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DESIGN FOR PLANT MODULARISATION: NUCLEAR AND SMR

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ABSTRACT

The UK Small Modular Reactor (UKSMR) programme has been established to develop an SMR for the UK energy market. Developing an SMR is a multi-disciplinary technical challenge, involving nuclear physics, electrical, mechanical, design, management, safety, testing to name but a few.

In 2016 Upadhyay & Jain performed a literature review on modularity in Nuclear Power. They concluded that although modularisation has been utilised in nuclear to reduce costs, more work needs to be done to "create effective modules". Hohmann et al also concluded the same for defining modules in the chemical process plant industry.

The aim of this paper is to further define modules with a particular focus on an SMR for the UK market, the UKSMR. The methods highlighted may be relevant and applied to other international SMR designs or other types of plant.

An overview and examination of modularisation work in nuclear to date is provided. The different configurations are defined for the Nuclear Steam Supply System (NSSS) in primary circuits and then for Balance of Plant (BOP) modules. A top level design process has been defined to aid in the understanding of design choices for current reactors and to further assist designing balance of plant modules.

The paper then highlights areas for additional research that may further support module design and definition.

NOMENCLATURE

ASME	American Society of Mechanical Engineers
BIM	Building Information Management
BOP	Balance of Plant
CAD	Computer Aided Design
CCGT	Combined Cycle Gas Turbine
CIPWR	Combined Integrated Pressurised Water Reactor
EPRI	Electronic Power Research Institute
FOAK	First of a Kind
IAEA	International Atomic Energy Agency
IPWR	Integrated Pressurised Water Reactor
KBE	Knowledge Based Engineering
LCOE	Levelised Cost of Electricity
LNPP	Large nuclear power plant
LOCA	Loss of coolant accident
MEP	Mechanical, Electrical and Plant
MIT	Massachusetts Institute of Technology
NOAK	Next of a Kind
NSSS	Nuclear Steam Supply System
P&ID	Process/ Piping and Instrumentation Diagram
PDS	Plant Design Software
PLM	Product Lifecycle Management

PWR	Pressurised Water Reactor
RPV	Reactor Pressure Vessel
SMR	Small Modular Reactors
TRL	Technology Readiness Level
UKSMR	Small Modular Reactor for the UK for the UK

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INTRODUCTION

With the global trend for supporting C02 emissions reduction, the UK government and others around the world have recognised Nuclear power as secure, low carbon, base load energy provider [CITATION Nat14 \l 2057].

The historic trend for nuclear power stations has been to utilise economies of scale; increasing power density and output to lower Levelised Cost of Electricity (LCOE). This has led to Large Nuclear Power Plant (LNPP) designs currently reaching over 1000 MW. Consequently, this has increased design complexity leading to construction and productivity issues causing long delays and rising costs [3-5].[CITATION Gil17 \l 2057][CITATION Koo17 \l 2057][CITATION Lov16 \l 2057]

This LNPP design methodology has proven to be challenging due to time-consuming, complex and low productivity construction [CITATION Ton16 \t \l 2057]. Two major companies have had problems in building current LNPPs. Westinghouse has filed for Chapter 11 Bankruptcy [CITATION Forld \l 2057] and Areva has been restructured by the French government with a $4.8billion capital injection [CITATION Wor17 \l 2057].

Modularisation is a method of breaking things down to organise them more efficiently. It has been used as a method of simplifying construction and reducing costs for nuclear power [CITATION Upa16 \l 2057]. The simplest form of construction is "Stick building" working in situ building piece by piece. Modularising to increase productivity and reduce the construction schedule by enabling parallel working have been key aspects of reducing construction costs of nuclear power. Containment rings were first "modularised" in the 1950s [CITATION Pre09 \l 2057], and Mechanical, Electrical and Plant (MEP) modules in the 1970s [CITATION Sto77 \l 2057], followed by Pre Cast Concrete and modular shipbuilding techniques in the 1980s [CITATION Seu88 \l 2057]. More advanced techniques and methods have been applied over time [13-24]. [CITATION Kha09 \l 2057][CITATION Man76 \l 2057][CITATION Can88 \l 2057][CITATION OEC00 \l 2057][CITATION OEC15 \l 2057][CITATION Bak83 \l 2057][CITATION Tec85 \l 2057][CITATION Lap89 \l 2057][CITATION Lap97 \l 2057][CITATION IAE04 \l 2057][CITATION IAE09 \l 2057][CITATION Bra97 \l 2057]

Small Modular Reactors (SMR) have been proposed as a method of reducing this construction risk by taking work offsite into a controlled factory environment [CITATION Rou17 \l 2057]. SMRs will employ standardisation, modularisation, management, factory quality and productivity improvements and therefore a reduced construction schedule. SMRs designs aim to produce lower LCOE compared to large nuclear to help compete against falling renewable energy costs.

There are many assessments of why an SMR may be better economically than a LNPP[CITATION Nat14 \l 2057][2, 26 – 31] citing the following advantages: [CITATION Hay91 \l 2057][CITATION Car07 \l 2057][CITATION Eco10 \l 2057][CITATION Rou15 \l 2057][CITATION Loc14 \l 2057][CITATION Loc11 \l 2057]

Simplified design; Incorporates fewer, easily replaceable components; Minimal assembly on site; Factory built productivity enhancements; Economies of mass production; Serial production; Lower cost of capital; Learner effects.

A 2016 literature review on nuclear modularisation by Upadhyay & Jain [CITATION Upa16 \n \t \l 2057] and on chemical plant modularisation [CITATION Luk17 \l 2057][CITATION Lap97 \l 2057][CITATION Kad07 \l 2057]found that only a few papers [21, 33] "discuss creating effective modules in nuclear power". They recommend that modules definition may be a significant area for further studies. As most SMRs are mainly in the concept stage of design [CITATION IAE16 \l 2057], further definition modules will be required as the SMR concept develops.

The aim of this paper is to build upon the literature review conducted by Upadhyay & Jain to provide an overview and examination of modularisation work completed to date and to provide more definition regarding module design.

The underlying methods for current design and construction in LNPPs are investigated and how these may apply to the new generation of Small Modular Reactor (SMR). It also discusses primary circuit designs for prominent SMRs and designing balance of plant modules.

There is a particular focus on an SMR for the UK market, the UKSMR.

A top level design process has been defined to aid in the understanding of design choices for current reactors and to assist further designing balance of plant modules.

The paper then highlights areas for additional research that may support further module design and definition.

MODULARISATION DEFINTIONS

The origin of modularity stems from the Bauhaus era of building construction according to Miller & Elgård [CITATION Tho98 \n \l 2057]. Modularisation, in the form of assembly based modularity, first began to be mentioned in the navel arena during the Second World War, followed by modularising by function in the 1960s [CITATION Hub88 \l 2057].

Miller & Elgård [CITATION Tho98 \n \t \l 2057] defined Modules, Modularity and Modularisation and Upadhyay & Jain [CITATION Upa16 \n \t \l 2057] defined these terms with respect to nuclear with a literature review.

Module definition

Upadhyay & Jain [CITATION Upa16 \n \t \l 2057] defined a module as “a unit for installation[CITATION IAE09 \l 2057] that is manufactured, assembled and tested in factory or workshop and transported to the NPP [CITATION Kad07 \l 2057] site in such a state of readiness that before installing the unit no further significant processing is required to be done on the unit." They identified 7 types of modules.

Modularity definition

Upadhyay & Jain [CITATION Upa16 \n \t \l 2057] describe three types of modularity. Defining “Scale modularity" as a construction technique where a large plant is combined of multiple NPP of small capacity. “Scope modularity" is defined as a construction technique where a large capacity single reactor NPP is divided into a number of modules for installation.” The drivers for this type of modularity can be for schedule or cost.

Comprehensive modularity – is the combination of both scale and scope modularity.”

Modularisation definition

The Cambridge University Press dictionary definition for modularisation is “the design or production of something in separate sections” [CITATION Mod17 \l 2057]. Presley & Weber [CITATION Pre09 \l 2057] define Modularisation as "the process of engineering and fabricating construction projects into shippable packages or segments that can be installed economically at the job site”.

Modularisation is therefore the process of breaking down a system into smaller parts in the aim of reducing costs. The main advantages being: factory built productivity increases, reduced construction schedule, reduced design time due to reused features, components and design rules.

NUCLEAR MODULARISATION TO DATE

In this section the different techniques for modularising nuclear power stations are presented, in the chronological order they are found in the literature.

1950s Parallel working (modular containment)

Modularisation has been utilised to some extent in the nuclear industry since the 1950s to reduce the construction schedule for containment rings [CITATION Pre09 \l 2057]. This method constructed the nuclear containment adjacent to the nuclear island, to enable parallel working and a reduction in schedule.

1950s Close coupled designs

A close coupled design stems from the early development of marine reactors for commercial use. A close coupled design is more compact than a LNPP and is more easily factory manufactured. The compact design would also enable smaller containments.

1970s MEP modules

A Stone and Webster report took modularisation one step further by analysing the applicability of MEP modules for the [CITATION Sto77 \l 2057] Stone and Webster reference nuclear power plant. It summarised that MEP modules may help to reduce construction costs. This concept has been developed since and is in use in current LNPP construction.

1980s Integral Reactor Module concept

A series of integral SMR reactor plants were revealed at the 1983 American Society of Mechanical Engineers (ASME) Joint Power Generation Conference [CITATION Sto77 \l 2057]. An integral SMR houses the primary circuit components inside the primary containment vessel and is easier to factory manufacture.

1980s Pre cast concrete

In 1983, Modular pre cast concrete and steel concrete structures [CITATION Bra97 \l 2057] were researched to enable schedule reductions. These are currently applied in very large modules for the nuclear island [CITATION Ton16 \l 2057].

1980s Shipbuilding techniques for current large reactors

Shipbuilding techniques were researched and applied to nuclear power plants [CITATION Lap89 \l 2057], as similarities were observed between the two methods of construction, noting productivity increases leading to reducing costs, increasing quality and reducing the schedule.

DESIGN FOR PLANT MODULARISATION

A top level design process has been defined to aid in the understanding of design choices for current reactors and to assist further designing balance of plant modules.

The Modularisation design process is covered in the following sections:

1. Modularisation project applicability
2. Build strategy
3. Module design configuration
4. System breakdown
5. Interfaces and definitions
6. Design tools
7. Equipment layout

1. ASSESS PROJECT APPLICABILITY

The first step to modularising a plant is to assess the applicability of modularisation for the project.

Mancini et al [CITATION Man16 \l 2057] conducted a study on oil and gas plant modularisation, which is also applicable to the nuclear sector. It aids in understanding if the project is suited to modularisation. They identified 13 Management and Organisational considerations, 9 Design considerations, 7 Site considerations and 5 Transport considerations.

When considering modularisation for a project, these considerations need to be assessed and taken into account. An assessment method for analysing modularisation for a project would be useful further research.

Nuclear specific key decisions to modularise

The decision to modularise large plants was focused on the benefits of parallel working and taking work away from in situ. Shipbuilding techniques were applied to construct large modules in an assembly area on site [CITATION Lap89 \l 2057]. The Electric Power Research Institute (EPRI) conducted a study on modularisation, applying the 1-3-8 rule from shipbuilding [25,39,40] to illustrate this increase in productivity which is defined as follows: [CITATION KBa09 \l 2057] [CITATION Rou17 \l 2057] [CITATION Ken10 \l 2057]

1 The standard unit of time to complete a piece of work in a factory environment.
3 The extra time taken to perform a piece of work in an assembly area next to the in situ work area.
8 The extra time taken to perform a piece of work in the in situ work area, due to working conditions.

Table 1 Comparison of plants designed for different build strategies

Assembly Method	**Factory Built**	**Assembly Area On Site**	**Stick build**
Productivity	1	3	8
Example Application	SMR	AP1000	EPR
Power	Up to 700MW	1100MW	1600MW
Modules definition	Designed for road transport	Very large modules	Components
Module weight	(UK) Road transport limit 650 tonnes	Crane limit >1000 tonnes	Crane limit >1000 tonnes
Length	45m	Crane limit	Crane limit
Width	6.1m	Crane limit`	Crane limit
Height	5m	Crane limit	Crane limit

Table 1 shows examples of the different construction techniques. SMRs are located on Step 1 of the 1-3-8 scale, whereas the current LNPPs utilising shipbuilding techniques are located around step 3 and Stick built LNPPs are located around step 8.

SMR specific key decisions to modularise

Taking the productivity one step further developed the idea for SMRs. In this case, the reactor and power station are designed to be factory built and transported to site. Factory build improves productivity, quality and management[CITATION Rou17 \l 2057]. This brings the assembly productivity into the highest productivity category in the 1-3-8 rule. This requires a new method of design from that which is used for very large modules as the modules will need to be designed for transport requirements rather than the crane limit on LNPP modules.

Furthermore, with the recent technology development in electric driverless transport, advanced manufacturing & robotics, these technologies could bring down the cost of this method of construction in the near future even more than is currently available today.

Another SMR requirement is that they are “smaller” than previous LNPP [CITATION IAE16 \l 2057]. Smaller, standardised components are more easily replaced than the large components in LNPPs [CITATION Wor171 \l 2057] [CITATION Con16 \l 2057]. Allowing more flexibility in the production of long lead time components may alleviate manufacturing problems and subsequent construction delays.

2. DEFINE BUILD STRATEGY

The next step is to understand the build strategy, supply chain, transport and logistics requirements.

Mancini et al [CITATION Man16 \l 2057] found the following considerations:

- Manufacturing facilities and locations
- Lifting/transport equipment
- Customs and export requirements
- Government transport requirements for vehicle size and weight constraints & police escorts required.
- Requirements/lead time for permits.

- Community and environmental risks.
- At site transport logistics

Current LNPPs are designed for economies of scale, meaning many of the modules were too large to be transported. This required an onsite assembly area to enable parallel working.

A key requirement for SMR is for the modules to be factory built and road transportable. Modules are therefore limited by government regulation for transport size

UKSMR specific build strategy

The UKSMR has a specific requirement for transport and construction in the UK. The modules will be subject to UK government regulation for transport size limits [CITATION Ove09 \l 2057] and [CITATION BE115 \l 2057] weight [CITATION VR115 \l 2057]. The maximum height for UK motorways is 5.1m, but Vessco Engineering recommend 4.5m for additional clearance [CITATION Van16 \l 2057] and state that the maximum load ever carried on UK roads was 640 tonnes. For comparison the Nuscale module weighs about 700 tons [CITATION Nus17 \l 2057] and the Westinghouse SMR upper module weighs 280 Tons [CITATION Car14 \l 2057].

It may be the case that the UK government will only grant oversize transport permissions when it can be proven that the design cannot be made to fit smaller transport requirements. Further consideration of this requirement may mean that equipment may need to be designed to be installed within normal road transport limits.

3. DECIDE MODULES CONFIGURATION

The next step is to classify and break down modules and systems. Upadhyay & Jain [CITATION Upa16 \n \t \l 2057] have highlighted 9 different types of module in current LNPPs:

- Power Plant, Reactor, Structural, System, Composite, Component, Mechanical, Electrical, Instrumentation

They defined a reactor module as consisting of the reactor vessel, fuel, heat transport system, steam generator, control & safety systems. This is also called the nuclear steam supply system or primary circuit. Module configuration can differ depending on design requirements. In most LNPP and SMRs, for manufacturing and cost benefits, these Primary Circuit components are designed as specialised, large components.

There are two designs which are configured differently, the combined integral reactor, and the Massachusetts Institute of Technology (MIT) pebble bed reactor.

Due to this, primary circuit modules are defined separately to the balance of plant modules in this paper. Other designs may define them differently depending on requirements and definitions.

The other decision is how to design and construct balance of plant modules. Where the balance of plant refers to all the supporting systems of a power plant needed to deliver the energy, other than the generating unit itself.

This paper will therefore be broken down into two sections:

- 3.1 - Primary circuit module design (Figure 1)
- 3.2 - Balance of plant module design (Figure 1)

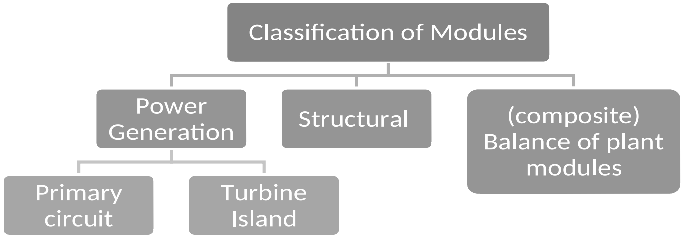

Figure 1- Breakdown of modules into primary circuit and balance of plant

How to configure modules can vary and may be a combination of all the above. Structural may be included into the module design for primary circuit or Balance of Plant (BOP) modules.

3.1. PRIMARY CIRCUIT MODULES

Within the primary circuit design there are different types of modularisation depending on design requirements, either for economies of scale or for factory build and transport.

For large plants, based on economies of scale, designed for construction in a parallel working area on site and maximum lift crane there are two methods of construction (Table 2):

3.1.1 -Very large modules using on site assembly
-Stick build.

For Small Modular reactors based on factory build and transport:

3.1.2 Integrated Pressurised Water Reactor (IPWR)
3.1.3 Combined IPWR (CIPWR)
3.1.4 Close Coupled

Table 2 Configurations of primary circuit

	Small Modular			Large Nuclear
	UKSMR Close Coupled	IPWR	CIPWR	OSA or Stick Build
Size	4.5 m	3.5-4.5 m	4.5 m	N/A
Weight	640 tonnes	280 tonnes	700 tonnes	>1000 tonnes
Modules	4	2	1	9
Power	440 MW	225 MW	600 MW	>1000 MW

3.1.1.LARGE NUCLEAR MODULE DESIGN

For large plants, based on economies of scale, two construction methods are applied, either stick build or using very large modules and shipbuilding techniques.

Shipbuilding techniques employ very large modules, and this design and construction technique translated across to the current large reactors. The very large modules of 500-<1000 tonnes [CITATION Upa16 \l 2057] were effectively designed for the lifting capacity of one of world’s largest cranes [CITATION Pav12 \l 2057]. The modules included steel concrete (SC) structures [CITATION Gen16 \l 2057] and allowed for parallel working in a construction area on site. This created the modularisation configuration in Figure 2, where the nuclear island was modularised into 9 very large modules. The containment for the nuclear island is also modularised into sections. [6, 10]. [CITATION Ton16 \l 2057] [CITATION Pre09 \l 2057]

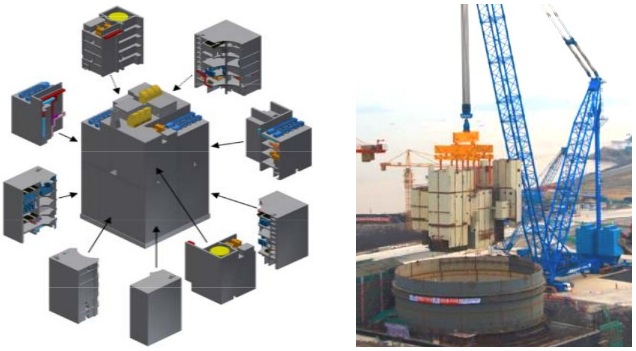

Figure 2 AP1000 nuclear island mega modules [CITATION Car14 \l 2057] being lifted into place [CITATION Ton16 \l 2057]

Lessons learnt from large nuclear

SMR's must learn from the recent experiences of new build large reactor technology. These large, complex designs have led to problems with construction, which has caused time and cost overruns. Key problems include: [CITATION Shy17 \l 2057]

- Poor project management
- Defects and rework, Reactor Pressure Vessel (RPV) cracks, groundworks
- Low productivity
- A lack of nuclear build experience
- Long design times
- Starting of build before the plant design is completed
- Lack of integrated design software

3.1.2. IPWR SMR MODULE DESIGN

An Integrated Pressurised Water Reactor (IPWR) is a design where the primary circuit components such as heat exchangers, pressuriser and reactor are located inside the primary pressure vessel. This design thinking increases safety due to the decreased chance of a loss-of-coolant accident (LOCA) due to no large pipes connecting the reactor to the steam generators.

Some prominent IPWR designs include Westinghouse [CITATION Car14 \l 2057], B&W Mpower, and Holtec. These designs utilise two modules, one for the reactor and another for the steam generator and pressuriser. The two modules are then connected together to form a single integrated primary circuit.

Whereas others (eg. The SMART SMR design[CITATION IAE16 \l 2057]) integrates the whole primary circuit into one module. These modules are built in a factory and transported to location.

This IPWR arrangement is essentially a conventional reactor with a single steam generator, limiting the power output to what is achieved with one steam generator at around 225MW [CITATION IAE16 \l 2057].

Liu and Fan [CITATION Fan14 \l 2057] discuss the technical feasibility of the IPWR design and state that the fundamental systems have reached technology readiness level (TRL) 7 to 8 and the largest challenge is the higher integration of the primary system.

However, two major events have stalled development in this area:

- Westinghouse bankruptcy [CITATION Forld \l 2057]
- B&W project wind down [CITATION For17 \l 2057]

3.1.3.CIPWR MODULE DESIGN

Another IPWR design (NuScale) combines 50 MW passive reactor modules to create up to a 600 MW plant (Combined (CIPWR)). The modules are passively safe meaning they use natural circulation for cooling. This approach employs economies of mass production rather than economies of scale to form a large 600 MW plant.

The same technological challenges discussed by Liu and Fan [CITATION Fan14 \l 2057] for IPWRs apply as work continues to ensure the design is feasible [CITATION NAM18 \l 2057].

3.1.4.CLOSE COUPLED MODULE DESIGN

A close coupled design is derived from the experience of building nuclear submarines, where the primary circuit is as compact as possible to minimise the containment volume and maximise available space inside of containment, instead of a dispersed design as seen in the current LNPPs.

They employ similar technology to the current large reactors but move most of the manufacture and assembly to a factory, significantly increasing productivity.

A close coupled design enables higher power output due to integrating more steam generators compared with single steam generators for IPWR designs.

Close coupled designs have TRLs of 9 due to proven designs and therefore less development risk. They need to prove that factory build productivity, economies of mass production, and project management can deliver on the claimed cost projections.

Heat Exchanger Modules concept

The other option for modularising the primary circuit is to modularise the heat exchangers. The MIT Advanced pebble bed reactor (Figure 3) [CITATION Kad07 \l 2057] developed the concept for modular heat exchangers and recuperators. This design would enable standardisation cost benefits compared to the large steam generators utilised today.

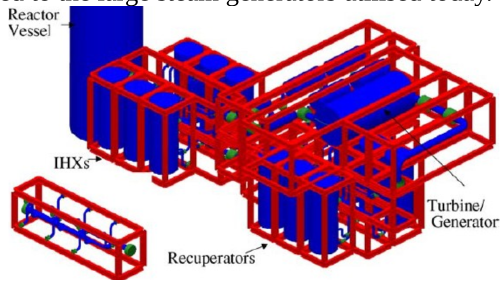

Figure 3 - MIT pebble bed reactor modules concept [CITATION Kad07 \l 2057]

Reactor Island Module design conclusion

The SMR Techno-Economic Assessment [CITATION Atk16 \l 2057] commissioned for the UK government found that First of a Kind (FOAK) costs for IPWR were between £86-124, with a central estimate of £101/MWh which is similar to the planned Hinckley Point C strike price of £97/MWh. However, both the CIPWR [CITATION NuS17 \l 2057] and UKSMR Close Coupled [CITATION Rol \l 2057] designs claim cost estimates of £60 per MWh in 2017. However, at such an early stage in the design process, it is difficult to understand which design option would provide the most economic option.

According to Ullman [CITATION DGU03 \l 2057] the concept design phase of a project commits nearly 80% of total project cost up front.

Proving predicted costs can be delivered is vital to public and government perception. However, cost data can only be related to previous design experience and projects and this cost uncertainty is an area for further investigation.

3.2. BALANCE OF PLANT MODULES

The Balance of Plant (BOP) consists of the other systems associated with generating power apart from power generation units themselves. Within nuclear, these can be a number of systems such as waste treatment, emergency cooling, safety and reactor control [CITATION Ber05 \l 2057].

A report in 1977 [CITATION Sto77 \l 2057] evaluated the applicability of grouping components into modules for the Stone and Websters pressurised water reactor reference design. By analysing and evaluating the practicality of such systems, it recommended a number of modules for implementation, citing benefits over stick built systems.

Further, the modularisation task team [CITATION Tec86 \l 2057] evaluated modularisation in the nuclear and non-nuclear and recommended its use in the nuclear island and some of the BOP to enable 12% cost savings and a schedule reduction from 8 to 6 years.

With the SMR requirement for factory build, Roulstone and Lloyd recommend increasing the factory share, including balance of plant, to at least 65% for SMRs to be competitive with renewables and Combined Cycle Gas Turbines[CITATION Rou17 \l 2057].

Currently Fluor claims with its 3rd Generation modular technology that 85% of the integrated equipment is completed in the factory [CITATION Flu17 \l 2057] providing 20% benefits.

To gain maximum factory productivity benefits, it would be practical to design modules with the highest percentage of work completed in the factory as possible. This means that for BOP modules there would be a need to integrate structural, mechanical and electrical equipment to the highest degree possible. This means the rest of the balance of plant modules would need to be configured as composite modules as defined by Upadhyay & Jain [CITATION Upa16 \l 2057]

3.2.1. Decide module design configuration

The module design decision can be affected by many different factors from module size and configuration, structural design, manufacturing and assembly requirements. There are two main approaches to MEP module design (Figure 4).

- Designing modules to fit equipment
- Designing equipment to fit modules

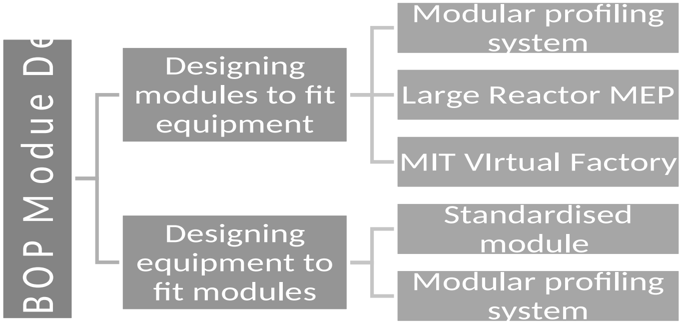

Figure 4 - Methods for designing modules

Designing modules to fit equipment

This is the approach taken by the MIT pebble bed reactor and current large reactors. A system or component is designed and then the module is designed to fit the system. With this method, the MIT advanced pebble bed reactor developed the idea for a virtual factory concept, where a module is sent to an equipment manufacturer to install their equipment, eliminating the need for a central assembly facility [CITATION Kad07 \l 2057].

Most large plants employ modules in some form with the Westinghouse AP1000 design employing some 342 structural, mechanical, electrical and piping modules [CITATION Ton16 \l 2057].

Designing equipment to fit modules

A standard module size (Figure 5) would enable economies of mass production and easy assembly much like an intermodal container port system.

Figure 5 Rolls-Royce standard frame concept

A modular profiling system utilising standard parts may be another method for designing module structure. The profile system allows easy design and assembly [CITATION Kan17 \l 2057], saving both time and costs. This would also enable custom modules of different sizes for different applications or custom supports inside a standardised module.

4. DECIDE SYSTEM BREAKDOWN

Plant design starts with system definition. The defined systems are outlined in a Process/ Piping and Instrumentation Diagram (P&ID). The design engineer then utilises these systems diagrams to produce a 3D plant design.

Once the module configuration is decided, the design needs to optimise breakdown of systems into modules to optimise cost and buildability. Analysis needs to be conducted on equipment size and relations to efficiently break down systems into modules.

5. SET INTERFACES AND DEFINTIONS

To effectively design modules, interfaces and definitions will need to be set early in the design process between modules such as connections, inputs and outputs. Interfaces must take into consideration: design, manufacturing, assembly, safety, security, maintenance and operational requirements.

A project which may further define manufacture and assembly requirements for modules is the Cammell Laird modular manufacturing facility [CITATION NAM17 \l 2057].

6. DECIDE DESIGN TOOLS

When designing plants and modules, the design team must choose tools to aid design. There are different tools available:

- Computer aided design (CAD)
- Plant Design Software (PDS),
- Building Information Management (BIM)
- Product Lifecycle Management (PLM):

The project needs to assess its requirements and acquire the most suitable software for the job.

Standard CAD software is mainly product based and not particularly suited to designing plants. Modern plant design softwares are bespoke applications for designing plants. The software [65-67] brings many advantages to the modern plant designer such as: [CITATION Ave17 \l 2057][CITATION Hex17 \l 2057] [CITATION Pla17 \l 2057]

- Parametric 3D modelling software that links the underlying database holding part and attribute information, and allows parts and their attributes to be adapted and updated automatically within an assembly.
- Automatic updates of P&ID's to the 3D model.
- Automated pipe routing.
- Integration and collaboration between employees.
- Library of standard parts.

7. EQUIPMENT LAYOUT

However, these are software tools. The intelligence resides in the designer’s interpretation of the system specification; to conceive, conceptualise and develop concept designs using these software tools.

According to Ullman[CITATION DGU03 \l 2057] the concept design phase of a project commits nearly 80% of total project cost up front. Subsequent design changes can have a major impact on the total project cost and schedule for delivery of components and large complex projects commonly experience delay and overruns [CITATION The14 \l 2057]. Design changes often arise because down stream engineering functions such as manufacturability and cost together with supply chain logistics have not been fully evaluated.

To mitigate the risk of design change, design rules are a convenient way of capturing knowledge about the product manufacturability in a systematic way. Design rules can be used to support the evaluation of potential solutions and inform on relative cost of materials and manufacturing solutions, assembly solutions and their impact on product performance and service life, maintenance and safety risk considerations etc.

Design rules may be incorporated within knowledge based systems to aid the designer. Such software tools with data input from the designer, are programmed to create concept designs, and to provide intelligent and automated evaluation of concept designs, delivering potential solutions

Design rules will need to be coded and developed from existing codes, standards and the design engineer. Other factors to consider are: Standardising components, Minimised pipe lengths, Minimised welding, Access for Maintenance, Optimal placement of valves, Vertical layout, optimal use of space, Tolerancing / Metrology specification out of factory, Welding quality, Definition of connections and outputs, Integration of civils, Electrical instrumentation and control.

The design may need to take into account the following technology developments and projects in Table 3.

Table 3 - Projects to consider in developing rules for design

Design stage		Project
Design	→	Plant design [CITATION Sea16 \l 2057]
Planning and construction management	→	Building information management software
Manufacture and assembly	→ → →	Modular manufacture of SMRs [CITATION Dep17 \l 2057] Modular manufacturing R&D centre [CITATION NAM17 \l 2057] Manufacturing innovation [CITATION NAM171 \l 2057]
Modular Civils		Modular concrete [CITATION Mod18 \l 2057] Concrete Construction for Modular Units [CITATION Gen16 \l 2057]
Supply chain	→	SMR reactor supply chain design [CITATION Imp15 \l 2057]

Other technology advancements	→	VR technology developments
	→	Autonomous transport
	→	Advanced manufacturing technology.

There are many configurations for equipment layout within and between the modules. Assessments will need to be performed to understand the best configuration with regards to manufacture, assembly, supply chain, maintenance and decommissioning like those considered in Table 3.

To analyse all possible design configurations for modules is a complex challenge. As the number of variables increases, the number of potential solutions increases exponentially, increasing computing power required and therefore makes finding an optimal solution more difficult. Such problems are described as combinatoric. Hence there is a desire to automate the process of finding potential solutions together with the solution evaluation process using knowledge based system software tools.

The Knowledge Based Engineering (KBE) definition is “to capture and re-use product and process engineering knowledge by automating parts of the design process” [CITATION WSk071 \l 2057]. This increases time for creative design, allowing more time to assess concept options.

The intelligence within the knowledge base system stems from the inference engine and the use of the optimisation techniques such as fuzzy logic, genetic algorithms, gradient based methods, there are often multi-objective criteria that may use advanced algorithms and machine learning.

A knowledge based engineering solution may help with computationally assessing module configuration options and providing a more efficient solution than may be available with manual module design.

CONCLUSION

This work sets a foundation for SMR module design and for further work to be undertaken and researched on balance of plant modules. It provided information on module configurations for primary circuits and further definition on BOP module design.

It has been highlighted that further definition needs to be decided on module structure, connections, integration and arrangement of mechanical, electrical and structural components.

Also established was that an assessment method for deciding whether to modularise a plant could be developed as this may be useful for projects considering modularisation.

Furthermore, another line of further research may be a KBE solution for module design. A KBE solution would be useful to design a more efficient module, requiring less design changes, and associated cost increases, later in the project. The KBE system would incorporate design rules into an automated decision making tool to analyse and assess multiple solutions to find the most efficient solution quickly. This provides the designer more time for detailed design[CITATION WSk071 \l 2057] and allows for a more effectively designed module.

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