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Off-site modular construction and design in Nuclear Power: A Systematic literature Review

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Abstract

Off-Site Modular Construction (OSMC) research has been a burgeoning research area over the past two decades due to low productivity of the traditional construction methods. Some large Gen 3 reactors may employ an on-site assembly area similar to shipbuilding techniques. This OSMC productivity has attracted the interest of the nuclear industry with over 50+ designs in commercial development. Off-site modular construction has been estimated to reduce the capital cost of an SMR by up to 37.98% compared to a stick-built method. The IAEA highlights the first commercial SMR "shop built and road transported to site" has an earliest operation date of 2026 (IAEA, 2018). This research paper aims to understand the current state of modular design in nuclear power by reviewing current literature with a systematic literature review. What can new small modular reactor designs learn from modularisation in large nuclear. What design and analysis techniques have been developed that may aid the design considering design, schedule, transportation and supply chain? What is the state of the art in the module design process? The research provides knowledge gaps and recommendations for further research.

Keywords

Systematic literature review,
Modular Nuclear Design,
Modular Nuclear Construction,
Small Modular Nuclear Reactor Plant,
Offsite prefabricated manufacture and construction

Abbreviations

Abbreviations	Description
BIM	Building Information Management/ Modelling
BOP	Balance of Plant
DSM	Design Structure Matrix
FOAK	First Of A Kind
HVAC	Heating, ventilation and Air Conditioning
IPCC	Intergovernmental Panel on Climate Change
LNPP	Large Nuclear Power Plant
LWR	Light Water Reactor
MEP	Mechanical Electrical Plumbing
MWe	Megawatt Electric
OSMC	Off-Site Modular Construction
PDMS	Plant Design Management System
PWR	Pressurized Water Reactor
P&ID	Process and Instrumentation Diagram
PFD	Process Flow Diagram
RCS	Reactor Cooling System
RPV	Reactor Pressure Vessel
SMR	Small Modular Reactor
VRE	Variable Renewable Energy
WBS	Work Breakdown Structure

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1 Introduction

The climate emergency has necessitated the move away from carbon intensive, fossil fuel energy generation to stop catastrophic climate change (IPCC, 2018). This has seen an exponential increase in wind and solar energy production over the past decade. However, although wind and solar electricity generation are cheap once construction is complete (no fuel costs), energy storage mechanisms are required once the integration of Phase 3+ (25%) Variable Renewable Energy (VRE) is reached (The International Energy Agency, 2019) and may become a major challenge by 2023. Some examples from integrated small scale energy grid systems may aid and make possible larger integrated grid systems (Kroposki, 2017).

Studies analysing 20-40% of wind integration find system integration costs, the cost to integrate VRE into electricity grid system (IEA, 2020), could increase generation costs by 35-50% (Hirth et al., 2015). German generation from renewables rose to cover 42.6% in 2019, the costs for Energiewende, the German transition to renewable energy, in the electricity sector up to 2030 is on the order of €600–700 billion (Unnerstall, 2017). A carbon tax of 30$/tCO2 in 2020 (growing by 5% per year), may increase VRE share over the period 2050–2100 to 62% of electricity generation (Pietzcker et al., 2017). Increasing renewables to 63% in 2050 would require 120 trillion USD in the REmap energy transition case (Steinbruner, 2014)

Nuclear power becomes more economically attractive at this point as it generates heat when the wind doesn't blow or when the sun doesn't shine. Nuclear power is a reliable source of low carbon power. The UN's Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2018) modelled future electricity generation and has forecast nuclear generation increases on average 2.5 times by 2050 over its 87 scenarios. Furthermore, 600GW of new nuclear may be needed by 2050 for net zero emissions (Lovering and McBride, 2020). Integrating higher levels of renewables may benefit from co-generation with nuclear (IAEA, (2019), Bragg-Sitton et al., (2020) and Forsberg and Bragg-Sitton, (2020)) providing energy for district heating (IAEA, (1998) and Reński et al., (2016)), desalination (IAEA, (2007), Ingersoll et al., (2014) and IAEA, (2015)), generation of hydrogen (Revankar and Bindra, 2019) and synthetic fuels, further increasing its economic potential (Locatelli et al., 2017). Indeed, most Small Modular Reactor (SMR) designs in development include considerations for at least some of these co-generation options and some reactors are designed specifically for district heating such as the DHR400, Happy 200, TEPLATOR, RUTA-70 and ELENA are stated for commercial operation in 2021, 2024, 2027 respectively (IAEA, 2020).

However, nuclear power costs have risen as accidents, regulation changes, political indecision and design changes have caused delays to building nuclear power plants in the 1980s and 90s (Lovering et al., (2016), Koomey et al., (2017), Gilbert et al., (2017) and Matsuo and Nei, (2019)) with one study finding up to 117% cost escalation (Koomey et al., 2017). The latest, First of a Kind, Gen 3 large nuclear power plants, such as the EPR (Teichel, 1996), and AP1000 (Schulz, 2006), in the western/ developed world, where cheap migrant labour is not an option, have been beset by delays and cost increases (Mignacca and Locatelli, 2020). These plants are based on economies of scale (Mandel, 1976), have multiple redundant backup systems but are difficult to construct. Economies of scale have ensured large nuclear power plants are complex, normally one off "megaprojects" , ensuring there are no learning benefits, and difficult to deliver on time and budget (Locatelli, 2018) as these western counties have lost their nuclear supply chain and expertise. Compared to technical progress in other industrial areas, the nuclear industry is considered slow largely due to the privacy and restricted amount of engaged research parties (Abu-Khader, 2009).

Generally, the construction industry has seen a decline in productivity over the past 40 years (Bock, 2015) and "modularising" by moving work off site, off the critical path, into an assembly area or dedicated factory where productivity is higher, has been developed as a solution. Modularisation in nuclear construction, by moving work off the critical path, has been considered (Stone & Webster Engineering Corporation, 1977) as well as techniques from other industries that might be applied (Technology Transfer Modularization Task team. DOE, 1985). Allen et al., (1988) suggested a modular construction method whereby equipment modules emanate from a spine of joined piping/electrical modules, aiming for easier construction. More in depth analysis into shipbuilding techniques for nuclear (Seubert, (1988) and Lapp, (1989)) were considered. This method of modularisation is concerned with "converting a large design to facilitate factory fabrication" (Mignacca and Locatelli, 2020). The typical example is the AP1000 plant, designed to be simpler (60% fewer valves, 75% less piping, 80% less control cable, 35% fewer pumps, and 50% less seismic building volume) along with modular piping, structural and valve modules (Sutharshan et al., 2011) and the reactor island split into 9 modules very large modules, utilising one of the world's largest cranes.

Moving work to Off-Site Modular Construction (OSMC) has increased productivity in construction in recent years (Jin et al., 2018) and the OSMC field has observed an exponential interest in research over the past decade (Hosseini et al., 2018). OSMC takes advantage of taking work off the critical path and the higher productivity in factories and can take more advantage from automation inspired by the automotive and manufacturing industries. A factory based workforce benefits from improved equipment, learner benefits, and a controlled environment (Bondi et al., 2016). OSMC has also seen interest in the nuclear industry defined as "shop built and transported to site for installation" by the International Atomic Energy Agency, (IAEA, 2020) with over 72 Small Modular Reactors in development worldwide. These are split into different technologies: 25 water cooled SMRs, 6 floating marine based water cooled SMRs, 14 High Temperature SMRs, 11 Fast Neutron Spectrum SMRs, 10 molten salt and 6 micro SMRs.

It is important to distinguish between the differences in modularisation in large nuclear power plants "converting a large design to facilitate factory fabrication" and smaller nuclear power plants "built by the assembly of nearly identical reactors of smaller capacity" defined as modularity (Mignacca and Locatelli, 2020) shown in Figure 2.

Although SMRs may not produce electricity at a significantly reduced cost compared to a large nuclear power plant (Mignacca and Locatelli, 2020), the main advantages of the smaller size of SMRs is the factory productivity, consequent easier construction management, lowering risk and the resultant reduced finance. This factory produced method may enable shorter build schedules, through productivity increases and parallel working (Locatelli et al., 2014). Further to this, standardisation and utilisation of commercial off shelf components enable direct cost reductions. Smaller plants also require much less capital compared to large reactors. Utility companies may therefore be more inclined to invest as there would be less risk.

This paper aims to understand the state of the art in modular design in nuclear power and provide recommendations for small modular reactors including what small modular reactor developments can learn from modularisation in large nuclear power, current nuclear design techniques and analysis from literature. This will be achieved through a systematic literature review.

2 Materials and Methods

The main aim of the paper is to understand the current state of modular design in nuclear power and their application to Small Modular Reactors. The lessons learned and highly recommended implementations from large nuclear power plants designs are considered. The paper does not consider structural modular design such as structural concrete (Braverman et al., 1997), steelwork, integrated Steel and Concrete (SC) or containment. This paper presents a Systematic Literature Review utilising a similar method as discussed in Jin et al., (2018) and Mignacca and Locatelli, (2020) and shown in Figure 1. The literature review search was performed on 10 March 2020.

The research aim of understanding the state of the art in nuclear power in this paper will be split into 4 objectives:

- What can small modular reactors learn from understanding the state of the art in current modularisation in nuclear power literature (both large and SMRs)?
- What is the state of the art in modular nuclear design process methods and recommendations?
- What are the latest design tools, analysis methods and considerations that may aid modularisation in SMRs?

To achieve this, search terms were identified for search in Scopus and the IAEAs International Nuclear Information System. The bibliometric research was set initially by inputting keywords in Scopus focusing on titles "TITLE", abstracts "ABS" and keywords "KEY". These search results were then initially screened for articles with keywords in different semantic meanings. A second round of screening was then conducted that removed articles that did not focus on the research question by reading the abstracts. Four separate searches in Scopus were performed denoted below and summarised in the appendix to allow repeatability of the search:

- Modular design in nuclear power

The search for "TITLE-ABS-KEY ("modul* design" AND nuclear AND power OR reactor OR plant)" provided 214 Scopus search results. After careful consideration of titles and abstracts, only 11 research items were identified as relevant to the research questions.

- Modular construction in nuclear power

The search for “KEY (modular AND construction AND nuclear) provided 266 Scopus search results, after careful consideration of titles and abstracts, only 8 research items were identified as relevant to the research questions.

- Modularization in nuclear

The search for “TITLE-ABS-KEY (modularization AND nuclear) provided 148 search results. After careful consideration of titles and abstracts, only 9 research items were identified as relevant to the research questions.

- Modular balance of plant in nuclear

The search for “TITLE-ABS-KEY (modul* "balance of plant" nuclear) provided 53 search results. After careful consideration of titles and abstracts, only two research items were identified as relevant to the research questions.

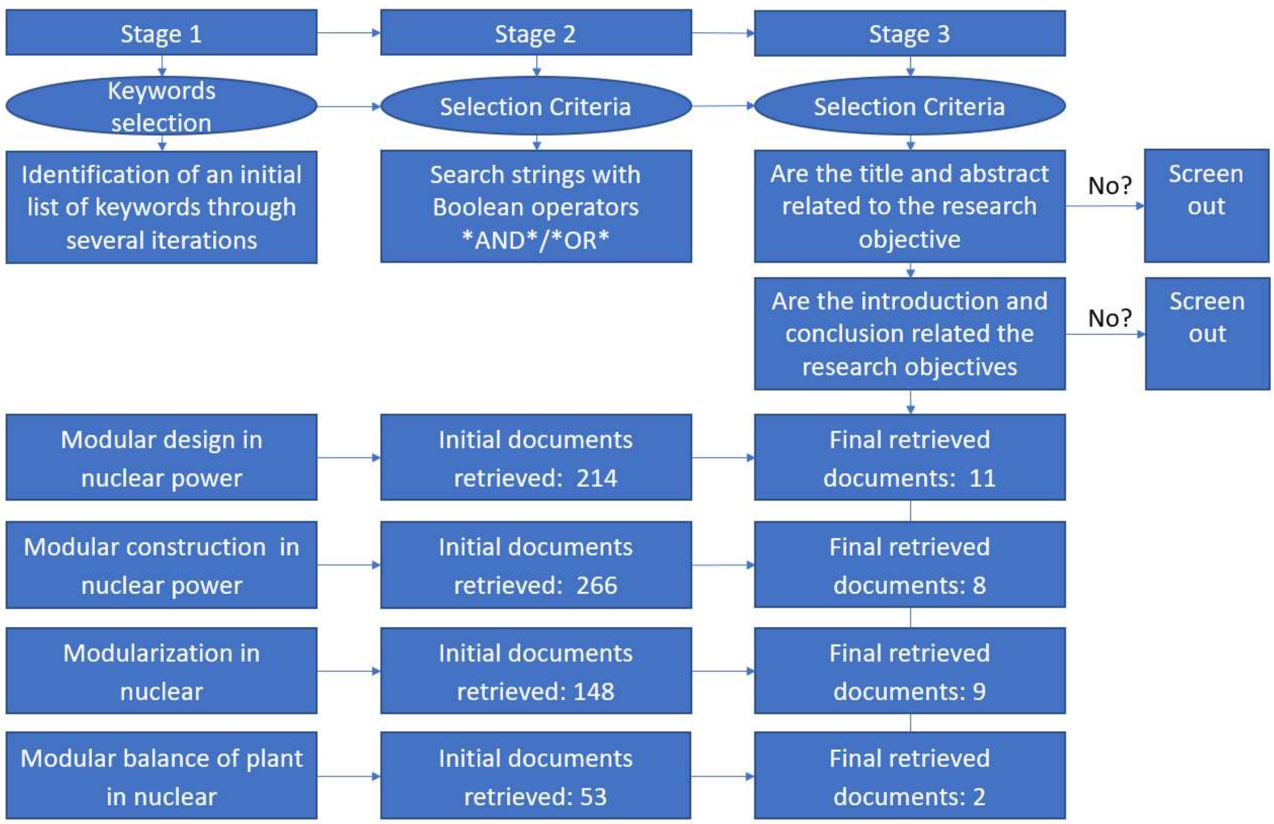

Figure 1 - Systematic Literature Review method adapted from Jin et al., (2018) and (Mignacca and Locatelli, 2020)

3 Results and discussion

This section discusses the results of the analysed literature. Starting with definitions of modular in nuclear power, the construction problems of large reactors, the movement towards small off-site nuclear power plants, modular design processes, tools and analysis for modularisation, lessons learned and recommended "advanced" construction techniques from large nuclear reactors.

3.1 Definitions

Upadhyay and Jain, (2016) describe the classification of modularity as scale "large capacity NPP is constructed by combining multiple identical NPPs of small capacity", scope " a large capacity single reactor NPP is constructed such that the NPP project is divided into a number of matching units for installation" and comprehensive modularity "a large-scale plant encompassing both the scale and the scope". In research by Mignacca and Locatelli, (2020) scope is defined as modularisation, modularity is defined as both scale and comprehensive modularity (Figure 2).

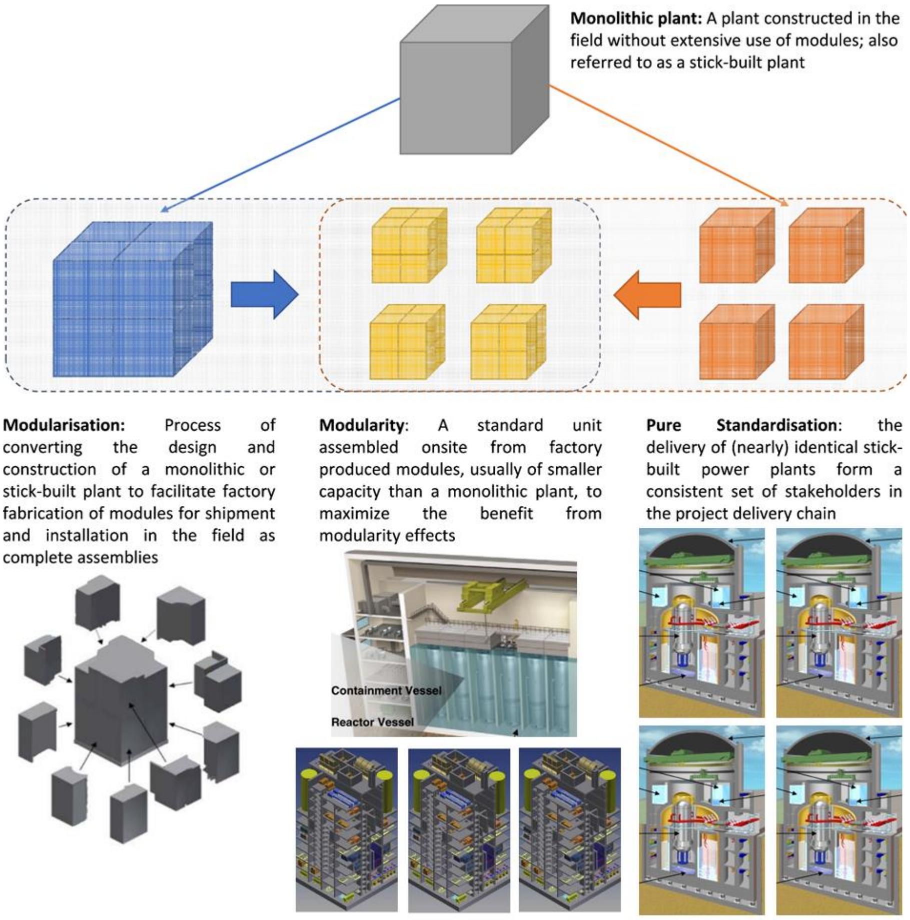

Figure 2 – (top) Definitions of Modularisation, Modularity and Standardisation (Mignacca and Locatelli, 2020). Partitioned large nuclear steam supply system (left, AP1000), Nuscale combined integrated modules (middle top, Ingersoll et al., 2014), integrated Westinghouse SMR NSSS modules (middle bottom, Giovanni Maronati et al., 2018) standardisation see Hanul Nuclear Power Plant (AB1600 plant in right picture (Arai et al., 2008))

3.2 Economics and Schedule Reductions of Large Reactors

Projects in Asia (Korean OPR-1000, APR-1400, UAE and VVER) and the German Konvoi designs have found success with standardised designs and cheap labour. However, in America and Europe and to some extent Japan, nuclear power costs have increased as accidents, regulation changes, political indecision and design changes have caused delays to building nuclear power plants in the 1980s and 90s (Lovering et al., (2016), Koomey et al., (2017), Gilbert et al., (2017) and Matsuo and Nei, (2019)). Here, nuclear plants have not been built for decades and therefore they have lost their supply chain and construction expertise, and new projects have encountered massive delays and cost increases. Modularising, by moving work off the critical path, to on site or off-site assembly, has been proposed as a method to reduce costs.

Studies that consider building parts of a large nuclear plant in an offsite factory and assembling on site estimate 12-15% can be saved on capital costs and a 25% decrease in the schedule. These include a Stone & Webster Engineering Corporation Report , (1977) which estimated $10-14 million in 1977USD could be saved, up to 12% of total capital costs, by modularisation of civil, mechanical, piping and electrical parts of the plant. The Technology Transfer Modularization Task team, (1985) estimated 12% of capital costs could be eliminated and the schedule reduced by 25%. Lapp, (1989) also estimated that capital cost savings of 15% could be achieved. These studies compare with oil and gas modularisation cost savings of up to 20% and up to a 50% reduction in the schedule (Mignacca et al., 2018) but do not seem to have translated into practice.

3.2.1 Current large reactor experience

The AP600 and A1000 were estimated to have produced cost reductions of 20% to 30% (Schulz, 2006) compared to competing large designs and for the cost of electricity to be between 1300-1500 $/kW for the AP600 (Winters et al., 2001) and 1000 $/kW for the AP1000. Fang et al., (2012) defined the “Modularity Degree” definition the percentage of the plant that is “modularised”. They compare a stick-built AP1000 “CA20 Module” cost (defined as a reference of 1) to the percentage of modular construction multiplied by cost ratios for prefabricated steel structure (8.5 cost ratio compared to stick built) on-site assembly & installation (2.5) and concrete placement (0.3) and conclude construction cost would be 30% higher. However, the shorted construction period ensures “that the plant can be built with a lower investment and cost”. Only 16.5% of the Auxiliary

Building concrete is “modularised” whereas 31.4% of the containment building concrete is modularised. Mechanical modules are 1% of the total cost. However, the 36-month AP1000 construction schedule has not been achieved with AP1000 plants at Vogtle, Haiyang and Sanmen all taking over 8 years to construct, and Virgil C. Summer units cancelled. If current Vogtle cost estimates of over $25 billion hold true, the cost of electricity would be 12500$/kW representing a 1150% increase on initial estimates (Ingersoll et al., 2020). Some of the AP1000 delays can be attributed to the construction of the basic concrete and rebar foundation, inexperienced nuclear construction companies, poor management, over regulation and deliberate delays by construction companies to increase profits (Giovanni Maronati et al., 2018) even though construction management practices have been extensively detailed (IAEA, 2011). Recently, Maronati and Petrovic, (2020) developed an approach to assess the range of possible risks and delays to the construction schedule “the unknown unknowns”, and evaluate their effect on cost and uncertainty in the construction schedule, offering necessary contingency plans.

The EPR encountered manufacturing and construction problems (Garnsey et al., 2010) leading to delays (Thomas, 2010). Thomas concludes the design is too complex, affecting its buildability for efficient construction. The previous generation 1450 MWe class (N4 design) again encountered thermal fatigue flaws in the heat removal system requiring redesign and replacement leading to a construction time of over 14 years. On the other hand, EDF, (2020) highlight a number of schedule reductions for the second EPR unit reactor base at Hinkley point C such as installing steel 45% faster, 50% reduction in cooling system components installation time and the liner cup floor construction reduced by 30%. They also highlight increasing use of prefabrication in factories as a success factor. A second plant at Sizewell C could decrease costs by 20% compared to Hinkley point C (Thomas and Mancini, 2020). This suggests standardisation and economies of multiple, leading to learner benefits (improving experience in the supply chain and management) can play a very important role in reducing nuclear power construction costs.

The APR1400 is designing and testing composite SC, mechanical & electrical modules (Lee et al., 2010). APR1400 units at Shin-Kori, Shin-Hanul and Barakah have maintained construction schedules over 7-9 years. Barakah 3&4 may maintain a construction schedule of 6 years, again showing the benefits of standardisation and learning from economies of multiples.

A large (1000 MWe) integral reactor concept may reduce costs by 5.84%–13.02% compared to other large reactors (G. Maronati et al., 2018). Although, utilising new technology such as Micro channel primary heat exchangers that may have a lower technology readiness level may increase construction risk and further work would be required to validate the design.

However, economies of scale have ensured large nuclear power plants are complex, normally one off "megaprojects", ensuring there are no learning benefits, and difficult to deliver on time and budget (Locatelli, 2018).

3.2.2 The movement towards Small Modular Reactors

Lloyd, (2019) estimates only 20% of large reactors can effectively be "modularised" off-site, whereas smaller reactors may offer up to 80% of construction off site, allowing to take much more advantage of off-site manufacture. The SIR integral design emerged in 1991 (Hayns and Shepherd, 1991), (Matzie et al., 1992) which focused on modularising the Nuclear Steam Supply System into an integrated module. This had the advantage of the elimination of a loss of coolant accident, enhancing safety while reducing costs. There is a lot of interest in SMRs with over 72 Small Modular Reactors (SMR) in development worldwide. These are split into different technologies accordingly such as 25 water cooled SMRs, 6 floating marine based water cooled SMRs, 14 High Temperature SMRs, 11 Fast Neutron Spectrum SMRs, 10 molten salt and 6 micro SMRs (IAEA, 2020).

3.2.3 Economics of SMRs

Multiple economic analyses estimate smaller, factory-built power plants can offset the economies of scale of larger plants with factory productivity, standardisation, reduced finance, reduced risk and economies of mass production and highlight SMRs can be at least as cheap as the latest large reactors (Mignacca and Locatelli, 2020) (Lovering and McBride, 2020) shown in Figure 3.

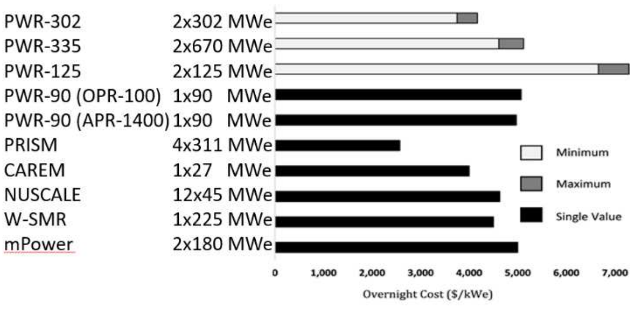

Figure 3 -SMR Overnight Cost Estimations (Mignacca and Locatelli, 2020)

Mignacca and Locatelli, (2020) provide a detailed cost analysis into all economic aspects of a small module reactor plant (SMR) and highlight more effort should be focused on a programme level perspective. Other different economic analyses predict SMRs can reduce costs compared to a large reactor by 17% (Carelli et al., 2010), 29.95% (Giovanni Maronati et al., 2018) and 37.98% (Black et al., 2019).

Giovanni Maronati et al., (2018) highlight that a general heuristic from shipbuilding shows work done in a factory can be 8 times more productive (Barry, 2009) than stick building at site (Figure 4), useful for when considering what parts of the plant to modularise, with more congested areas gaining the most benefit.

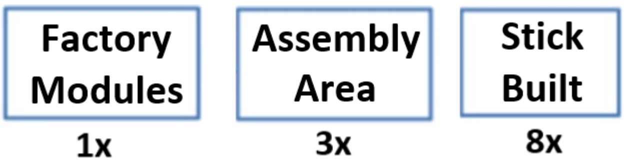

Figure 4 – 1-3-8 rule from shipbuilding (Giovanni Maronati et al., 2018)

Mignacca and Locatelli, (2020) highlight cost reductions can be achieved through: Building Information Modelling (4–10%), open-top construction (2%), co-location (5-14%), learning (5%-10%), construction schedule (20%), O&M (+19% to -20%), decommissioning (13%-20%). Whereas the Generation IV International Forum, (2007) guidelines for estimating Factory-Produced Modular Units recommend a number of reductions can be achieved (Table 1), the largest being reduced finance through schedule reduction and direct labour savings from a factory workforce.

Consideration	**Stick-Built plant**	**Modularised Plant**	**% Reduction**	
			low	high
Direct construction cost	All field construction	With shop fabrication	0	5
FOAK – NOAK Learning effect	Larger plants, less doubling of experience (8 each)	Smaller plants, larger number of plants for same capacity (32 each)	0	10
Direct labour	All field construction	Transfer to shop	30	50
Direct labour hours (productivity)	Direct hours	Reduced field work, lower worker densities, improved access	10	25

Construction/ installation schedule	Regular work schedule	Parallel construction, early start fabrication, reduced field work	30	50
Field indirect cost	Regular work schedule	Reduced field work, reduced construction schedule	30	50
Field management costs	All field construction	Reduced field work, reduced construction schedule	15	25
Direct cost contingency	All field construction	Shop safety, security, environment, seasons, support, interference, logistics, controls, etc.	10	20
Owner's costs	Regular work schedule	Early plant start-up, factory and site	0	10
Supplementary costs	All field construction	Provisions for D & D	0	
Capitalised finance cost	Regular work schedule, all field construction	Parallel construction, early start fabrication, early start operations	30	50
Annualised costs	Regular work schedule	Designed for Operation and Maintenance	0	5
Total				
Robotics and automation	Minimum utilisation	Future potential	30	50
Autonomous Electric Transport (Wrigley et al., 2018)		2% of the resultant module total cost.	0	2

Table 1 - Comparison of stick-built and modular plant features (Generation IV International Forum, 2007)

3.3 Modular Design methodology

There are two methods to modularise the nuclear island and nuclear steam supply system, breaking a large system down by partitioning or integrating the system into one module (Figure 5). Integrated modules can be combined to form a larger plant. “Packaging of the Nuclear Steam Supply System for shop fabrication” technologies were introduced (Technology Transfer Modularization Task team. DOE, 1985), and onsite assembly using shipbuilding techniques was studied further (Lapp, 1989) and implemented in the AP1000 (Sutharshan et al., 2011) shown in Figure 5 (left).

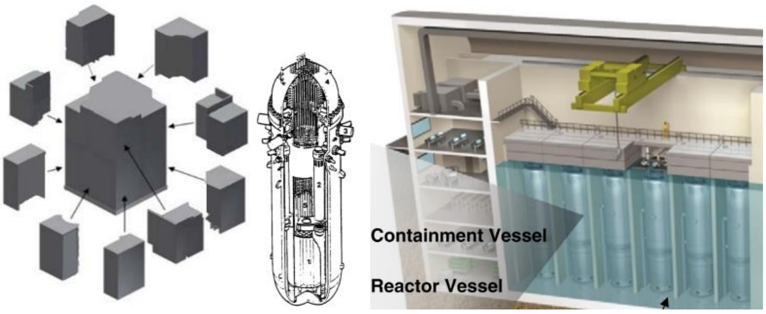

Figure 5 – Partitioned nuclear steam supply system, integrated modules and combined integrated modules

The chosen method will depend on the economics of each method with the largest size of integral reactor being around 300MWe depending on transport constraints (IAEA, 2020).

3.3.1 Balance of plant/ secondary systems modules analysis

With the nuclear island taking up 28% of the whole plant costs (World Nuclear Association, 2020), modularising the rest of the plant may also provide significant benefits to associated costs in the Conventional island (15%), Balance of plant (18%) and site development and civil works (20%).

A few studies have considered the modular design and cost savings of the conventional island and balance of plant. The Stone & Webster Engineering Corporation, (1977) modularisation report showed that civil parts of the plant may be modularised, saving $1.5million+ (1977 USD) on Reinforcing and Structural Steel and over $4million+ (1977 USD) on Precast Concrete. It also highlighted pipe racks could save between $3-6million (1977 USD), along with savings in electricals and equipment (Figure 6).

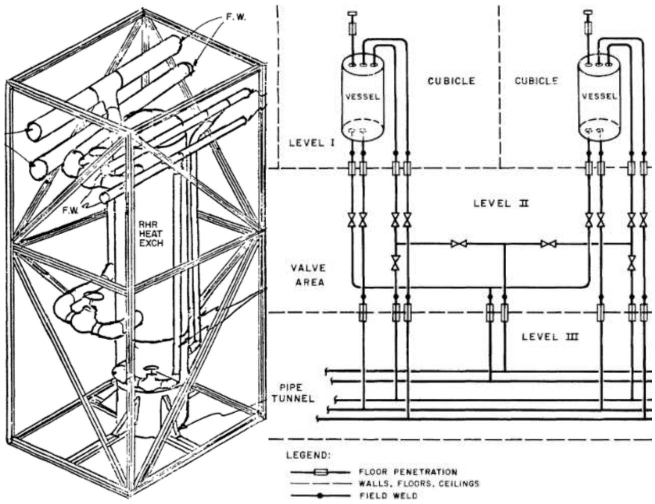

Figure 6 – Modules for RHR (left) and demineraliser equipment (Stone & Webster Engineering Corporation, 1977) (from the OSTI - U.S. Department of Energy database)

Allen et al., (1988) suggested a modular construction method whereby equipment modules emanate from a spine of joined piping/electrical modules.

The virtual factory method of constructing a reactor (Figure 7) using component module space frames was introduced by Kadak and Berte, (2006).

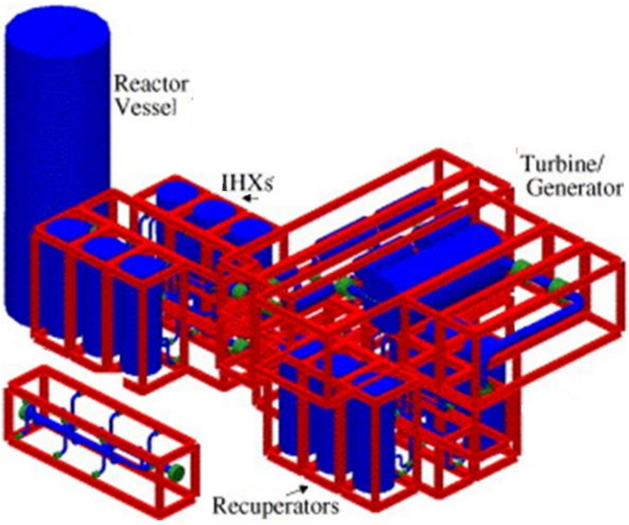

Figure 7 - Modular pebble bed reactor designed with space frames and a "virtual Factory" (Kadak and Berte, 2006)

In this method, the equipment items are placed into the discrete space frames by the component manufacturers. The virtual factory technique eliminates the need and costs for a balance of plant assembly factory. The disadvantage is increased labour on site as there are a larger number of individual modules, necessitating additional attachment work, contrary to the SMR goal of 'factory built'. Consequently, this technique could be more suitable to 'one off' construction developments(research reactors and prototypes), where learning rates and additional capital costs would be more than the additional site costs.

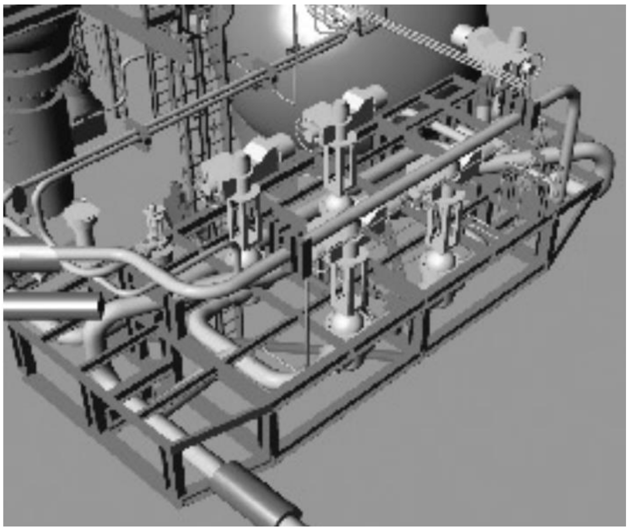

Figure 8 – AP1000 piping module (Sutharshan et al., 2011)

The AP600/AP1000 plants use over 270 modules including piping (Figure 8) structural, and valve modules (Figure 9), designed to be rail transportable (Schulz, 2006). Although being designed for rail or barge transport may have impeded their transportability and utilising inexperienced nuclear contractors caused construction problems and delays (Giovanni Maronati et al., 2018).

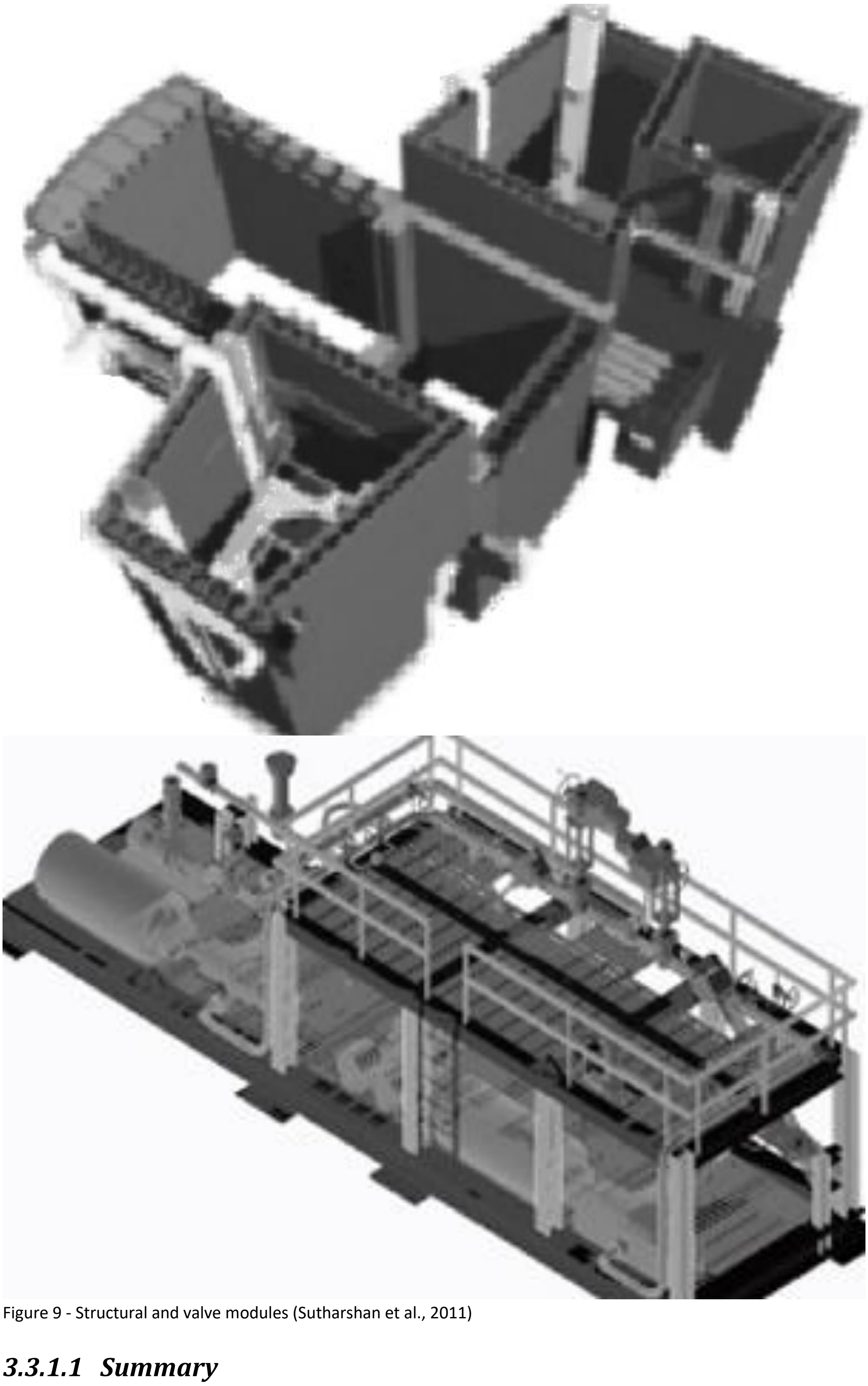

Figure 9 - Structural and valve modules (Sutharshan et al., 2011)

3.3.1.1 Summary

Research so far has considered designing the module to fit the system. Rather than being designed for rail or barge shipping, factory-built modules should be designed for maximum road transport limits to enable easier logistics and accessibility and to ensure more work is moved off site. This would require a change in strategy to design the system to the module rather than designing the module to fit the system. A standardised module grid for standardised modules may benefit construction through methods such as those utilised in oil and gas and industrial process plants (Figure 10). A standardised grid would enable easier planning, manufacture, construction and reduce errors over the whole process. Equipment from the Shearon Harris 900 MWe power plant was analysed for road transport and found a number of the equipment would be too large for standardised road transport (Boric Acid Tank, Recycle holdup tank, Turbine Driven AFW Pump) and may need to be redesigned for road transportable modules (Wrigley et al., 2020).

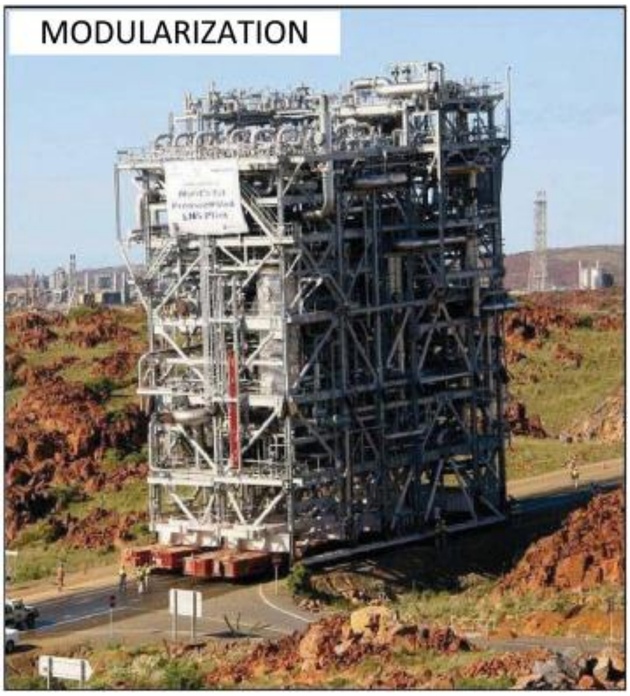

Figure 10 – Economically successful modularisation in oil and gas industrial process plant (Mokhatab et al., 2013) ©Elsevier

3.4 Design methods and tools

This section will cover the research articles regarding design methods and tools.

The Technology Transfer Modularization Task team, (1985) studied a number of industry examples of modularisation in areas such as Shipbuilding, Petrochemical, Aerospace, Automobile, and the Heavy Lift Industry. The report also highlighted several smaller, advanced modular reactors that were in development. It suggested a 600MWe Light Water Reactor (LWR) plant for modularisation that results in total capital costs which are 12 percent lower and a reduction in the overall schedule from 8 years to 6 years. New nuclear projects should again consider updated lessons learned investigations into these industries. Shipbuilding techniques were then studied for application in nuclear power (Seubert, 1988) discussing the Product Work Breakdown Structure (PWBS) for different modularised naval vessels and their possible application to a nuclear power plant.

A Design (or Dependency) Structure Matrix (Eppinger and Browning, 2018) was created for the Shearon Harris Westinghouse 3 loop DRYAMB plant systems, showing interacting systems (Lapp, 1989). The N^2 systems engineering analysis method (Bustnay and Ben-Asher, 2005) was implemented to reorder and cluster highly linked systems (Figure 11). These clustered and highly linked systems indicated they should be closely adjacent to each other when designing the plant and this was used as a heuristic guide to assign system equipment to plant areas (Figure 12). An onsite assembly area technique was also proposed, similar to shipbuilding methods, to take work off the critical path, minimising the construction schedule, observing efficiency growth leading to lowering costs and higher quality. When taking an onsite assembly approach derived from shipbuilding, the work can be approximated as 3/8th the time it would take to complete in situ (Barry, 2009). This approach is used on the latest large gen 3 plants (Westinghouse AP1000), involving breaking down the nuclear steam supply system into 9 large modules (Figure 5 (left)) to be assembled in an on-site factory and one of the world's largest cranes. The authors highlighted potential capital cost savings of 15%.

System Number	4	1	3	2	8	5	23	7	9	11	22	13	18	25
4	1	0	0	27	0	0	0	0	0	4	0	0	0	0
1	0	1	72	96	36	33	7	0	0	0	2	0	0	0
3	0	72	1	18	24	6	0	0	0	0	0	0	0	0
2	27	96	18	1	0	9	3	6	0	0	0	0	0	0
8	0	36	24	0	1	12	0	36	40	40	2	0	0	0
5	0	33	6	9	12	1	6	20	32	0	2	0	0	0
23	0	7	0	3	0	6	1	19	0	4	0	2	0	0
7	0	0	0	6	36	20	19	1	0	4	4	9	0	0
9	0	0	0	0	40	32	0	0	1	0	0	0	0	0
11	4	0	0	0	40	0	4	4	0	1	5	0	0	0
22	0	2	0	0	2	2	0	4	0	5	1	0	0	0
13	0	0	0	0	0	0	2	9	0	0	0	1	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	1	0
25	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Figure 11 - Reordered systems matrix from (Lapp, 1989)

Traditional plant design utilises the heuristic knowledge of the design engineer to layout a plant. Utilising knowledge based engineering techniques, (the capture, reuse, codification and analysis of data (Rocca, 2012)) can enable design engineers to create designs more easily and faster (P. Wrigley et al., 2019) by taking as much as 80% of time out of the traditional design process (Skarka, 2007). Layout optimisation using mathematical programming was developed in the 1980s to help plant designers layout industrial plants (Moran, 2016), (Ejeh et al., 2019). This was successfully applied to a Mitsubishi Nuclear Power Plant design with the automation of constraints generated by an expert system (Fujita et al., 1995). Wrigley et al., (2019) developed on previous work (Lapp, 1989) by using a simple quadratic assignment linear programming model solved through a genetic algorithm to arrange modules in the plant , lowering the objective function of reducing pipe length from 14914 to 8036, a reduction of 46% (Figure 12). Piping can be up to 20% of an industrial plant costs (Moran, 2016), however, more detailed analysis would be required to understand nuclear regulatory constraints for spatial separation of safety systems.

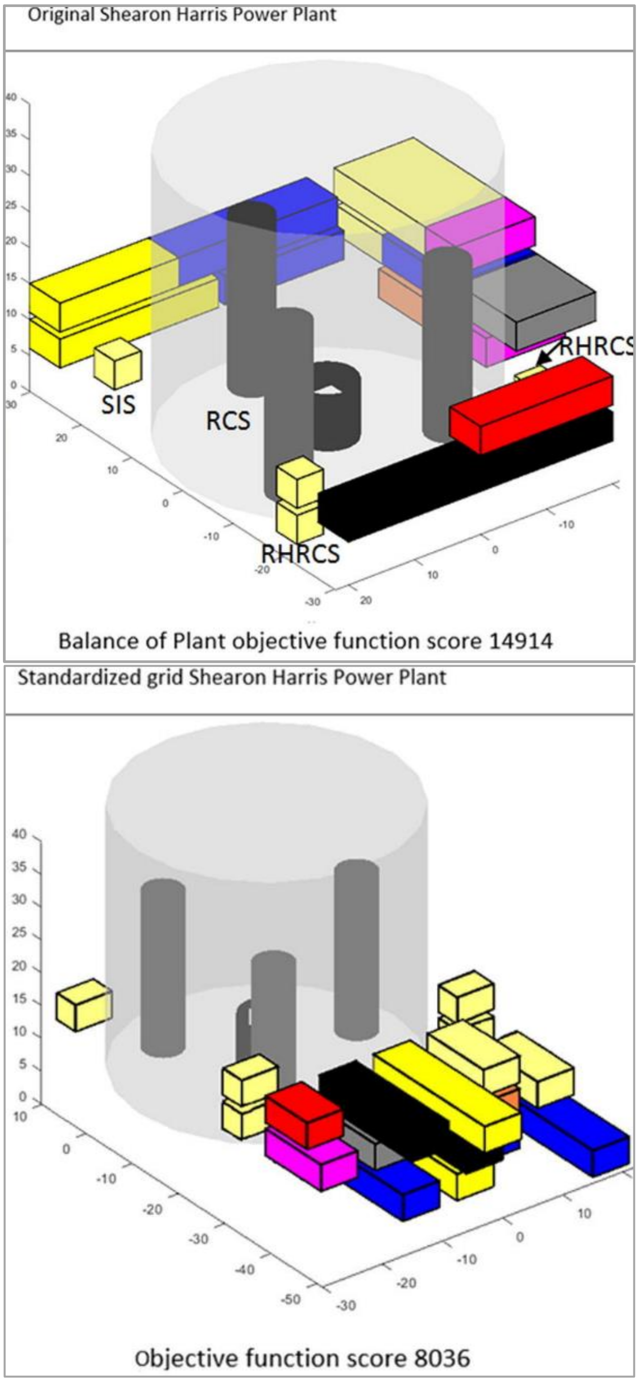

Figure 12 - (Lapp, 1989) highly clustered systems assigned to plant areas (left), optimised module layout (right) (P. A. Wrigley et al., 2019)

Modular nuclear power plant design and construction was discussed for modification projects (Morton et al., 1989), which may be useful to consider when designing nuclear power for off-site construction.

3.4.1 Plant size vs modularisation model

Clara A Lloyd and Roulstone, (2018) expand upon the degree of modularisation work by Fang et al., (2012). Using an economic model to analyse modules from Stone & Webster Engineering

Corporation, (1977) for road transport limits such as reinforcing steel, structural steel, liner, precast concrete modules and mechanical modules, they recommend at least 60% of a 300MWe SMR plant is modularised to be cost competitive with a large plant. The aim for SMRs would be to move as much work to an offsite factory as possible. More detailed analysis would be required to understand which parts of the plant gain a benefit from this method.

3.4.2 Schedule analysis

Clara A. Lloyd and Roulstone, (2018) also describe a methodology to translate a large reactor build schedule (Sizewell B) into a build schedule for an SMR. They analyse several different theoretical power plant sizes with regards to construction duration. They concluded that a 20% reduction in schedule could be possible with a 66% degree of modularisation for a 300MWe SMR (Lloyd, 2019) and transportation logistics are the factor that limits the maximum attainable degree of modularisation for components, whereas structural modules are larger and harder to transport.

3.4.3 Transportation and logistics

Mignacca et al., (2019) highlighted several factors to be considered in SMR design, focusing on transportation, and crane options. They recommend early communication and engagement with transportation companies in the design stage. Furthermore, the "best transport method" for SMR modules is reliant on the site of the SMR construction. Factors can be considered after the location of the SMR site is decided such as insurance, special equipment, licences, quality control, possible incidents and obstructions, environment, etc. For standardisation of an SMR plant, it may be useful to employ a centralised module factory, and for those locations that may allow shipping or barge transport, utilise a shipyard to assemble to modules into larger modules, depending on shipyard, transportation and site constraints.

3.4.4 Supply chain analysis

Lyons and Roulstone, (2018) analyse the supply chain for modularisation, recommending at least 10 GW of 250 MWe standard units is needed to achieve sufficient production volume and production rate for cost competitiveness for optimal economies of scale and learning (Lyons, 2020).

3.4.5 Heat Exchanger sizing

The log mean temperature difference method was used to size heat exchangers on the IRIS plant. Each equipment item is positioned for functionality considering the modularisation aspects of design. Finally, factors of improved accessibility for maintenance and construction are indicated (Williamson and Townsend, 2003).

3.4.6 Systems description

Memmott et al., (2012) discuss the balance of plant (BOP) systems designs for the Westinghouse Small Modular Reactor which leverages existing AP1000 designs and considers minimising the size of equipment to facilitate rail shipping. It is, however, mainly a systems description document and does not discuss much design for modular construction. A description of the Westinghouse SMR building layout was provided and indicated how the design features improve the safety and robustness of the plant (Cronje et al., 2012).

Small Modular reactor programmes should consider cutting edge integration of all design software such as requirements management, model-based systems engineering, construction and project scheduling, 3D design and construction software and Building Information Management (BIM).

3.5 Modular Design process

Small modular reactors need to integrate module design into the whole plant design process. Several research articles have considered the design process for modules.

Akagi et al., (2002) define Hitachi's module design strategy, they recommend and propose a new design process completing module design in parallel with layout design (Figure 13).

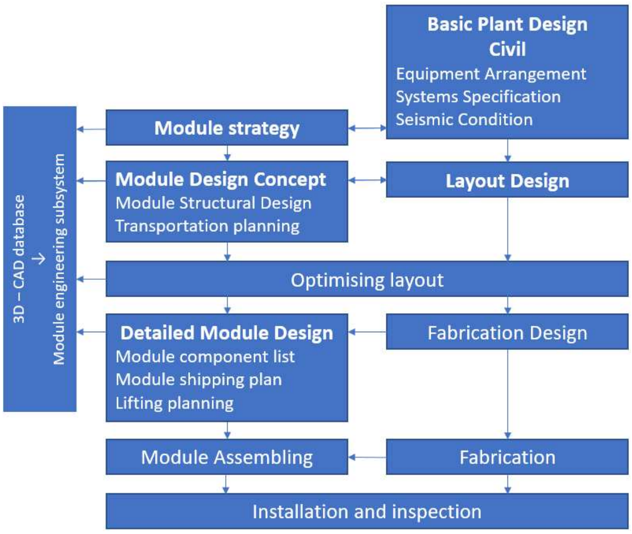

Figure 13 – Hitachi's parallel module design process (Akagi et al., 2002)

The module design process recommends the following considerations at each stage:

1. Selection of module strategy for an area, either stick built or off-site module by examining critical paths in the construction schedule.
2. Module design concept stage, considering Installation, schedule, temporary structures, and integration with other site areas.
3. Structural design considering crane capability, installation schedule, transportation method and installation procedure
4. Transportation scheme and module size are decided considering factors such as the installation method, the limitations of transportation, transportation costs, the design/ manufacturing schedule, delivery date requirements, the storage capacity at the location and transportation planning
5. Design, material, manufacturing, transportation and installation costs are compared to the stick built costs. This analysis was detailed further in Takada et al., (2005)

Yotsuya et al., (2004) outline Hitachi's plan for composite modularisation "integrated civils, mechanical and electrical" considering transportation, SC structures and the management plan. This is further refined in Obata et al., (2010) suggesting open top construction for modules built on site, large crane and large modules utilisation (Figure 14).

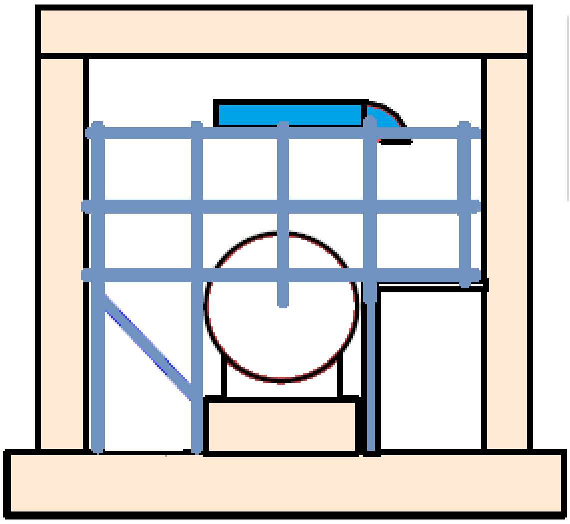
Figure 14 - open top construction for modules

Smith et al., (2013) further refine Hitachi's module design strategy for the Advanced Boiling Water Reactor, suggesting to review lessons learned from previous projects first and identifying project modularisation factors early, such as construction, procurement, cost, layout, construction site factors (safety, access, lay-down areas, infrastructure crane capacity), location factors (labour, environmental, local factors, unionised workforce) transportation and module assembly facility factors. They highlight a number of other more detailed stages in their design process such as:

1. Rules and guidelines for module development, define module boundaries/ sizes,
2. Schedule, cost and constructability analysis
3. Risk analysis
4. Module plan
5. Detailed design including planning, transportation and design factors
6. Procurement
7. Construction consideration and planning

Barry, (2009) details the types of modules made in submarines and GE Hitachi, the test procedures used, and how to protect them in transit.

Lu et al., (2013) describe the CPR1000 modular design process (Figure 15), which is then integrated with the AVEVA Plant Design Management System (PDMS) and provided an example of the method being utilised for an equipment item module (Tank and valves). It was also applied to the steel containment modularisation for the CPR1000 plant (Lu, 2013).

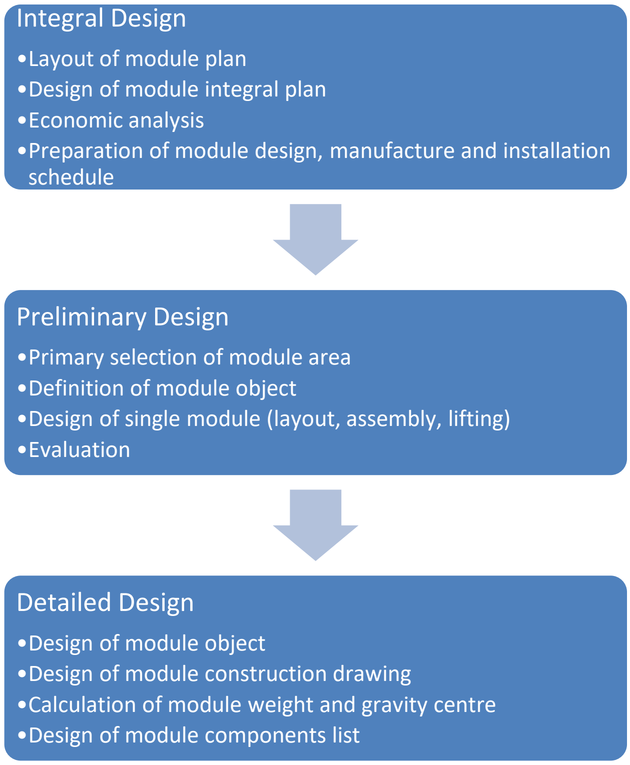

Figure 15 - Modular design process (Lu et al., 2013)

Wrigley et al., (2018) again consider several factors for modularisation in the design process such as assessing the project applicability considering location, logistics, geography, supply chain, multiple units, local workforce. The next step is to define the build strategy considering manufacturing facilities and locations, lifting/transport equipment, customs and export requirements, government transport requirements (vehicle size, police escorts, weight constraints, requirements/lead time for permits), community and environmental risks and at site transport logistics. After this the module configuration is decided, designing the modules to the system, designing the system to modules and system breakdown. The module interfaces and definitions are set and integrated design tools are considered (Computer aided design (CAD), Plant Design Software (PDS), Building Information Management (BIM), Product Lifecycle Management (PLM), Construction schedule tools and VR).

Akagi et al., (2002) recommend the application of 3D cad throughout the whole design and construction process (Figure 13) which helps integration and planning across all disciplines. Along with the simplification and streamlining of module manufacturing through a module factory including new technologies for the module factory such as: Intelligent pipe welding system, real-time self-welding quality checking, automatic lifting and handling horizontal level controller, a 3D laser measurement system. They also recognise a number of problems with modularisation:

- Temporary structures to ensure module integrity for transportation and lifting,
- Cost Evaluation of large modules vs low density modules
- Earlier engineering management is required
- Delivery planning and scheduling is increased

Furthermore, recent developments in building design software such as Building Information Management should be considered for new nuclear power plant designs.

3.6 "Advanced" large nuclear construction techniques

León et al., (2009) analyse a number of recent large nuclear construction projects including Kasiwazaki, Lingao, Qinshan, Tarapur, Shin Kori, Olkiluoto, Kudankulam-1. They summarise construction methods to shorten the construction period such as open top installation, advanced welding techniques, steel plate reinforced concrete and slip-forming, prefabricated modular rebar assemblies and automated rebar installation examples, all weather construction, bending small bore pipes to reduce welding requirements, excavation methods, cable rollers and splicing for cable installation, improved zoning for schedule management, holistic centralised digital databases for information management and control for all parts of the design process and linking it to 3D design and scheduling.

3.6.1 Korea

Jung et al., (2010) discuss the experience and insights from research and development and recent nuclear construction projects in Korea. Effective use of open top construction, Steel plated concrete, flux cored arc welding and automatic welding, the elimination of elbow fittings through bending of small bore pipe the parallel installation of Reactor Pressure Vessel (RPV) internals and the Reactor Cooling System (RCS), the application of a 3D-CAD system for information and control were highlighted as successful. They suggested mechanical rebar splices need improvement. Areas that still need improvement and further research are highlighted as the need to complete the total plant design before fabricating modules; the need for factories or workshops to fabricate modules; earlier expenses on engineering, materials and components for fabricating modules; the need for expensive heavy lift cranes; and the costs of transporting the modules.

A decision-making tool comprising of a screening and weighting criteria was developed in order to aid module selection (Lee et al., 2010). They detail a mock-up test of a composite module and provide recommendations for future research such as the fact that steel plated concrete has comparatively decreased strength requiring improvement of the structural integrity in earthquakes and therefore the adoption of seismic isolation should be considered. Questions over the lifetime durability of steel plated concrete remain and consequently should be applied selectively. Further study is also required where different structural types meet. Clara A. Lloyd and Roulstone, (2018) highlight recent research may provide more information and suitability on the design and implementation of steel plated concrete (Laing O'rourke Plc., 2016).

3.6.2 Hitachi ABWR

Obata et al., (2010) suggest open top construction for modules built on site, large crane and large modules utilisation, all weather construction utilising a temporary removable roof and 3D animated computer aided construction planning.

4 Conclusions and Research directions

600GW of new nuclear may be required globally by 2050 for net zero carbon and both large and small modular reactors may have a part to play (Lovering and McBride, 2020). This paper reviewed modular design and construction in nuclear power, highlighting lessons learned for SMRs, design configurations, design tools and analysis methods that may aid the design of new SMRs.

4.1 Lessons learned from large nuclear

The nuclear industry in America and Europe has lost vital experience in construction, management and the supply chain, often meaning reactors are delayed and overbudget. Large plants designed for economies of scale have ensured these plants are complex, normally one off "megaprojects", ensuring there are no learning benefits, and difficult to deliver on time and budget (Locatelli, 2018). Some of the AP1000 delays can be attributed to construction of the basic concrete and rebar foundation, inexperienced nuclear construction companies, poor management, over regulation and deliberate delays by construction companies to increase profits (Giovanni Maronati et al., 2018). EPR manufacturing and construction experienced problems leading to delays (Thomas, 2010). Thomas concludes the design is too complex, affecting its buildability for efficient construction.

Standardisation has shown repeated designs can enable learner benefits to reduce costs in Korea, German Konvoi and VVER designs.

Lessons learned from large nuclear construction state that projects require better construction management, open top construction, improvement and automation of rebar, all weather construction, SC concrete, early design freezing, integration with 3D based design and "4D" construction schedules. These lessons learned and the lessons learned from AP1000 and EPR should be taken into consideration when designing small modular reactor plants.

4.2 Modular design

Modular design has been present for decades in nuclear power as highlighted by the Stone & Webster Engineering Corporation, (1977) report. Small modular "packaging of the Nuclear Steam Supply System for shop fabrication" technologies were introduced slightly later (Technology Transfer Modularization Task team. DOE, 1985), with a number of small modular nuclear plants discussed at the 1983 ASME Joint Power Generation Conference in Indianapolis. Packaging of the Nuclear Steam Supply System for onsite assembly using shipbuilding techniques was studied further (Lapp, 1989) and implemented in the AP1000 (Sutharshan et al., 2011). The AP1000 has encountered construction problems due to its large size, lack of economies of learning and inexperience in construction and management.

However, “modularisation” by moving work off the critical path has been shown to reduce construction schedules in industrial process plants (Mignacca et al., 2018). It has also been shown that only 20% of a large nuclear plant may be modularised off site and that smaller reactors may benefit more from factory build as up to 80% of the construction work may be moved off site (Lloyd, 2019). Economic analysis has shown that small modular reactors may be at least as cheap as current large reactors, able to offset the economies of scale through factory productivity, standardisation, reduced finance, reduced risk and economies of mass production (Mignacca and Locatelli, 2020) (Lovering and McBride, 2020). Small modular integral reactors have been highlighted to reduce costs by 17% (Carelli et al., 2010), 37.98% (Black et al., 2019) or 42% (Giovanni Maronati et al., 2018) compared to large reactors (depending on the analysis method).

Most studies focus on the economics of a design and focus on the nuclear steam supply system. However, very little research focuses on layout design for the balance of plant systems. Stone & Webster Engineering Corporation, (1977) assessed modularisation of different aspects of a nuclear plant citing a 12% reduction of costs could be achieved. Lapp, (1989) introduced a matrix reordering technique to cluster highly linked balance of plant systems (Sutharshan et al., 2011). Kadak and Berte, (2006) introduced the virtual factory method of modularisation whereby equipment items are installed into modules by equipment manufacturers, eliminating the need for a module factory, but more suited for one off projects or research reactors as modules are not optimised for road transport and maximum work off site.

Much more work could be achieved on the design of small modular reactor modules for road transport, understanding the effects on factory manufacture, transportation and logistics, and on-site assembly. Automating parts of the design process allows more concepts to be analysed and more focus on other aspects of the design (P. Wrigley et al., 2019) and is recommended to be pursued further.

4.3 Political support is key for new nuclear

Both large and small reactors require political (and public) support as a key factor to enable a sustained multi-unit programme facilitating benefits from standardisation, learner benefits from economies of multiples, supply chain and construction expertise build up, all reducing cost and increasing certainty. For small modular reactors to be a success, political support is required for multi units, enabling the development and investment into advanced manufacturing and assembly facilities.

4.4 Build analysis techniques and software tools

There has been a lot of economic analysis on recognising that SMRs can be economically competitive with large reactors, replacing economies of scale with reduced size, risk and finance, and economies of learning and mass production (Carelli et al., 2010) (Giovanni Maronati et al., 2018) (Mignacca and Locatelli, 2020) (Lovering and McBride, 2020).

Some analysis has been conducted on the schedules (Clara A. Lloyd and Roulstone, 2018), supply chain (Lyons and Roulstone, 2018) and transportation (Mignacca et al., 2019).

Further development of analysis techniques would be recommended for optimisation of assembly and manufacturing plants (layout, location, scheduling, logistics), supply chain, scheduling, logistics, construction planning and assessment and contingency planning for unforeseen delays (Maronati and Petrovic, 2020).

4.5 Review other industries

Research was completed assessing other industries methods (Shipbuilding, Petrochemical, Aerospace, Automobile, and the Heavy Lift Industry) that could be applied to nuclear power (Technology Transfer Modularization Task team. DOE, 1985). Shipbuilding techniques were studied further (Lapp, 1989) (Seubert, 1988) (Mitenkov et al., 2007) but these methods have proved difficult perhaps due to a lack of experience and economies of learning (Giovanni Maronati et al., 2018).

Multiple SMRs, “built in factories” (IAEA, 2020) would require learning from mass production techniques used in automotive and aerospace. A review into automotive and aerospace production and industry 4.0+ techniques that could be applied to a module manufacturing facility would be recommended. Along with advanced manufacturing techniques that may enable cheaper and faster production of equipment and components (Gandy et al., 2018). Cutting edge manufacturing could also be applied to the construction site through the use of robots and additive manufacture (Bock, 2015) (Yang et al., 2019) and automated transport and logistics (Wrigley et al., 2018).

More analysis, development and utilisation of commercial off the shelf equipment and components are required. SMR factory-built modules may benefit from a standardised module grid such as those utilised in oil and gas and industrial process plants. A standardised grid (Figure 16) would enable easier planning, manufacture, construction and reduce errors over the whole process.

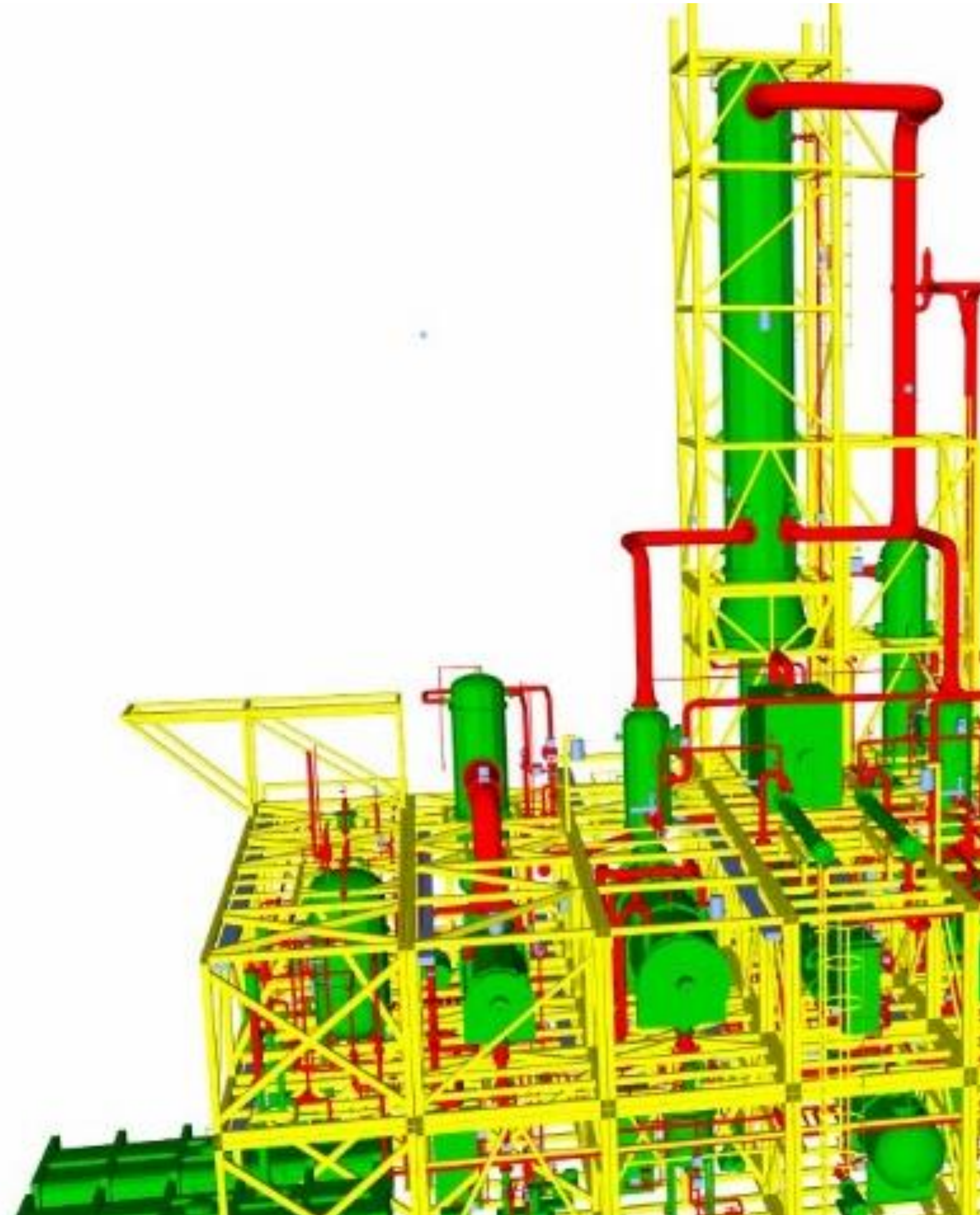

Figure 16 – Factory built, modular industrial process plants ©(Zeton, 2019)

4.6 Further development of modular design process

Smith et al., (2013) provide the most comprehensive and detailed modular design process as a good reference, this should be combined and augmented with analysis techniques for design, VR, planning, schedule, logistics, transportation, construction and BIM.

4.7 Recommendations for further research

Several recommendations for further research can be obtained.

1. Consider lessons learned from large nuclear construction in the design of small modular nuclear plants.
2. Integrated and collaborative software for the whole design process and management.
3. Further development of analysis tools for design, scheduling, logistics, layout, construction.
4. Further development of the design process for modules and integration with analysis tools.
5. Consider methods and techniques from other industries such as modular construction, automotive, aerospace and industrial process plants.
    a. Consider designing the module to fit the system in standardised modules sized and maximised for road transport and the implementation of a standardised grid.
6. More analysis, development, testing and utilisation of commercial off the shelf equipment and components are required.

4.8 Limitations of the study

The results reported within this paper should be considered with some limitations. The results are constrained by the initial selection of keywords and therefore limit the coverage of the current literature.

A number of research items from the INIS IAEA database were not available: (Fang, 2010), (Song et al., 2011), (Fang, 2015), (Takada et al., 2005) (Yongfei, 2017) (Lepelletier and Danguy des Deserts, 2014)

Appendix – Literature search papers

	Search terms			
	Modular nuclear design	Modular nuclear construction	Modularization AND nuclear	Modular Nuclear Balance of Plant
(Technology Transfer Modularization Task team. DOE, 1985)	X			
(Seubert, 1988)	X			
(Morton et al., 1989),	X			
(Lapp, 1989)	X			
(Akagi et al., 2002),	X			
(Kadak and Berte, 2006)	X			
(Carelli et al., 2010)	X			
(Lu et al., 2013)	X			
(Lu, 2013).	X			
(Upadhyay and Jain, 2016)	X			
(Black et al., 2019)	X			
(Yotsuya et al., 2004)		X		
(León et al., 2009)		X		
(Lee et al., 2010)		X		
(Obata et al., 2010)		X		
(Jung et al., 2010).		X		
(Cronje et al., 2012)		X		
(Fang et al., 2012)		X		
(Smith et al., 2013).		X		
(Giovanni Maronati et al., 2018) (G. Maronati et al., 2018).			X	
(Holcomb et al., 2011). (Clara A Lloyd and Roulstone, 2018)			X	
(Generation IV International Forum, 2007) (Clara A. Lloyd and Roulstone, 2018)			X	
(Mignacca et al., 2018).			X	
(Lyons and Roulstone, 2018)			X	
(Mignacca et al., 2019)			X	
(Lloyd, 2019).			X	
(Lyons, 2020).			X	
(Mignacca and Locatelli, 2020).			X	

(Williamson and Townsend, 2003).				X
(Memmott et al., 2012)				X
Research not available found in the INES IAEA database				
(Takada et al., 2005)				
(Fang, 2010)				
(Song et al., 2011)				
(Fang, 2015)				
(Hu and Wang, 2017)				
(Yongfei, 2017)				

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