	0.39	0.39	0.39	0.33	0.20
Fuel Building	1.00	0.98	0.93	0.93	0.93	0.93	0.93	0.79	0.79
Polar Crane Modules	0.55	0.55	0.55	0.09	0.09	0.09	0.09	0.09	0.09
Main Condenser Heat Rejection	1.00	1.00	1.00	0.66	0.66	0.66	0.66	0.66	0.66
Miscellaneous Equipment	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DoM$_{max}$ (weight average)	**0.86**	**0.78**	**0.52**	**0.28**	**0.24**	**0.21**	**0.20**	**0.20**	**0.18**

The S&W module scheme doesn't provide module data for the I&C and/or electric plant systems, although the report says these systems can easily be modularised. In the cost and schedule modelling, therefore, the weight average DoM$_{max}$ is used for for these accounts. However, to reflect the fact that these systems and components are more easily modularisable than the average values would suggest, the DoM$_{max}$ is increased by assuming an additional 50% of the non-transportable weight can be transported and modularised.

This applies to a portion of the Turbine Plant Equipment – specifically the Turbine Generator (Account 231) and Turbine Plant I&C (Account 236) – as well as the Electric Plant Equipment (Account 24) since these systems and components are similar to equipment in the chemical process and shipbuilding industries that is already modularised.

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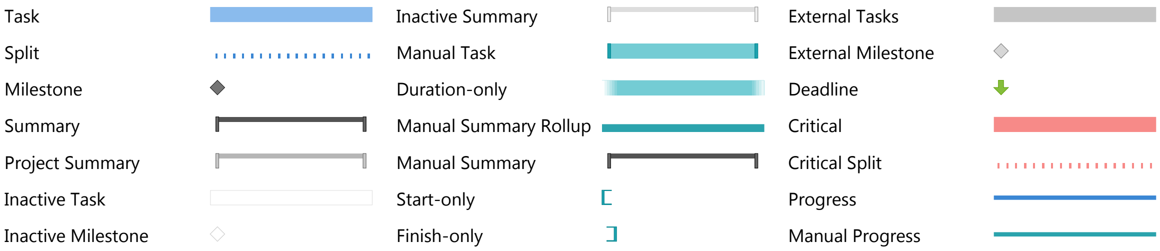
APPENDIX V

This appendix includes Gantt charts from the construction programme scenarios discussed in Section V.4, Chapter V. There are a few important points to make about the following Gantt charts.

- Critical tasks are marked in red on each schedule.
- Specific dates are not shown for each task in order to normalise the results and to aid with comparisons between schedules.
- The construction duration is consistent with the definition used throughout this project; that is, the time between the first pour of structural concrete and commercial operation. Site preparation activities (Account 211) are not included in modularisation and/or construction duration; however, they have been included in the overall schedule plotting to reflect the fact that they are important in the wider context of reactor construction.
- Tasks that have been modularised are indicated by an asterisk (*) beside the left hand end of the relevant bar; to illustrate which construction tasks are included in the different modularisation scenarios.

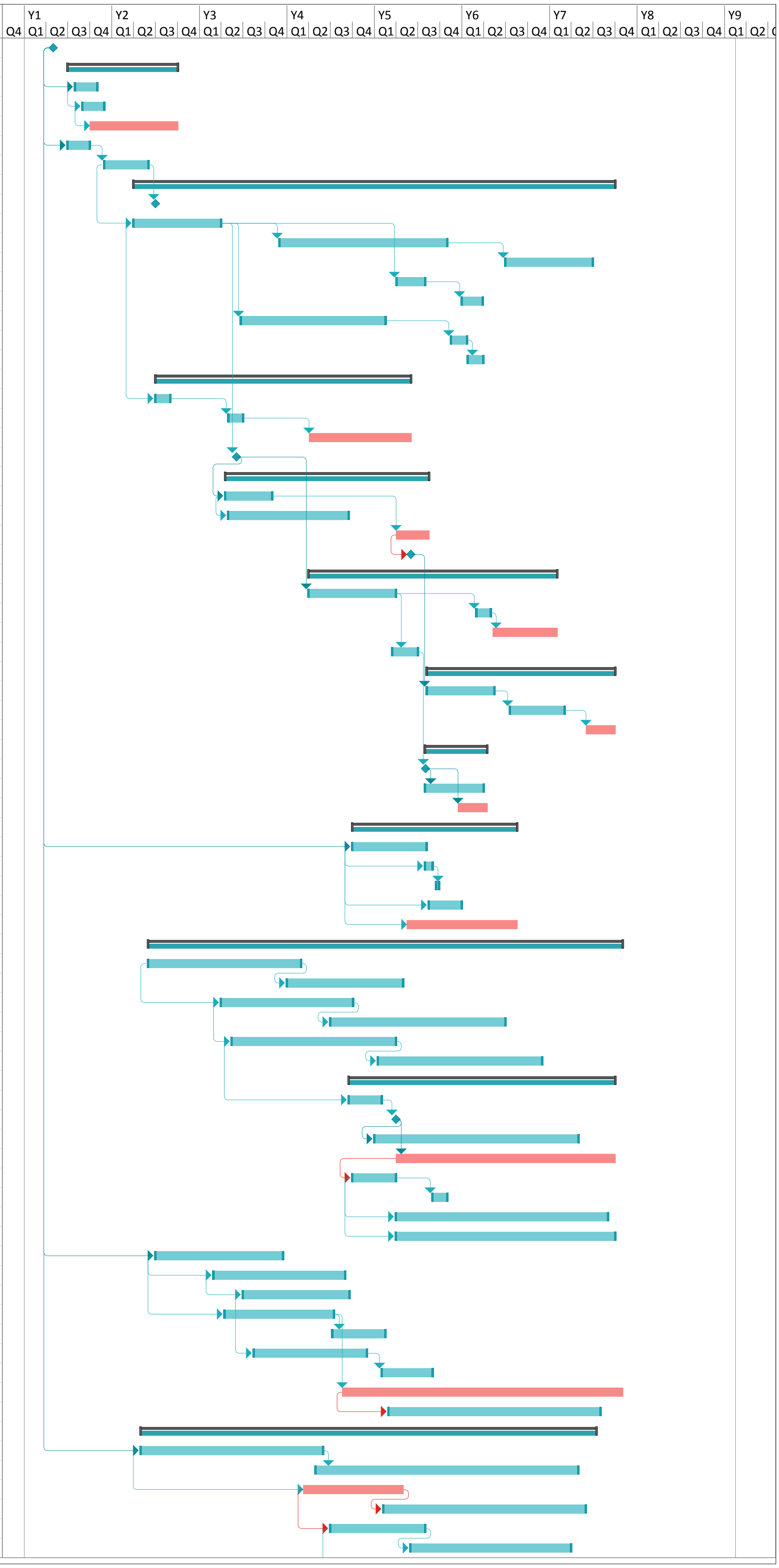
  Some tasks are marked as modular but the durations aren't shorter than the stick-built reference case. This means that, although that particular task is included in the modularisation scheme, it isn't affected by modularisation. For example, the Nuclear Steam Supply (NSSS) system consists of already-modular equipment items, even in stick-built plants.

The legend for all the following Gantt charts is below:

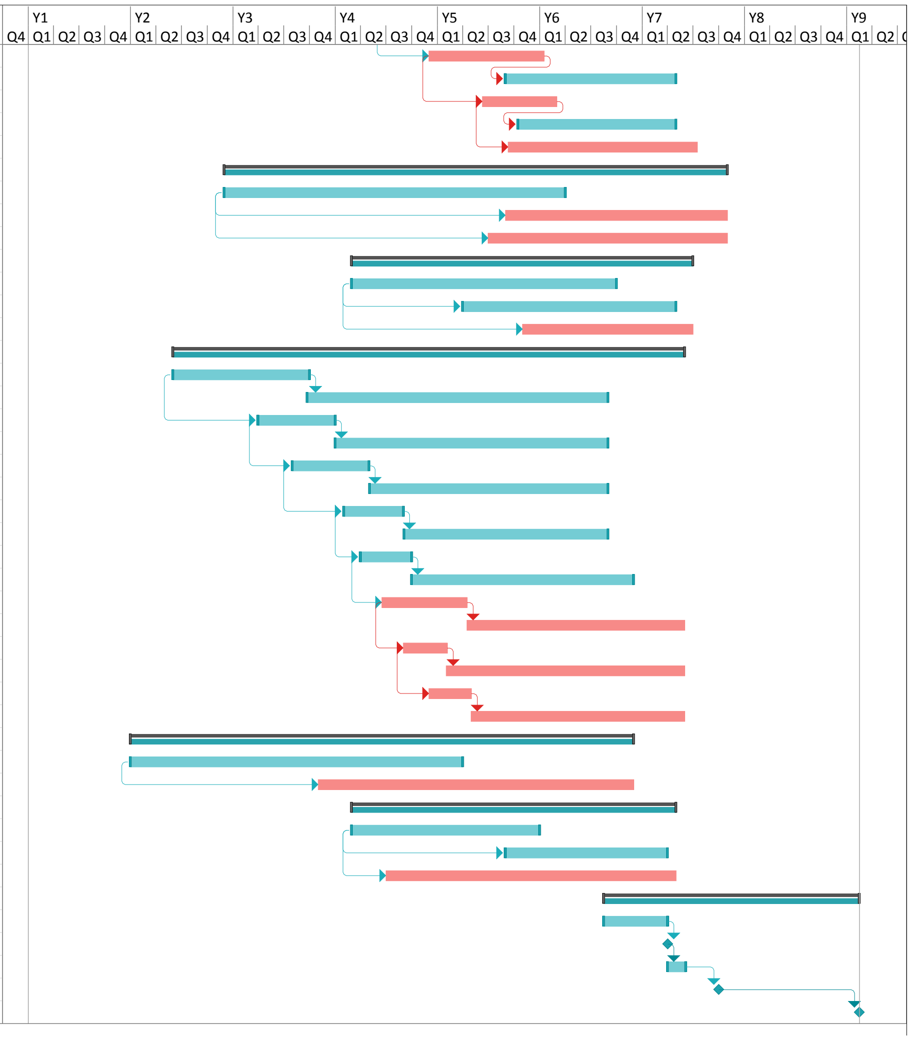


V.1. Stick-Built Reference 1200 MWe LR

ID	Task Name	Days
1	Contract awarded to JLC	
2	**211 Yardwork**	**460**
3	Clear site	93
4	Dewatering	91
5	Bulk excavation	368
6	Diaphragm wall	92
7	Mass concrete & blinding	184
8	**212 Reactor Containment Bldg**	**2010**
9	FPSC Sizewell B	
10	Tendon gallery, keyhole & base slab	365
11	Topping slab & secondary shield wall	700
12	Secondary containment	365
13	Wall to +37.5	119
14	Wall to +39.7	87
15	Primary shield wall	604
16	ISI gallery roof (1)	67
17	ISI gallery roof (2)	65
18	**Refuelling Pond**	**1067**
19	Fuel pond liner erection (1)	62
20	Fuel pond liner erection (2)	61
21	Refuelling pond	426
22	Reactor base pour	
23	**Dome Liner**	**850**
24	Liner base	196
25	Liner barrel	503
26	Dome liner	137
27	Dome liner lift	
28	**Primary Containment**	**1038**
29	Primary containment barrel (1)	365
30	Primary containment barrel (2)	60
31	Pre-stress primary containment	269
32	Polar crane	107
33	**Dome**	**786**
34	Dome concrete	282
35	Dome	228
36	Dome cladding	122
37	**221 Reactor Equipment**	**259**
38	RPV lift	
39	Reactor vessel internals	244
40	Construction access closure	122
41	**220a Nuclear Steam Supply (NSSS)**	**688**
42	NSSS supports & restraints	310
43	NSSS main components (1)	31
44	NSSS main components (2)	12
45	Loop pipes	138
46	Secondary pipework	461
47	**213 Turbine Room + Heater Bay**	**1644**
48	Raft, culverts, retaining walls	638
49	Superstructure	485
50	Turb hall: electrical annexe [E]	551
51	Turb hall: M&E annexe [E]	731
52	Turb hall: electrical annexe [W]	685
53	Turb hall: M&E annexe [W]	685
54	**231 Turbine Generator**	**1951**
55	Cranes	138
56	Access for turbine contractor	
57	TG 1 (incl commissioning)	851
58	TG 2 (incl commissioning)	915
59	Erect roof (1)	182
60	Erect roof (2)	61
61	Plant installation	884
62	Finishes	915
63	Mech annexe: raft & tower [E]	533
64	Mech annexe: raft & towers [centre]	549
65	Mech annexe: raft & tower [W]	445
66	Mech annexe: structure to +26.3 [E]	456
67	Mech annexe: structure above +26.3	221
68	Mech annexe: structure to +26.3 [W]	472
69	Mech annexe: structure above +26.3	212
70	Mech annexe: M&E below +16.2	1171
71	Mech annexe: M&E above +16.2	884
72	**215 Prim Aux Bldg + Tunnels**	**1902**
73	Aux bldg: structure to +6.55	761
74	Aux bldg: M&E below +6.55	1096
75	Aux bldg: structure to +14.47	417
76	Aux bldg: M&E at +6.55	844
77	Aux bldg: structure to +21.13	396
78	Aux bldg: M&E at +14.47	670

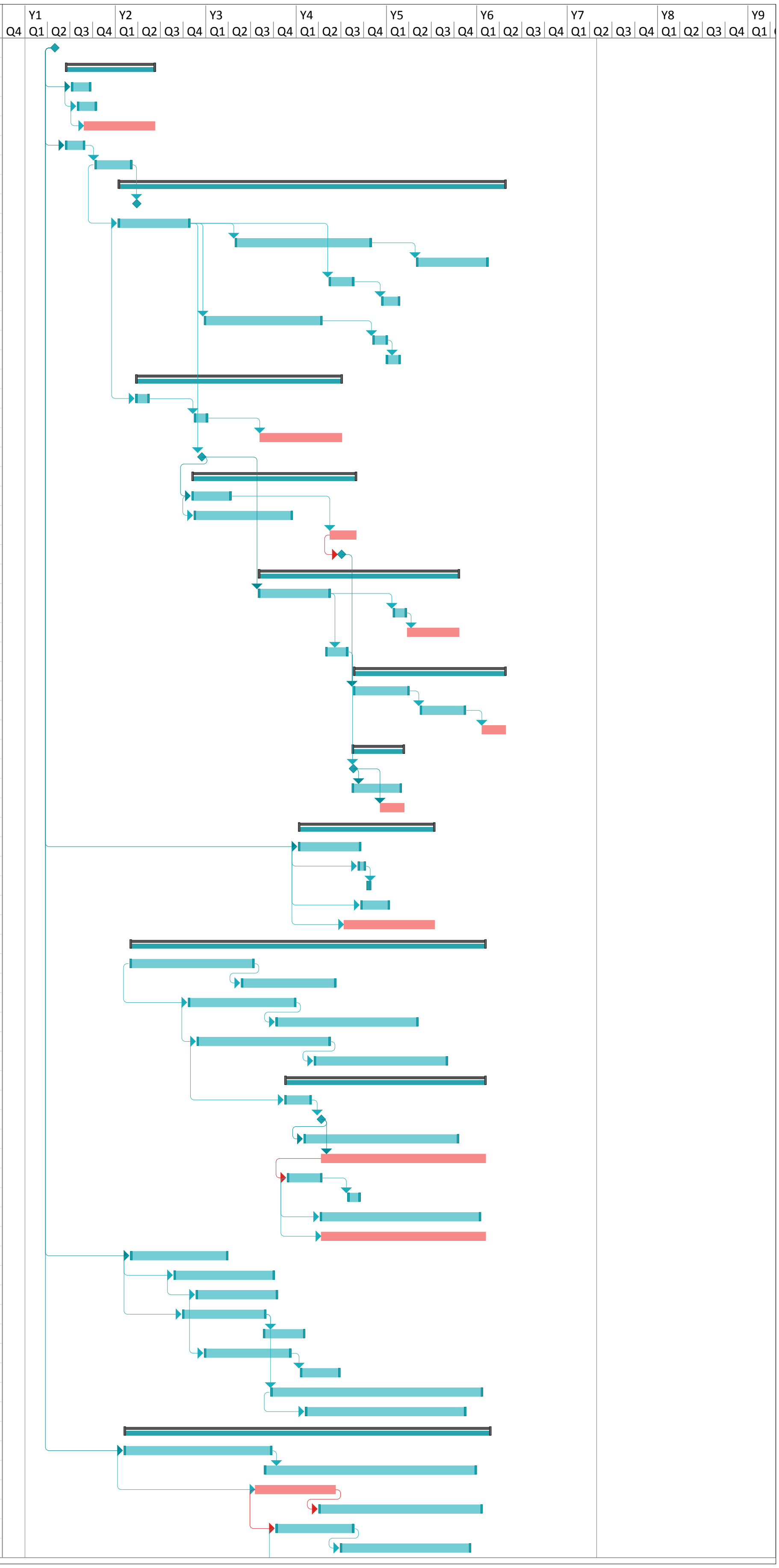


ID	Task Name	Days
79	Aux bldg: structure to +28.87	411
80	Aux bldg: M&E at +21.13	608
81	Aux bldg: structure to +37.33	265
82	Aux bldg: M&E at +28.87	563
83	Aux bldg: M&E steam & feed cell	675
84	**216 Waste Process Building**	**1796**
85	Civil works	1217
86	Plant installation	792
87	Finishes	854
88	**217 Fuel Storage Building**	**1218**
89	Civil works	945
90	Plant installation	761
91	Finishes	608
92	**218a Control Rm/D-G Building**	**1826**
93	Control bldg: structure to +2.77	487
94	Control bldg: M&E below +2.77	1074
95	Control bldg: structure to +6.55	275
96	Control bldg: M&E at +2.77	974
97	Control bldg: structure to +11.23	273
98	Control bldg: M&E at +6.55	851
99	Control bldg: structure to +15.99	212
100	Control bldg: M&E at +11.23	728
101	Control bldg: structure to +21.13	183
102	Control bldg: M&E at +15.99	792
103	Control bldg: structure to +25.99	304
104	Control bldg: M&E at +21.13	777
105	Control bldg: structure to +31.03	156
106	Control bldg: M&E at +25.99	851
107	Control bldg: structure to +37.33	151
108	Control bldg: M&E at +31.03	762
109	**218k Pipe Tunnels**	**1796**
110	Civil works	1186
111	Plant installation	1126
112	**218b Administration + Service Bldg**	**1157**
113	Civil works (ancillary bldgs)	671
114	Plant installation (ancillary bldgs)	578
115	Finishes (ancillary bldgs)	1035
116	**Commissioning**	**912**
117	RV open for flushing	228
118	Cold hydro	
119	Box up	64
120	Load fuel	
121	Commercial operation	

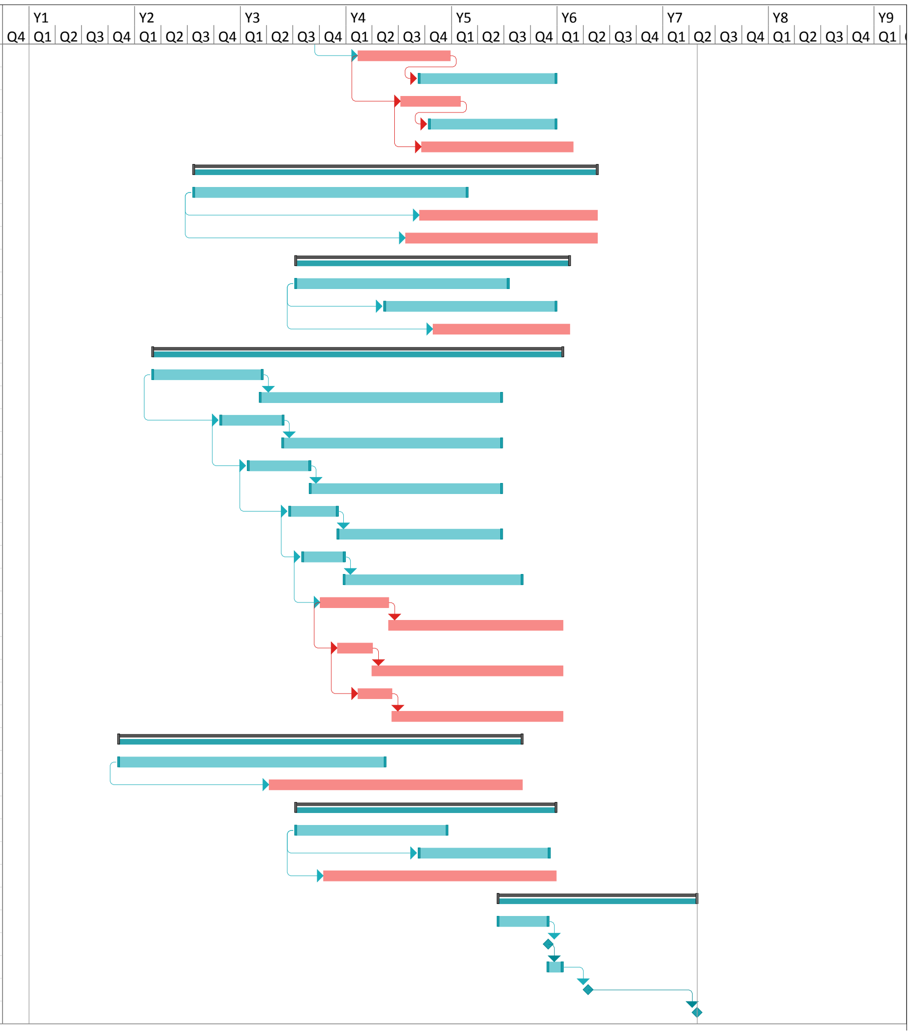


V.2. Stick-Built 300 MWe SMR; Scaling Case II (T = W = 0.4)

ID	Task Name	Days
1	Contract awarded to JLC	
2	**211 Yardwork**	**357**
3	Clear site	72
4	Dewatering	71
5	Bulk excavation	286
6	Diaphragm wall	71
7	Mass concrete & blinding	143
8	**212 Reactor Containment Bldg**	**1562**
9	FPSC Sizewell B	
10	Tendon gallery, keyhole & base slab	284
11	Topping slab & secondary shield walls	544
12	Secondary containment	284
13	Wall to +37.5	92
14	Wall to +39.7	68
15	Primary shield wall	469
16	ISI gallery roof (1)	52
17	ISI gallery roof (2)	50
18	**Refuelling Pond**	**829**
19	Fuel pond liner erection (1)	48
20	Fuel pond liner erection (2)	47
21	Refuelling pond	331
22	Reactor base pour	
23	**Dome Liner**	**660**
24	Liner base	152
25	Liner barrel	391
26	Dome liner	106
27	Dome liner lift	
28	**Primary Containment**	**807**
29	Primary containment barrel (1)	284
30	Primary containment barrel (2)	47
31	Pre-stress primary containment	209
32	Polar crane	83
33	**Dome**	**611**
34	Dome concrete	219
35	Dome	177
36	Dome cladding	95
37	**221 Reactor Equipment**	**205**
38	RPV lift	
39	Reactor vessel internals	193
40	Construction access closure	97
41	**220a Nuclear Steam Supply (NSSS)**	**545**
42	NSSS supports & restraints	246
43	NSSS main components (1)	25
44	NSSS main components (2)	10
45	Loop pipes	109
46	Secondary pipework	365
47	**213 Turbine Room + Heater Bay**	**1433**
48	Raft, culverts, retaining walls	496
49	Superstructure	377
50	Turb hall: electrical annexe [E]	428
51	Turb hall: M&E annexe [E]	568
52	Turb hall: electrical annexe [W]	532
53	Turb hall: M&E annexe [W]	532
54	**231 Turbine Generator**	**807**
55	Cranes	100
56	Access for turbine contractor	
57	TG 1 (incl commissioning)	618
58	TG 2 (incl commissioning)	664
59	Erect roof (1)	132
60	Erect roof (2)	44
61	Plant installation	642
62	Finishes	664
63	Mech annexe: raft & tower [E]	387
64	Mech annexe: raft & towers [centre]	399
65	Mech annexe: raft & tower [W]	323
66	Mech annexe: structure to +26.3 [E]	331
67	Mech annexe: structure above +26.3	161
68	Mech annexe: structure to +26.3 [W]	343
69	Mech annexe: structure above +26.3	154
70	Mech annexe: M&E below +16.2	850
71	Mech annexe: M&E above +16.2	642
72	**215 Prim Aux Bldg + Tunnels**	**1477**
73	Aux bldg: structure to +6.55	591
74	Aux bldg: M&E below +6.55	851
75	Aux bldg: structure to +14.47	324
76	Aux bldg: M&E at +6.55	656
77	Aux bldg: structure to +21.13	308
78	Aux bldg: M&E at +14.47	520



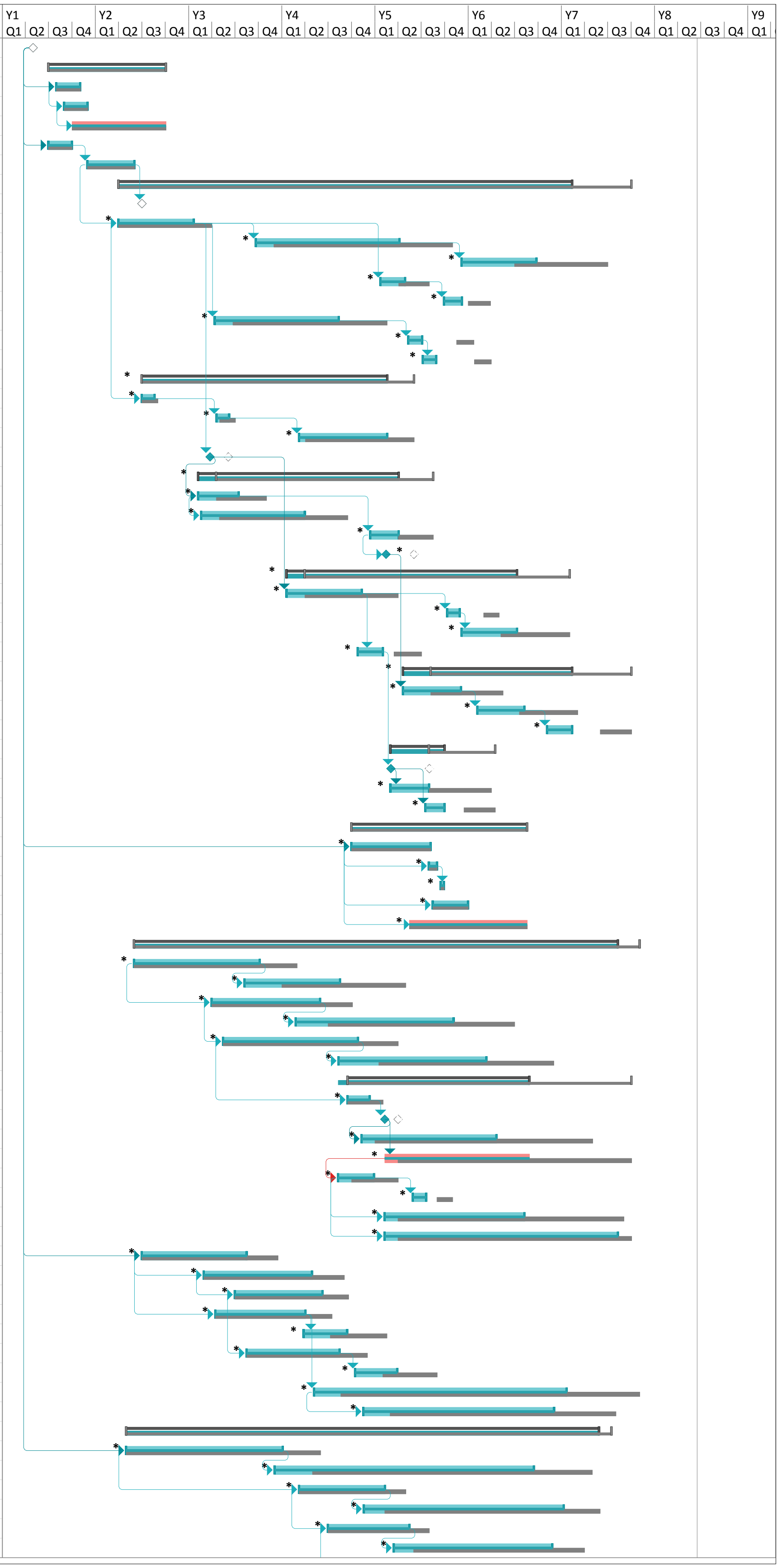
ID	Task Name	Days
79	Aux bldg: structure to +28.87	319
80	Aux bldg: M&E at +21.13	472
81	Aux bldg: structure to +37.33	206
82	Aux bldg: M&E at +28.87	437
83	Aux bldg: M&E steam & feed cell	524
84	**216 Waste Process Building**	**1395**
85	Civil works	945
86	Plant installation	615
87	Finishes	663
88	**217 Fuel Storage Building**	**946**
89	Civil works	734
90	Plant installation	591
91	Finishes	472
92	**218a Control Rm/D-G Building**	**1418**
93	Control bldg: structure to +2.77	378
94	Control bldg: M&E below +2.77	834
95	Control bldg: structure to +6.55	214
96	Control bldg: M&E at +2.77	757
97	Control bldg: structure to +11.23	212
98	Control bldg: M&E at +6.55	661
99	Control bldg: structure to +15.99	165
100	Control bldg: M&E at +11.23	565
101	Control bldg: structure to +21.13	142
102	Control bldg: M&E at +15.99	615
103	Control bldg: structure to +25.99	236
104	Control bldg: M&E at +21.13	604
105	Control bldg: structure to +31.03	121
106	Control bldg: M&E at +25.99	661
107	Control bldg: structure to +37.33	117
108	Control bldg: M&E at +31.03	592
109	**218k Pipe Tunnels**	**1395**
110	Civil works	921
111	Plant installation	875
112	**218b Administration + Service Bldg**	**899**
113	Civil works (ancillary bldgs)	521
114	Plant installation (ancillary bldgs)	449
115	Finishes (ancillary bldgs)	804
116	**Commissioning**	**687**
117	RV open for flushing	172
118	Cold hydro	
119	Box up	48
120	Load fuel	
121	Commercial operation	



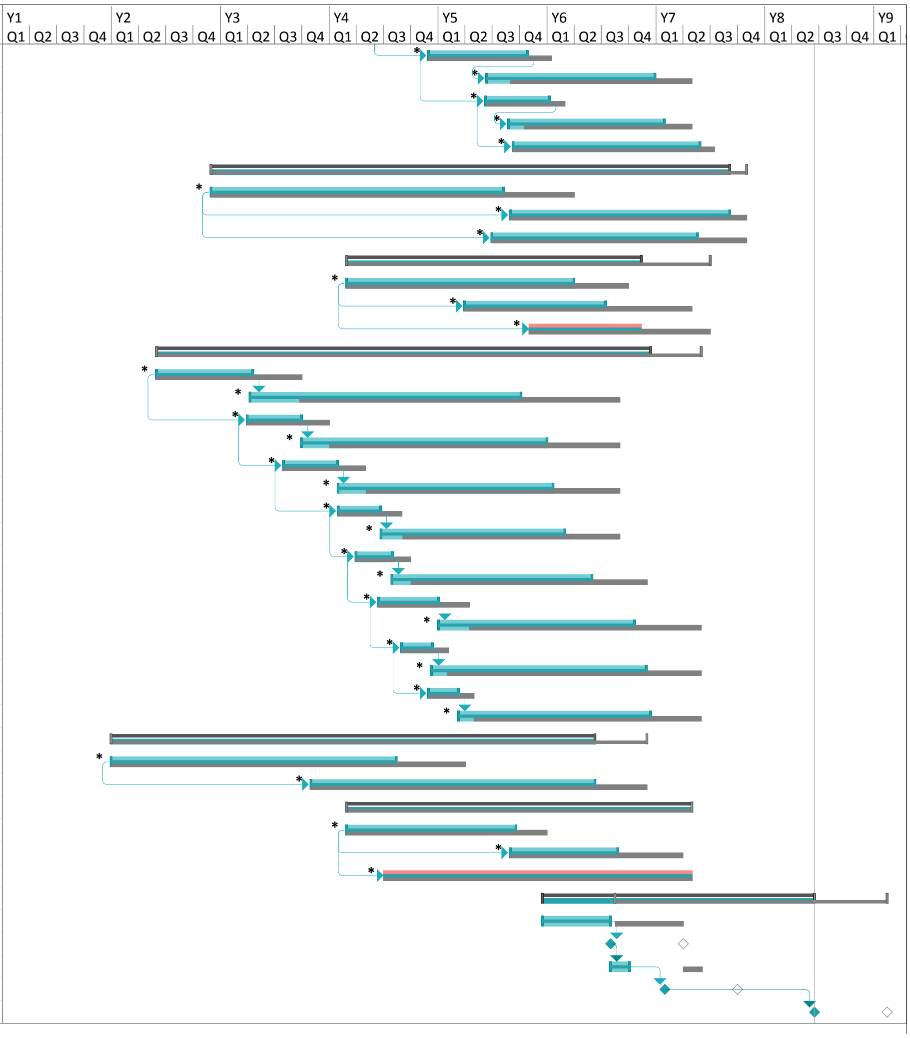
V.3. Full Modular 1200 MWe LR; $DoM_{input} = 0.4$

Grey bars indicate the schedule of a stick-built 1200 MWe reference LR.

ID	Task Name	Days
1	Contract awarded to JLC	
2	211 Yardwork	460
3	Clear site	93
4	Dewatering	91
5	Bulk excavation	368
6	Diaphragm wall	92
7	Mass concrete & blinding	184
8	212 Reactor Containment Bldg	1790
9	FPSC Sizewell B	
10	Tendon gallery, keyhole & base slab	296
11	Topping slab & secondary shield walls	568
12	Secondary containment	296
13	Wall to +37.5	97
14	Wall to +39.7	71
15	Primary shield wall	490
16	ISI gallery roof (1)	54
17	ISI gallery roof (2)	53
18	Refuelling Pond	978
19	Fuel pond liner erection (1)	52
20	Fuel pond liner erection (2)	51
21	Refuelling pond	357
22	Reactor base pour	
23	Dome Liner	796
24	Liner base	164
25	Liner barrel	421
26	Dome liner	115
27	Dome liner lift	
28	Primary Containment	907
29	Primary containment barrel (1)	296
30	Primary containment barrel (2)	49
31	Pre-stress primary containment	218
32	Polar crane	98
33	Dome	667
34	Dome concrete	229
35	Dome	185
36	Dome cladding	99
37	221 Reactor Equipment	213
38	RPV lift	
39	Reactor vessel internals	151
40	Construction access closure	76
41	220a Nuclear Steam Supply (NSSS)	688
42	NSSS supports & restraints	310
43	NSSS main components (1)	31
44	NSSS main components (2)	12
45	Loop pipes	138
46	Secondary pipework	461
47	213 Turbine Room + Heater Bay	1896
48	Raft, culverts, retaining walls	492
49	Superstructure	374
50	Turb hall: electrical annexe [E]	425
51	Turb hall: M&E annexe [E]	622
52	Turb hall: electrical annexe [W]	529
53	Turb hall: M&E annexe [W]	583
54	231 Turbine Generator	712
55	Cranes	86
56	Access for turbine contractor	
57	TG 1 (incl commissioning)	528
58	TG 2 (incl commissioning)	567
59	Erect roof (1)	140
60	Erect roof (2)	52
61	Plant installation	548
62	Finishes	915
63	Mech annexe: raft & tower [E]	411
64	Mech annexe: raft & towers [centre]	424
65	Mech annexe: raft & tower [W]	343
66	Mech annexe: structure to +26.3 [E]	352
67	Mech annexe: structure above +26.3	171
68	Mech annexe: structure to +26.3 [W]	364
69	Mech annexe: structure above +26.3	164
70	Mech annexe: M&E below +16.2	995
71	Mech annexe: M&E above +16.2	752
72	215 Prim Aux Bldg + Tunnels	1860
73	Aux bldg: structure to +6.55	613
74	Aux bldg: M&E below +6.55	1028
75	Aux bldg: structure to +14.47	336
76	Aux bldg: M&E at +6.55	792
77	Aux bldg: structure to +21.13	319
78	Aux bldg: M&E at +14.47	628



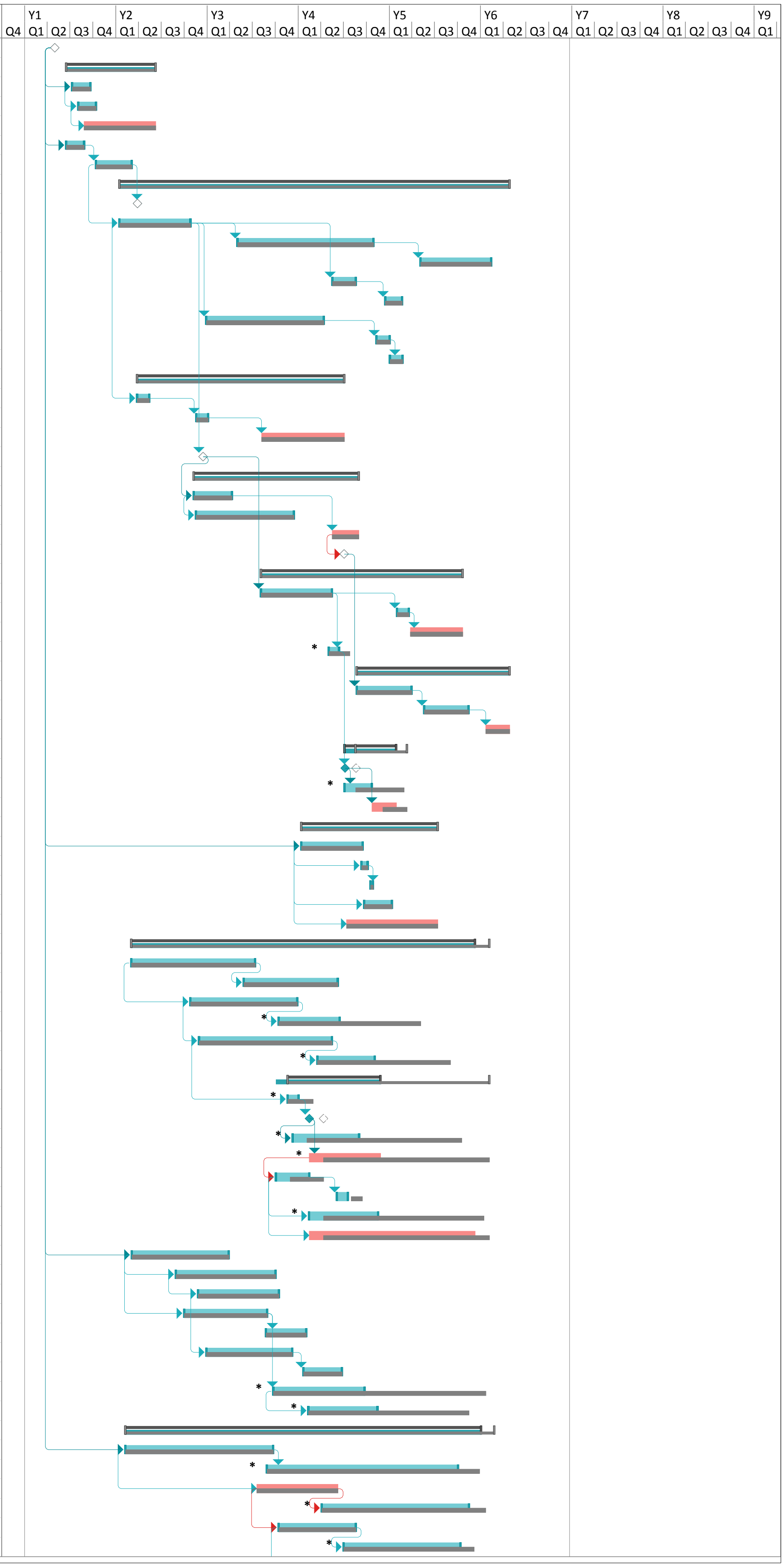
ID	Task Name	Days
79	Aux bldg: structure to +28.87	331
80	Aux bldg: M&E at +21.13	570
81	Aux bldg: structure to +37.33	214
82	Aux bldg: M&E at +28.87	528
83	Aux bldg: M&E steam & feed cell	633
84	216 Waste Process Building	1747
85	Civil works	981
86	Plant installation	743
87	Finishes	689
88	217 Fuel Storage Building	987
89	Civil works	767
90	Plant installation	472
91	Finishes	377
92	218a Control Rm/D-G Building	1664
93	Control bldg: structure to +2.77	343
94	Control bldg: M&E below +2.77	909
95	Control bldg: structure to +6.55	194
96	Control bldg: M&E at +2.77	825
97	Control bldg: structure to +11.23	192
98	Control bldg: M&E at +6.55	720
99	Control bldg: structure to +15.99	149
100	Control bldg: M&E at +11.23	616
101	Control bldg: structure to +21.13	129
102	Control bldg: M&E at +15.99	671
103	Control bldg: structure to +25.99	214
104	Control bldg: M&E at +21.13	658
105	Control bldg: structure to +31.03	110
106	Control bldg: M&E at +25.99	720
107	Control bldg: structure to +37.33	106
108	Control bldg: M&E at +31.03	645
109	218k Pipe Tunnels	1623
110	Civil works	962
111	Plant installation	953
112	218b Administration + Service Bldg	1157
113	Civil works (ancillary bldgs)	568
114	Plant installation (ancillary bldgs)	359
115	Finishes (ancillary bldgs)	1035
116	Commissioning	912
117	RV open for flushing	228
118	Cold hydro	
119	Box up	64
120	Load fuel	
121	Commercial operation	



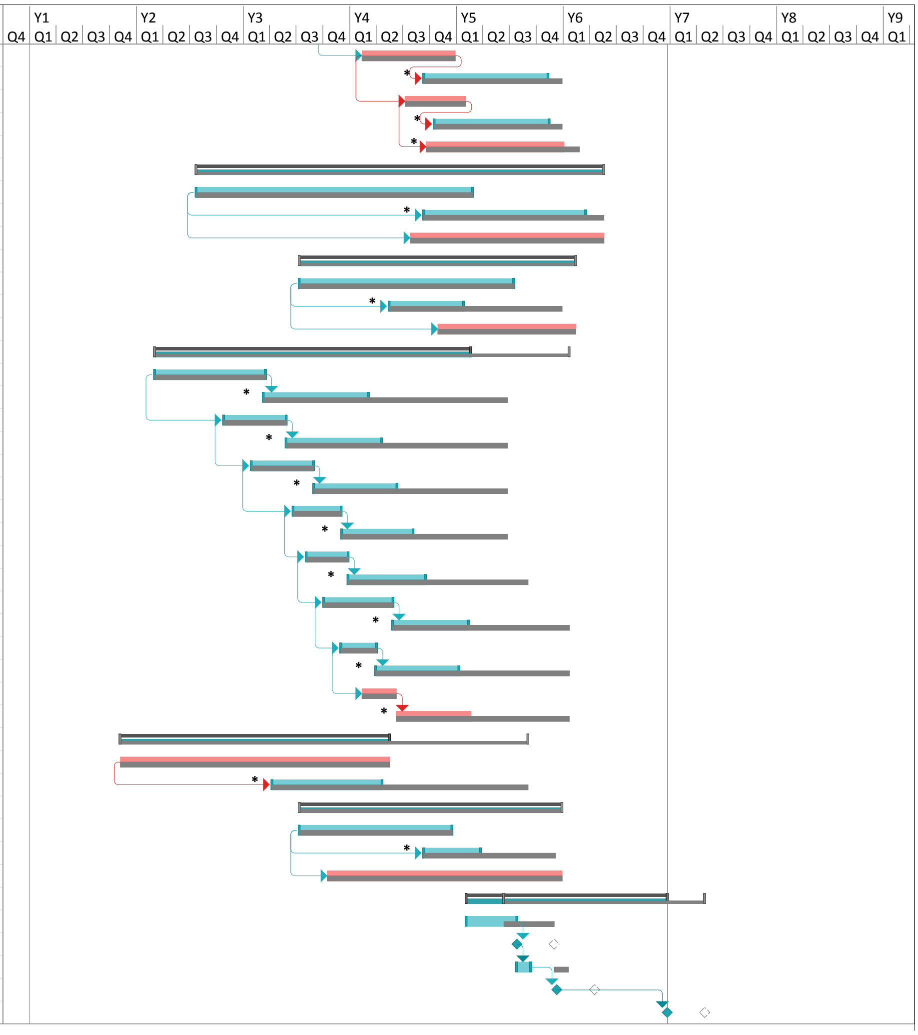
V.4. Low Modular 300 MWe SMR; $DoM_{input} = 0.6$; Scaling Case II (T = W = 0.4)

Grey bars indicate the schedule of a stick-built 300 MWe reference SMR.

ID	Task Name	Days
1	Contract awarded to JLC	
2	211 Yardwork	357
3	Clear site	72
4	Dewatering	71
5	Bulk excavation	286
6	Diaphragm wall	71
7	Mass concrete & blinding	143
8	212 Reactor Containment Bldg	1562
9	FPSC Sizewell B	
10	Tendon gallery, keyhole & base slab	284
11	Topping slab & secondary shield wal	544
12	Secondary containment	284
13	Wall to +37.5	92
14	Wall to +39.7	68
15	Primary shield wall	469
16	ISI gallery roof (1)	52
17	ISI gallery roof (2)	50
18	Refuelling Pond	829
19	Fuel pond liner erection (1)	48
20	Fuel pond liner erection (2)	47
21	Refuelling pond	331
22	Reactor base pour	
23	Dome Liner	660
24	Liner base	152
25	Liner barrel	391
26	Dome liner	106
27	Dome liner lift	
28	Primary Containment	807
29	Primary containment barrel (1)	284
30	Primary containment barrel (2)	47
31	Pre-stress primary containment	209
32	Polar crane	39
33	Dome	611
34	Dome concrete	219
35	Dome	177
36	Dome cladding	95
37	221 Reactor Equipment	206
38	RPV lift	
39	Reactor vessel internals	108
40	Construction access closure	97
41	220a Nuclear Steam Supply (NSSS)	545
42	NSSS supports & restraints	246
43	NSSS main components (1)	25
44	NSSS main components (2)	10
45	Loop pipes	109
46	Secondary pipework	365
47	213 Turbine Room + Heater Bay	974
48	Raft, culverts, retaining walls	496
49	Superstructure	377
50	Turb hall: electrical annexe [E]	428
51	Turb hall: M&E annexe [E]	244
52	Turb hall: electrical annexe [W]	532
53	Turb hall: M&E annexe [W]	229
54	231 Turbine Generator	1374
55	Cranes	43
56	Access for turbine contractor	
57	TG 1 (incl commissioning)	266
58	TG 2 (incl commissioning)	286
59	Erect roof (1)	132
60	Erect roof (2)	44
61	Plant installation	276
62	Finishes	664
63	Mech annexe: raft & tower [E]	387
64	Mech annexe: raft & towers [centre	399
65	Mech annexe: raft & tower [W]	323
66	Mech annexe: structure to +26.3 [E]	331
67	Mech annexe: structure above +26.:	161
68	Mech annexe: structure to +26.3 [W	343
69	Mech annexe: structure above +26.:	154
70	Mech annexe: M&E below +16.2	366
71	Mech annexe: M&E above +16.2	276
72	215 Prim Aux Bldg + Tunnels	1424
73	Aux bldg: structure to +6.55	591
74	Aux bldg: M&E below +6.55	765
75	Aux bldg: structure to +14.47	324
76	Aux bldg: M&E at +6.55	589
77	Aux bldg: structure to +21.13	308
78	Aux bldg: M&E at +14.47	468



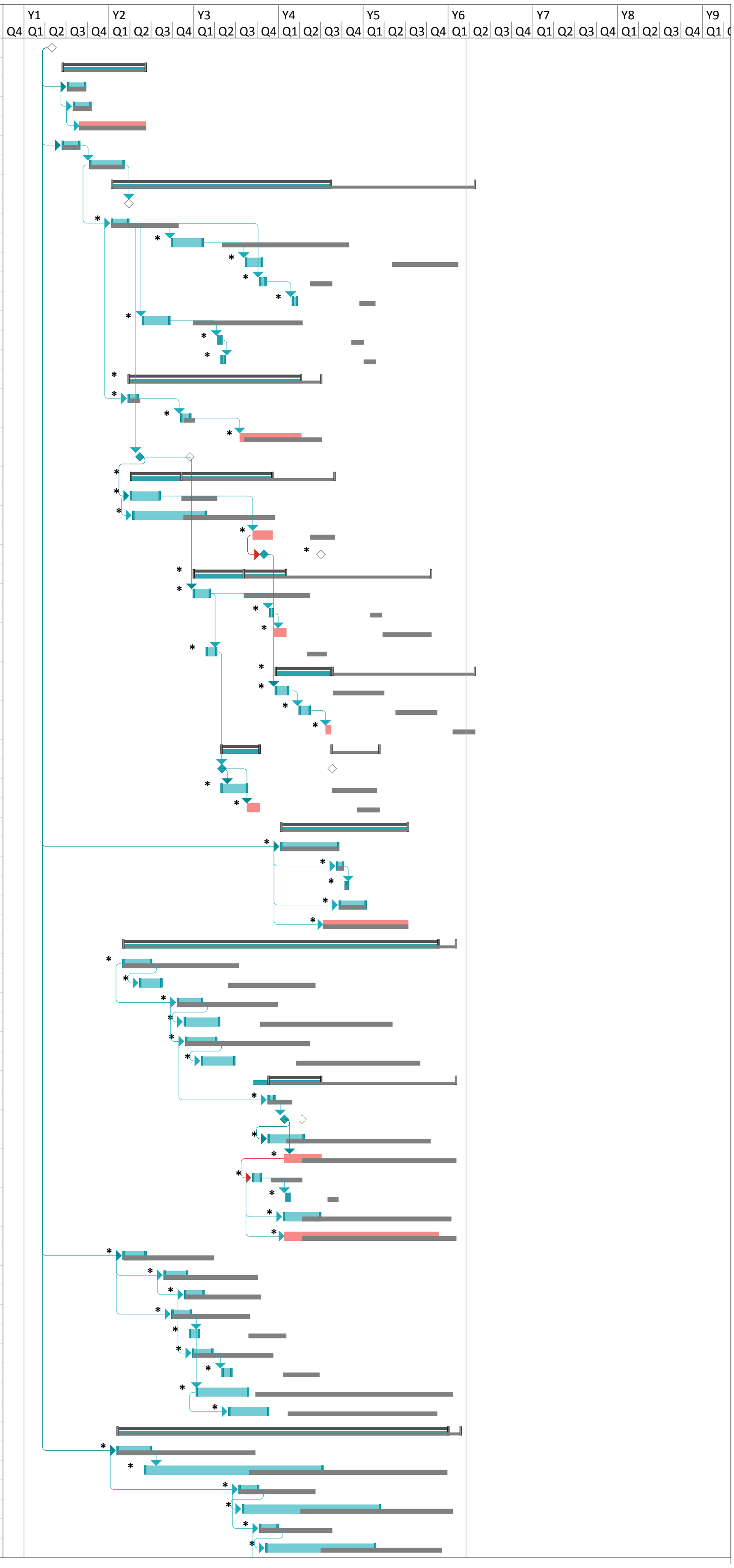
ID	Task Name	Days
79	Aux bldg: structure to +28.87	319
80	Aux bldg: M&E at +21.13	424
81	Aux bldg: structure to +37.33	206
82	Aux bldg: M&E at +28.87	393
83	Aux bldg: M&E steam & feed cell	471
84	216 Waste Process Building	1395
85	Civil works	945
86	Plant installation	553
87	Finishes	663
88	217 Fuel Storage Building	946
89	Civil works	734
90	Plant installation	254
91	Finishes	472
92	218a Control Rm/D-G Building	1081
93	Control bldg: structure to +2.77	378
94	Control bldg: M&E below +2.77	359
95	Control bldg: structure to +6.55	214
96	Control bldg: M&E at +2.77	325
97	Control bldg: structure to +11.23	212
98	Control bldg: M&E at +6.55	284
99	Control bldg: structure to +15.99	165
100	Control bldg: M&E at +11.23	243
101	Control bldg: structure to +21.13	142
102	Control bldg: M&E at +15.99	265
103	Control bldg: structure to +25.99	236
104	Control bldg: M&E at +21.13	260
105	Control bldg: structure to +31.03	121
106	Control bldg: M&E at +25.99	284
107	Control bldg: structure to +37.33	117
108	Control bldg: M&E at +31.03	254
109	218k Pipe Tunnels	921
110	Civil works	921
111	Plant installation	376
112	218b Administration + Service Bldg	899
113	Civil works (ancillary bldgs)	521
114	Plant installation (ancillary bldgs)	193
115	Finishes (ancillary bldgs)	804
116	Commissioning	687
117	RV open for flushing	172
118	Cold hydro	
119	Box up	48
120	Load fuel	
121	Commercial operation	



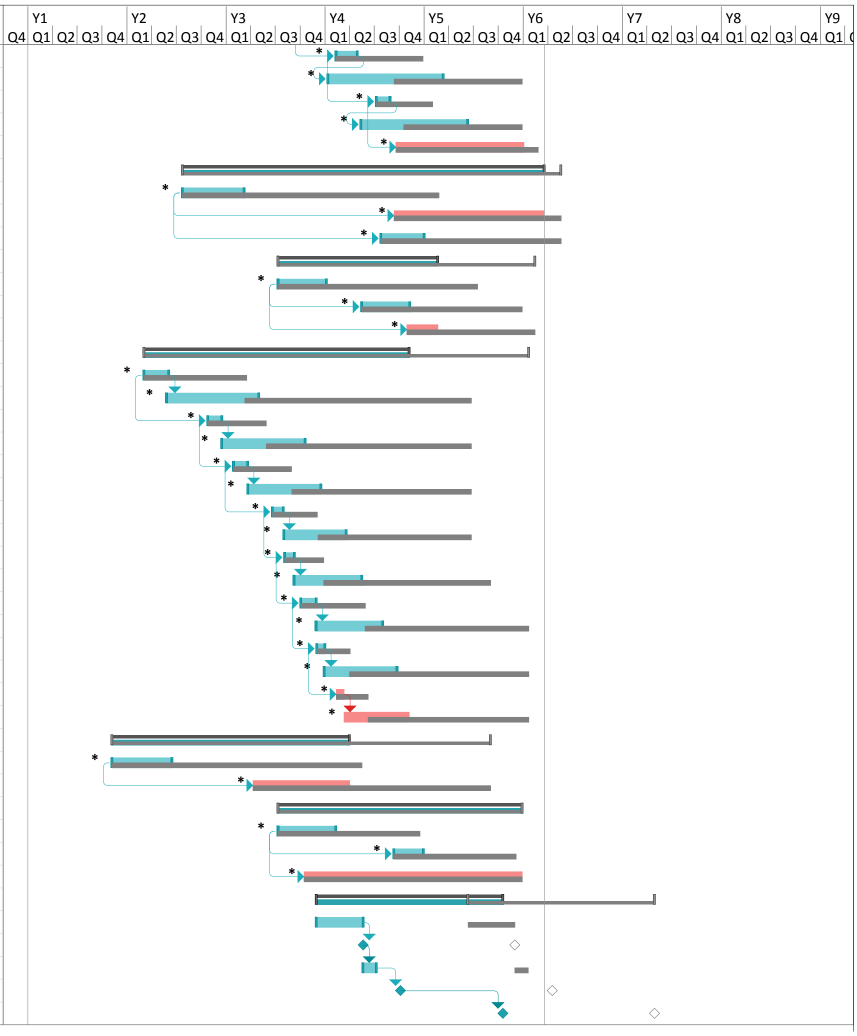
V.5. Full Modular 300 MWe SMR; DoM$_{input}$ = 0.8; Scaling Case II (T = W = 0.4)

Grey bars indicate the schedule of a stick-built 300 MWe reference SMR.

ID	Task Name	Days
1	Contract awarded to JLC	
2	211 Yardwork	357
3	Clear site	72
4	Dewatering	71
5	Bulk excavation	286
6	Diaphragm wall	71
7	Mass concrete & blinding	143
8	212 Reactor Containment Bldg	943
9	FPSC Sizewell B	
10	Tendon gallery, keyhole & base slab	69
11	Topping slab & secondary shield walls	131
12	Secondary containment	69
13	Wall to +37.5	22
14	Wall to +39.7	16
15	Primary shield wall	113
16	ISI gallery roof (1)	13
17	ISI gallery roof (2)	12
18	Refuelling Pond	742
19	Fuel pond liner erection (1)	38
20	Fuel pond liner erection (2)	38
21	Refuelling pond	263
22	Reactor base pour	
23	Dome Liner	607
24	Liner base	121
25	Liner barrel	311
26	Dome liner	85
27	Dome liner lift	
28	Primary Containment	398
29	Primary containment barrel (1)	69
30	Primary containment barrel (2)	11
31	Pre-stress primary containment	50
32	Polar crane	39
33	Dome	238
34	Dome concrete	53
35	Dome	43
36	Dome cladding	23
37	221 Reactor Equipment	163
38	RPV lift	
39	Reactor vessel internals	108
40	Construction access closure	54
41	220a Nuclear Steam Supply (NSSS)	545
42	NSSS supports & restraints	246
43	NSSS main components (1)	25
44	NSSS main components (2)	10
45	Loop pipes	109
46	Secondary pipework	365
47	213 Turbine Room + Heater Bay	481
48	Raft, culverts, retaining walls	119
49	Superstructure	90
50	Turb hall: electrical annexe [E]	103
51	Turb hall: M&E annexe [E]	151
52	Turb hall: electrical annexe [W]	128
53	Turb hall: M&E annexe [W]	141
54	231 Turbine Generator	1355
55	Cranes	24
56	Access for turbine contractor	
57	TG 1 (incl commissioning)	148
58	TG 2 (incl commissioning)	159
59	Erect roof (1)	32
60	Erect roof (2)	12
61	Plant installation	154
62	Finishes	664
63	Mech annexe: raft & tower [E]	93
64	Mech annexe: raft & towers [centre]	96
65	Mech annexe: raft & tower [W]	78
66	Mech annexe: structure to +26.3 [E]	80
67	Mech annexe: structure above +26.3 [E]	39
68	Mech annexe: structure to +26.3 [W]	82
69	Mech annexe: structure above +26.3 [W]	37
70	Mech annexe: M&E below +16.2	226
71	Mech annexe: M&E above +16.2	170
72	215 Prim Aux Bldg + Tunnels	1424
73	Aux bldg: structure to +6.55	142
74	Aux bldg: M&E below +6.55	765
75	Aux bldg: structure to +14.47	78
76	Aux bldg: M&E at +6.55	589
77	Aux bldg: structure to +21.13	74
78	Aux bldg: M&E at +14.47	468

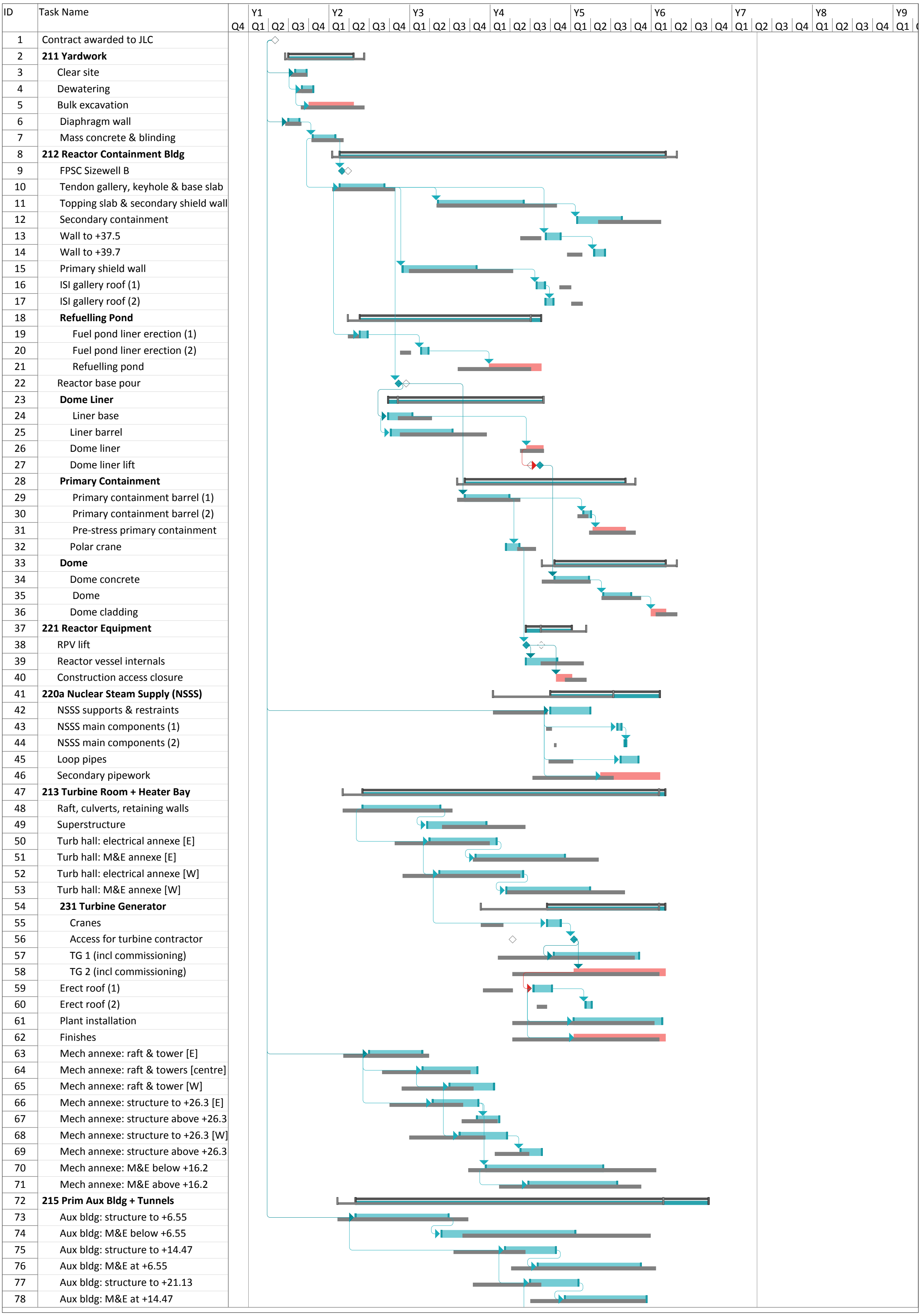


ID	Task Name	Days
79	Aux bldg: structure to +28.87	77
80	Aux bldg: M&E at +21.13	424
81	Aux bldg: structure to +37.33	49
82	Aux bldg: M&E at +28.87	393
83	Aux bldg: M&E steam & feed cell	471
84	216 Waste Process Building	1333
85	Civil works	227
86	Plant installation	553
87	Finishes	159
88	217 Fuel Storage Building	588
89	Civil works	177
90	Plant installation	177
91	Finishes	113
92	218a Control Rm/D-G Building	978
93	Control bldg: structure to +2.77	91
94	Control bldg: M&E below +2.77	339
95	Control bldg: structure to +6.55	51
96	Control bldg: M&E at +2.77	307
97	Control bldg: structure to +11.23	51
98	Control bldg: M&E at +6.55	269
99	Control bldg: structure to +15.99	40
100	Control bldg: M&E at +11.23	230
101	Control bldg: structure to +21.13	34
102	Control bldg: M&E at +15.99	250
103	Control bldg: structure to +25.99	57
104	Control bldg: M&E at +21.13	245
105	Control bldg: structure to +31.03	29
106	Control bldg: M&E at +25.99	269
107	Control bldg: structure to +37.33	28
108	Control bldg: M&E at +31.03	241
109	218k Pipe Tunnels	876
110	Civil works	223
111	Plant installation	355
112	218b Administration + Service Bldg	899
113	Civil works (ancillary bldgs)	212
114	Plant installation (ancillary bldgs)	108
115	Finishes (ancillary bldgs)	804
116	Commissioning	687
117	RV open for flushing	172
118	Cold hydro	
119	Box up	48
120	Load fuel	
121	Commercial operation	

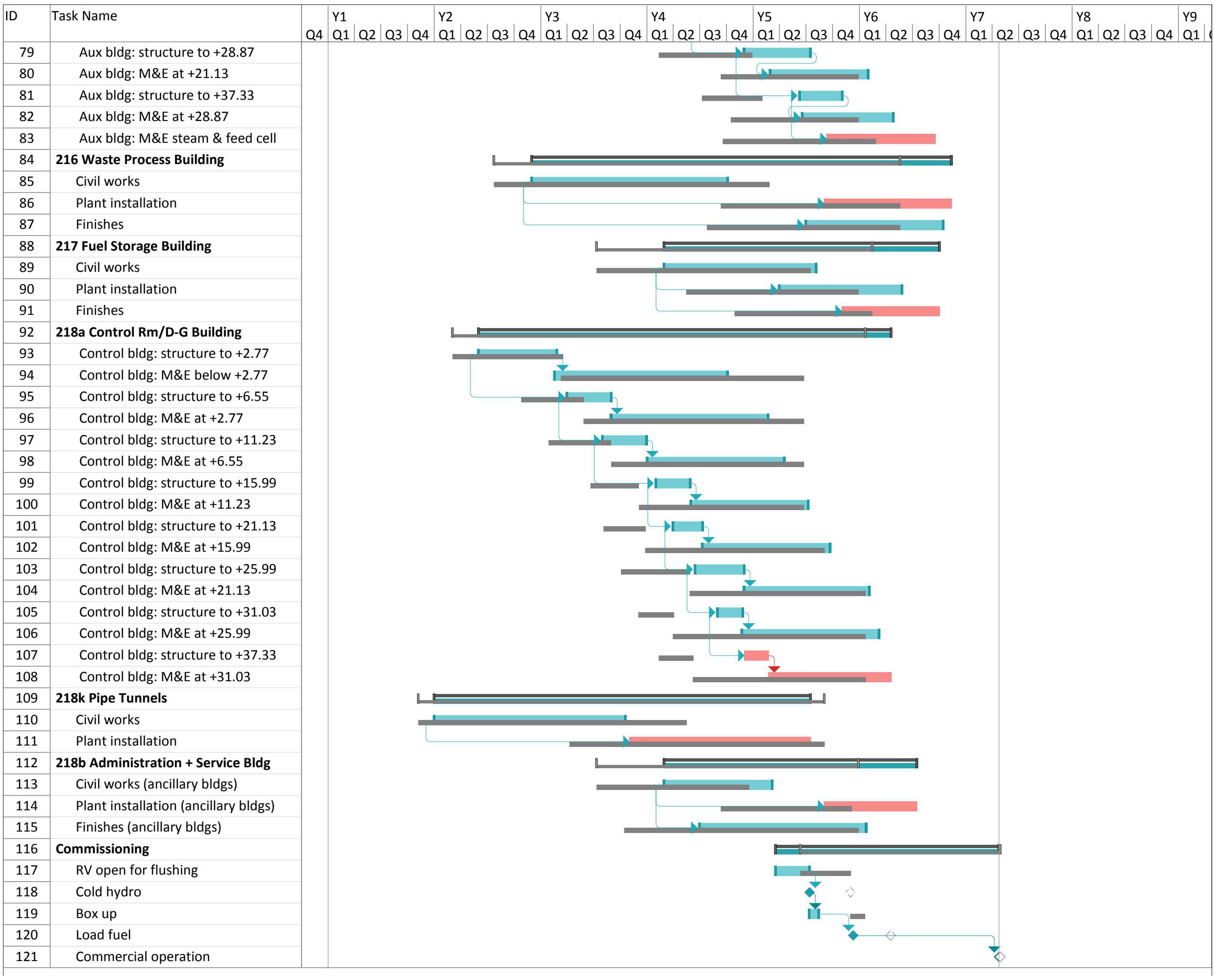


V.6. Stick-Built 300 MWe SMR; Scaling Case I (T = 0.8 and W = 0.0)

Grey bars are for a stick-built 300 MWe reference SMR with Scaling Case II (T = W = 0.4).



ID	Task Name
1	Contract awarded to JLC
2	**211 Yardwork**
3	Clear site
4	Dewatering
5	Bulk excavation
6	Diaphragm wall
7	Mass concrete & blinding
8	**212 Reactor Containment Bldg**
9	FPSC Sizewell B
10	Tendon gallery, keyhole & base slab
11	Topping slab & secondary shield wall
12	Secondary containment
13	Wall to +37.5
14	Wall to +39.7
15	Primary shield wall
16	ISI gallery roof (1)
17	ISI gallery roof (2)
18	**Refuelling Pond**
19	Fuel pond liner erection (1)
20	Fuel pond liner erection (2)
21	Refuelling pond
22	Reactor base pour
23	**Dome Liner**
24	Liner base
25	Liner barrel
26	Dome liner
27	Dome liner lift
28	**Primary Containment**
29	Primary containment barrel (1)
30	Primary containment barrel (2)
31	Pre-stress primary containment
32	Polar crane
33	**Dome**
34	Dome concrete
35	Dome
36	Dome cladding
37	**221 Reactor Equipment**
38	RPV lift
39	Reactor vessel internals
40	Construction access closure
41	**220a Nuclear Steam Supply (NSSS)**
42	NSSS supports & restraints
43	NSSS main components (1)
44	NSSS main components (2)
45	Loop pipes
46	Secondary pipework
47	**213 Turbine Room + Heater Bay**
48	Raft, culverts, retaining walls
49	Superstructure
50	Turb hall: electrical annexe [E]
51	Turb hall: M&E annexe [E]
52	Turb hall: electrical annexe [W]
53	Turb hall: M&E annexe [W]
54	**231 Turbine Generator**
55	Cranes
56	Access for turbine contractor
57	TG 1 (incl commissioning)
58	TG 2 (incl commissioning)
59	Erect roof (1)
60	Erect roof (2)
61	Plant installation
62	Finishes
63	Mech annexe: raft & tower [E]
64	Mech annexe: raft & towers [centre]
65	Mech annexe: raft & tower [W]
66	Mech annexe: structure to +26.3 [E]
67	Mech annexe: structure above +26.3
68	Mech annexe: structure to +26.3 [W]
69	Mech annexe: structure above +26.3
70	Mech annexe: M&E below +16.2
71	Mech annexe: M&E above +16.2
72	**215 Prim Aux Bldg + Tunnels**
73	Aux bldg: structure to +6.55
74	Aux bldg: M&E below +6.55
75	Aux bldg: structure to +14.47
76	Aux bldg: M&E at +6.55
77	Aux bldg: structure to +21.13
78	Aux bldg: M&E at +14.47



ID	Task Name
79	Aux bldg: structure to +28.87
80	Aux bldg: M&E at +21.13
81	Aux bldg: structure to +37.33
82	Aux bldg: M&E at +28.87
83	Aux bldg: M&E steam & feed cell
84	**216 Waste Process Building**
85	Civil works
86	Plant installation
87	Finishes
88	**217 Fuel Storage Building**
89	Civil works
90	Plant installation
91	Finishes
92	**218a Control Rm/D-G Building**
93	Control bldg: structure to +2.77
94	Control bldg: M&E below +2.77
95	Control bldg: structure to +6.55
96	Control bldg: M&E at +2.77
97	Control bldg: structure to +11.23
98	Control bldg: M&E at +6.55
99	Control bldg: structure to +15.99
100	Control bldg: M&E at +11.23
101	Control bldg: structure to +21.13
102	Control bldg: M&E at +15.99
103	Control bldg: structure to +25.99
104	Control bldg: M&E at +21.13
105	Control bldg: structure to +31.03
106	Control bldg: M&E at +25.99
107	Control bldg: structure to +37.33
108	Control bldg: M&E at +31.03
109	**218k Pipe Tunnels**
110	Civil works
111	Plant installation
112	**218b Administration + Service Bldg**
113	Civil works (ancillary bldgs)
114	Plant installation (ancillary bldgs)
115	Finishes (ancillary bldgs)
116	**Commissioning**
117	RV open for flushing
118	Cold hydro
119	Box up
120	Load fuel
121	Commercial operation

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APPENDIX VII

VII.1. Uncertainty Parameters

Table A.VII.1. Transport model parameters (Chapter IV).

INPUTS		**Application**	**Basis**			
			Assumed	Base Data	Constraint	Solution Space
Reference Reactor Power	Power_{ref}			Y		
Target Reactor Power	Power_{i}					Y
Module Quantity	Q			Y		
Module Weight	m			Y		
Module Width	W			Y		
Module Length	L			Y		
Module Height	H			Y		
Scaling Exponent	n	Module Weight	Y			
Module Division Factor	MDF	Limiting Dimension/Weight				Y
Transport Envelopes	1/2/3/4	Limiting Dimension/Weight			Y	
Fraction special transport allowed	x	Transport Envelope 3				Y
OUTPUT						
DoM_{max} – the maximum transportable fraction of modules (weight based)						Used in Ch. V & VI

Table A.VII.2. Schedule model parameters (Chapter V).

INPUTS	Application		Basis			
			Assumed	Base Data	Constraint	Solution Space
Reference Reactor Power	Power_{ref}			Y		
Target Reactor Power	Power_{i}					Y
Task Time (duration)				Y		
Wait Time (duration)				Y		
Scaling Exponent	n	Module Weight	Y			
Fraction of Task Time that scales	T	Task Time (duration)		(Y)		Y
Fraction of Wait Time that scales	W	Wait Time (duration)		(Y)		Y
Modularisation of Task and/or Wait Time		Task and/or Wait Time (duration)				Y
Input Degree of Modularisation	DoM	Task and/or Wait Time (duration)				Y
Extent of Modularisation	None/Low/Med/Full	Task and/or Wait Time (duration)				Y
Onsite Module Assembly Time		5% of Module Task Time	Y			
OUTPUT						
NPP Construction Schedule – the time to build an NPP (first structural concrete to commercial power production, in years)						Used in Chapter VI

Table A.VII.3. Cost model parameters (Chapter VI).

INPUTS		**Application**	**Basis**			
			Assumed	Base Data	Constraint	Solution Space
Reference Reactor Power	Power_{ref}			Y		
Target Reactor Power	Power_i					Y
Scaling Exponent	n	Cost Account	Y			
Direct Costs	Factory Cost			Y		
	Site Labour Cost			Y		
	Site Material Cost			Y		
Indirect Costs	Indirect Services			Y		
	Indirect Labour			Y		
Input DoM	DoM	Direct Costs				Y
Extent of Modularisation	None/Low/Med/Full	Direct Costs				Y
Modular Cost Factors: Direct Costs	Material savings factor	Account 21: 5% more expensive All other accounts: 10% cheaper	Y			
	Labour savings factors	NI: 70% more productive BoP: 75% more productive	Y			
	Factory labour cost savings	Factory labour: 65% cheaper	Y			
	Freight cost	+ 2% to module (direct site + labour) costs	Y			
	Overheads	+ 200% to mod direct labour	Y			
Modular Cost Factors: Indirect Costs	Modularisation based	- % of Indirects relative to mod cost savings	Y			
	Time based	- % of Indirects relative to mod time savings	Y			
	Standardisation	Remove 80% Home Office	Y			
Learning Rate[9]		OCC/TCIC/LCOE	Y			
Interest Rate		OCC/TCIC/LCOE	Y			
OUTPUTS						
NPP Cost – in the form of OCC, TCIC, and/or LCOE as appropriate						

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[9] Learning rate uncertainty is not investigated in this project as much more detailed work has been done in this space by Lyons [16].

VII.2. Scaling Exponent Summary

Table A.VII.4. Scaling exponents from literature and experience (from Table 3 in [12]).

Study/Author	Year	Scale Exponent n
[-]	1968	0.75
[-]	1968	0.51
McNelly & Koke	1969	0.64
Bennett, Bowers	1971	0.68
Leedy & Scott	1973	0.40
Davis	1975	0.47
Mandel	1976	0.46
Woite	1976	0.71
Comtois	1977	0.86
	1977	0.76
Mooz, Rand	1978	0.80
	1978	0.50
	1978	0.70
Mooz, Rand	1979	1.00
Crowley	1978	0.45
Woite	1979	0.40
Gehring	1979	0.24
	1979	0.49
Fjeldsted	1980	0.59
McMahon	1980	0.43
Nieves *et al.*, Battelle	1980	0.25
Komanoff	1981	0.80
McMahon	1981	0.43
Crowley	1981	0.40
Nobile & Kettler	1982	0.63
	1982	0.53
	1982	0.63
Perl	1982	0.49
Bowers *et al.* [153]	1987	0.64
Cantor & Hewlett* [19]	1988	0.65
Berthélemy & Rangel* [44]	2015	0.90
	2015	0.79
	2015	0.80
	2015	0.81

Mean scaling exponent, n_μ	0.606
Sigma, σ	0.183

* Statistical studies of scaling exponents for NPPs; not included in original Carelli *et al.* study [12]

VII.3. Parameter Variability: Upper and Lower Bounds

Table A.VII.5. Variability range set for module cost factors and scaling exponents.

Modular Cost Factors		**+25%** upper bound	**μ** as per EMWG	**-25%** lower bound
Materials	Account 21 Materials	1.063	1.05	1.038
	All other equipment & commodities (NOAK;FOAK)	0.925	0.90	0.875
Labour Hours - shop:field productivity	Nuclear island	0.39	0.31	0.23
	BOP scope	0.31	0.25	0.19
Labour Cost	Factory ($/hr)	15.00	12.00	9.00
	Site ($/hr)	42.50	34.00	25.50
OTHER	Freight	0.025	0.02	0.015
	Overheads	2.50	2.00	1.50
	Installation	0.063	0.05	0.038
	Standardisation	25.00	20.00	15.00

Scaling Exponent

	$n_\mu - \sigma$	**n_μ**	**$n_\mu + \sigma$**
Cost-weighted average scaling exponent	0.423	0.606	0.789