A Novel Mathematical Layout Optimisation Method and Design Framework for Modularisation in Industrial Process Plants and SMRs

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Declaration

I declare the content of this thesis is wholly my own work. I would like to acknowledge, however, although the MILP model that I developed was my initiative, the contributions of Kevin Eilis to debugging the genetic algorithm model and suggesting a few improvements and Sam O Neill for debugging the MILP model, suggesting a few improvements, time to optimality work and conversion to Python from MATLAB for use in Gurobi was invaluable.

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Abstract

Nuclear power has been proposed as a low carbon solution to electricity generation when intermittent wind and solar renewable energy are not generating. Nuclear can provide co-generation through district heating, desalination, hydrogen production or aid in the process of producing synfuels. However, current new large nuclear power plants are expensive, time consuming to build and plagued by delays and cost increases. An emerging trend in the construction industry is to manufacture parts off the critical path, off site in factories, through modular design to reduce schedules and direct costs. A study from shipbuilding estimates work done in a factory may be 8 times more efficient than performing the same work on site. This productivity increase could be a solution to the problems in nuclear power plant construction. It is an emerging area and the International Atomic Energy Agency records over 50 Small Modular Reactor designs in commercial development worldwide. Most Small Modular Reactor designs focus on integrating the Nuclear Steam Supply System into one module.

The aim of this Applied Research Programme was to develop an efficient and effective analysis tool for modularisation in industrial plant systems. The objectives were to understand the state of the art in modular construction and automating design through a literature review. The literature review in this thesis highlighted that automating earlier parts of the plant design process (equipment databases, selection tools and modular Process and Instrumentation Diagrams) have been developed in modular industrial process plant research but 3D layout has not been studied. It was also found that layout optimisation for industrial process plants has not considered modularisation. It was therefore proposed to develop a novel mathematical layout optimisation method for modularisation of industrial plants. Furthermore, the integration within the plant design process would be improved by developing a method to integrate the output of the optimisation with the plant design software. A case study was developed to analyse how this new method would compare against the current design process at Rolls-Royce.

A systems engineering approach was taken to develop the capabilities of the optimisation by decomposing the three required constituents of modularisation: development of a model to optimise layout of modules utilising the module designs from previous research (Lapp, 1989), development of a model to optimise the layout equipment within modules and development of a combined and integrated model to optimise assignment and layout of equipment to modules. The objective function was to reduce pipe length as it can constitute up to 20% of process plant costs (Peters, Timmerhaus, & West, 2003) and to reduce the number of modules utilised.

The results from the mathematical model were compared against previous layout designs (Lapp, 1989), highlighting a 46-88.7% reduction in pipework and considering pipework costs can be up to 20% of a process plant cost, this could be a significant saving. This does not consider the significant schedule and productivity savings by moving this work offsite.

The second model (Bi) analysed the layout of the Chemical Volume and Control System and Boron Thermal Regeneration System into one and two modules, reducing pipe cost and installation by 67.6% and 85% respectively compared to the previously designed systems from (Lapp, 1989).

The third model (Bii) considered the allocation of equipment to multiple modules, reducing pipe cost and installation by 80.5% compared to the previously designed systems from (Lapp, 1989), creating new data and knowledge.

Mixed Integer Linear Programming formulations and soft constraints within the genetic algorithm function were utilised within MATLAB and Gurobi.

Furthermore, by integrating the optimisation output with the plant design software to update the new locations of equipment and concept pipe routing, efficiency is vastly improved when the plant design engineer interprets the optimisation results. Not only can the mathematical layout optimisation analyse millions more possible layouts than an engineering designer, it can perform the function in a fraction of the time, saving time and costs. It at least gives the design engineer a suitable starting point which can be analysed and the optimisation model updated in an iterative process. This novel method was compared against the current design process at Rolls-Royce, it was found that an update to a module would take minutes with the novel optimisation and integration with the plant design software method, rather than days or weeks for the manual process. However, the disadvantage is that more upfront work is required to convert engineering knowledge into mathematical terms and relationships.

The research is limited by the publicly available nuclear power plant data. Future work could include applying this novel method to wider industrial plant design to understand the broader impact. The mathematical optimisation model can be developed in the future to include constraints in other research such as assembly, operation and maintenance costs.

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Abbreviations

Abbreviations	Description
AFW	Auxiliary Feed Water System
BA	Boric Acid
BEA	Bond Energy Algorithm
BIM	Building Information Modelling
BOP	Balance of Plant
BRS	Boron Recycle System
BTRS	Boron Thermal Regeneration System
BTR	Boron Thermal Regeneration
CAD	Computer Aided Design
CCW	Component Cooling Water
CP_{ij}	Connections Penalty Matrix
CCS	Core Cooling System
CSS	Chemistry Sampling System
CVCS	Chemical and Volume Control System
DSM	Design (Dependency) Structure Matrix
EE	Electrical and Equipment
FLP	Facility Layout Problem
FOAK	First of A Kind
HVAC	Heating, Ventilation and Air Conditioning
I&C	Instrumentation and Controls
IPCC	Intergovernmental Panel on Climate Change
LWR	Light Water Reactor
LCOE	Levelised Cost of Electricity
LOCA	Loss of Coolant Accident
MEP	Mechanical Electrical and Plumbing
MINLP	Mixed Integer Non-Linear Programming
MILP	Mixed Integer Linear Programming
MWe(h)	Megawatt Electric (hour)
NLP	Nonlinear Programming
NSSS	Nuclear Steam Supply System
O&M	Operation and Maintenance
OSMC	Off-Site Modular Construction
P&ID	Process and Instrumentation Diagram
PFD	Process Flow Diagrams
PSP	Pipe Size Penalty
PWBS	Product Work Breakdown Structure
PWR	Pressurised Water Reactor
RCS	Reactor Coolant System
R&D	Research and Development
RHR(CS)	Residual Heat Removal and (Containment Spray)
RPV	Reactor Pressure Vessel
SGBD	Steam Generator Blowdown
SIS	Safety Injection System
SMR	Small Modular Reactor
SCP	Safety Class Penalty
SWS	Service Water System
VRE	Variable Renewable Energy

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1 CHAPTER 1
Introduction

This introduction provides an overview of the Applied Research Programme and thesis. It briefly explains the observations that led to the Applied Research Programme being initiated such as global warming, renewable integration issues, current expensive large nuclear power plants and the move to off-site modular construction that may be solutions to reducing nuclear power plant construction cost. Following this, the aims, objectives and scope for the Applied Research Programme are outlined. The objectives were revised after the literature review and an Applied Research Programme proposal was developed to align with the new knowledge. The thesis structure is also discussed to provide an overview of the thesis content

1.1 Global CO2 Emissions Reduction Challenge

c. The European Commission calls for a climate-neutral Europe by 2050 and the UK has committed into law to being carbon neutral by 2050.

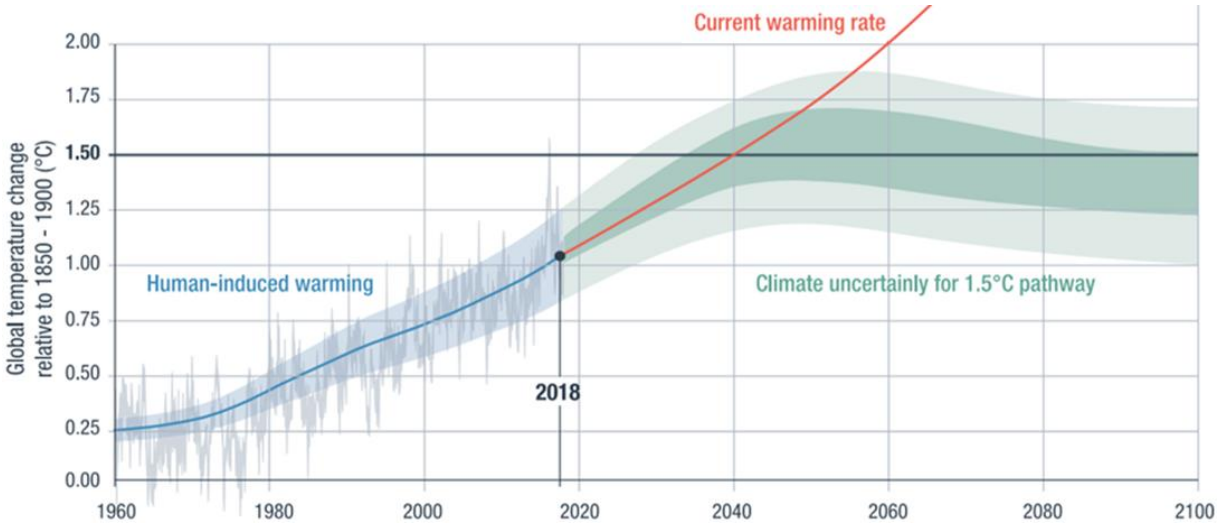


Figure 1-1 – Human-induced warming reached approximately 1°C above pre-industrial levels in 2017. At the present rate, global temperature would reach 1.5°around 2040 from the Global Warming of 1.5°C report (IPCC, 2018a) *©IPCC*

Wind and solar generation have increased exponentially over the past decade and generation is cheap once construction is complete. However, energy storage mechanisms are required once the integration of Phase 3+ (25%) Variable Renewable Energy (VRE) is reached (The International Energy Agency, 2019). Studies analysing wind integration between 20-40% find marginal integration costs could increase generation costs by 35-50% (Ueckerdt, 2014), and system integration costs could soon equal generation costs.

The UK is already approaching this phase as shown by a snapshot of electricity generation in January 2020 (Figure 1-2). In early January, with 12GW of wind, fossil fuels are only producing around 3GW of

power overnight. Whereas a week later, fossil fuels are consistently producing between 10-25GW for 5 days. Tens of Gigawatts of energy storage mechanisms are required when the wind does not blow to become carbon neutral by 2050.

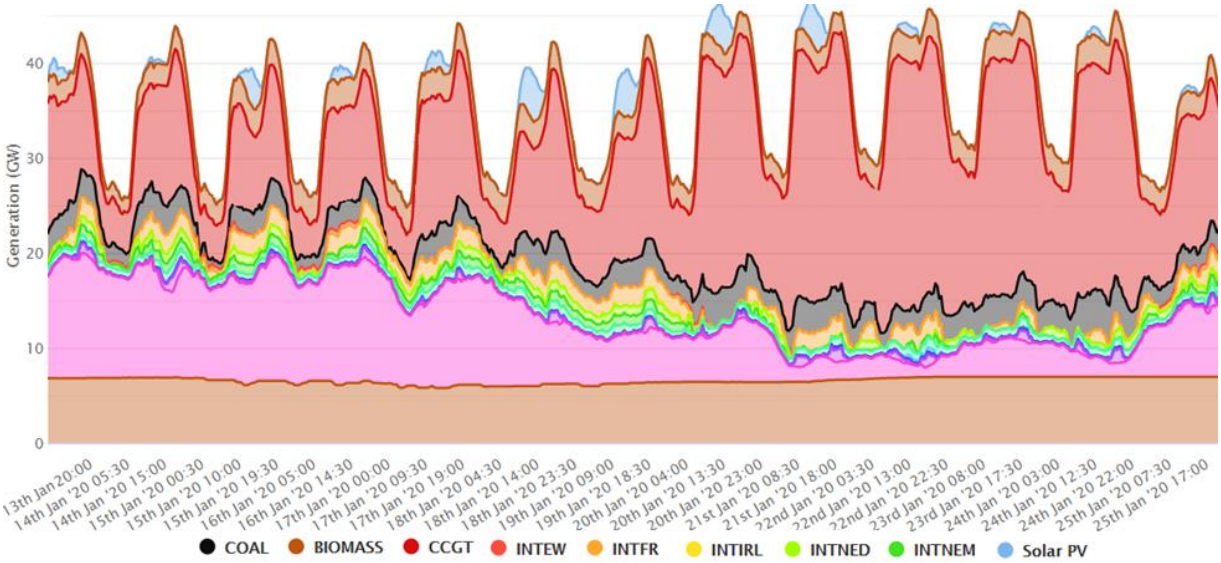


Figure 1-2 – UK variation in wind electricity generation from 13th January 2020 to 25th January 2020 University of Sheffield, 2020

Nuclear power starts to become more economically attractive at this point and has been proposed as a solution to low carbon, secure energy supply (Harrabin, 2019). Nuclear can also be used for cogeneration (D. T. Ingersoll, Houghton, Bromm, & Desportes, 2014) such as district heating (Reński, Duzinkiewicz, Minkiewicz, Jaskólski, & Kaczmarek-Kacprzak, 2016), generation of hydrogen (Revankar & Bindra, 2019) and synthetic fuels, further increasing its economic potential (Locatelli, Fiordaliso, Boarin, & Ricotti, 2017).

It has been estimated Nuclear Power has averted an average of 1.84 million air contamination associated mortalities and 64 gigatonnes of CO2 comparable greenhouse gas emissions that would have ensued from burning fossil fuels since 1950 (Kharecha & Hansen, 2013). This is about the equivalent of half the carbon locked in the Amazon rainforest (Rainforest Trust, 2017).

The UN's Intergovernmental Panel on Climate Change (IPCC) modelled future electricity generation and has forecast nuclear generation increases on average 2.5 times by 2050 over its 87 scenarios (IPCC, 2018b). The UK (National Grid, 2019) future energy scenarios recognises "New nuclear build is required in all scenarios" to meet the 2 degrees target. Nuclear may be a necessary part of decarbonising the energy mix, depending on how energy storage and renewable intermittency can be managed in the future, especially throughout winter in higher latitudes.

1.2 Problem Statement

Conversely, nuclear power is historically expensive (Lovering, Yip, & Nordhaus, 2016 and Koomey, Hultman, & Grubler, 2017), due to poor construction productivity, large complex plants and associated high safety systems and regulations.

Construction costs for the UK's second Light Water Reactor (LWR), and first in 30 years, Hinkley Point C, are currently estimated at £20 billion for two reactors. The other two European Pressurised Water Reactors at Olkiluoto (Finland) and Flamanville (France) have encountered cost increases from a predicted £3 billion to around £10 billion per reactor. This has caused the French Government to nationalise the reactor plant design and construction company Areva/Framatome under the French state electricity provider, EDF. The plans for AP1000 plants (A Westinghouse 1000MWe Reactor) at Moorside UK from NuGen have been abandoned and Kepco has also pulled out of buying NuGen at Moorside. Hitachi's Wylfa Advanced Boiling Water Reactor nuclear plant has been suspended due to unsatisfactory financial negotiations with the UK Government. The VC summer AP1000 plants in the USA have been abandoned, whereas AP1000 construction costs at Vogtle have escalated to over $25 billion.

With the high cost of constructing nuclear power plants in the western world, the argument against nuclear is now mainly one of cost as plans for a Sizewell C EPR in Essex could cost £60/MWh(Megawatt Hour) (O'Connell, 2019). Recent offshore wind "contracts for difference" bids were £39.65/MWh (Harrabin, 2017). However, this does not account for the variability of wind where high penetration of variable renewable energy could significantly increase electricity prices as wind power only generates power at between 20-40% of the time (OECD/NEA, 2019). To remain economical compared to variable renewable energy, new nuclear power plants must reduce costs and provide cogeneration options. A solution to this may be to move work off the critical path into factories to increase productivity, reduce schedules and risk.

1.2.1 Cost Reduction Methods in Nuclear Power

There has been a lot of research and development undertaken to understand how the cost of nuclear could be lowered (see section 2.1.4 - Reducing Nuclear Construction Costs). Modularisation has been employed to reduce the costs of containment ring construction in the late 1950s (Presley, Weber, & CB&I, 2009). A modularisation study on plant systems estimated costs could be reduced by $10-14 million, up to 12% of total capital costs (Stone & Webster Engineering Corporation, 1977). Other methods were developed utilising an onsite assembly area derived from shipbuilding to assemble large modules, citing capital costs reductions of 15% (Lapp, 1989).

The integral reactor concept was established, a factory-built transportable module, housing the primary cooling system (Hayns & Shepherd, 1991), increasing safety. Recent economic studies on integral reactors suggest they could be between 17% (Carelli et al., 2010), 38% (Black, Aydogan, & Koerner, 2019) and up to 42% (Giovanni Maronati, Petrovic, Van Wyk, Kelley, & White, 2018) more economic than equivalent large reactors.

The virtual factory method of constructing a reactor was proposed by (Kadak & Berte, 2006), eliminating the need for a module factory.

In recent years, there has been a move to off-site manufacture in the construction industry to improve productivity in the construction sector (UK GOV Science and Technology Select Committee, 2018). A study in shipbuilding highlighted work done in a factory could be 8X more productive and cost-effective than performing the work on-site (Barry, 2009).

There are over 50 Small Modular Reactors (SMR) in commercial development. The definition for SMRs is “shop fabricated and then transported as modules to the sites for installation” (IAEA, 2020).

Rolls-Royce has opted for a three-loop SMR rather than an integral reactor design. They believe costs can be reduced (Figure 1-3): from £92/MWh for current large nuclear to £65/MWh for a small modular plant (Rolls-Royce, 2018).

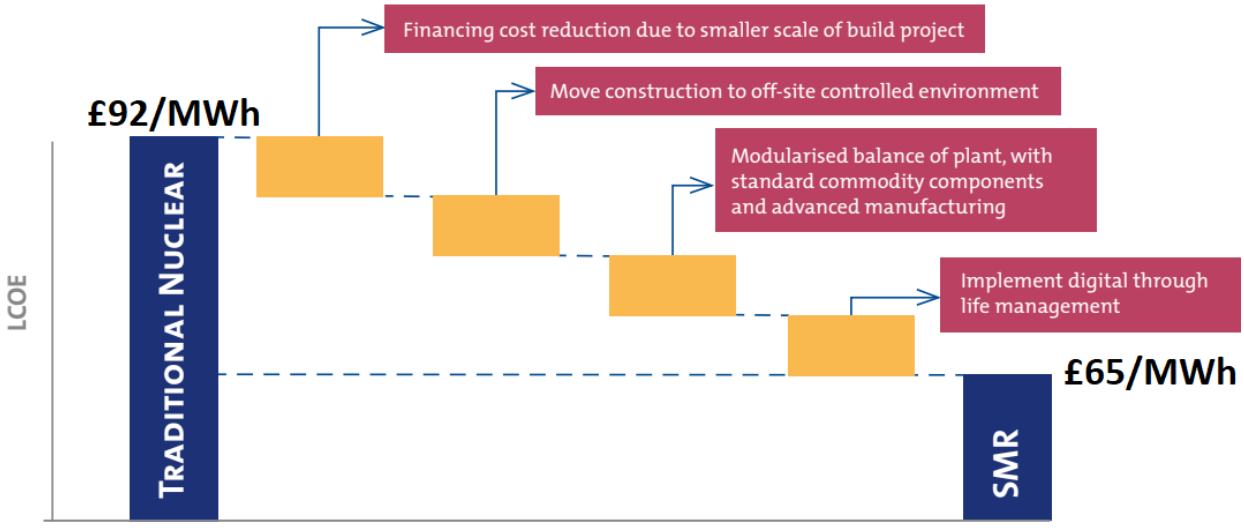


Figure 1-3 – Rolls-Royce SMR cost savings ©Rolls-Royce

These savings come from 4 main factors (Figure 1-3): reduced finance, off-site construction, digital through-life management and modularised balance of plant designed to be factory manufactured and road transportable (Figure 1-4).

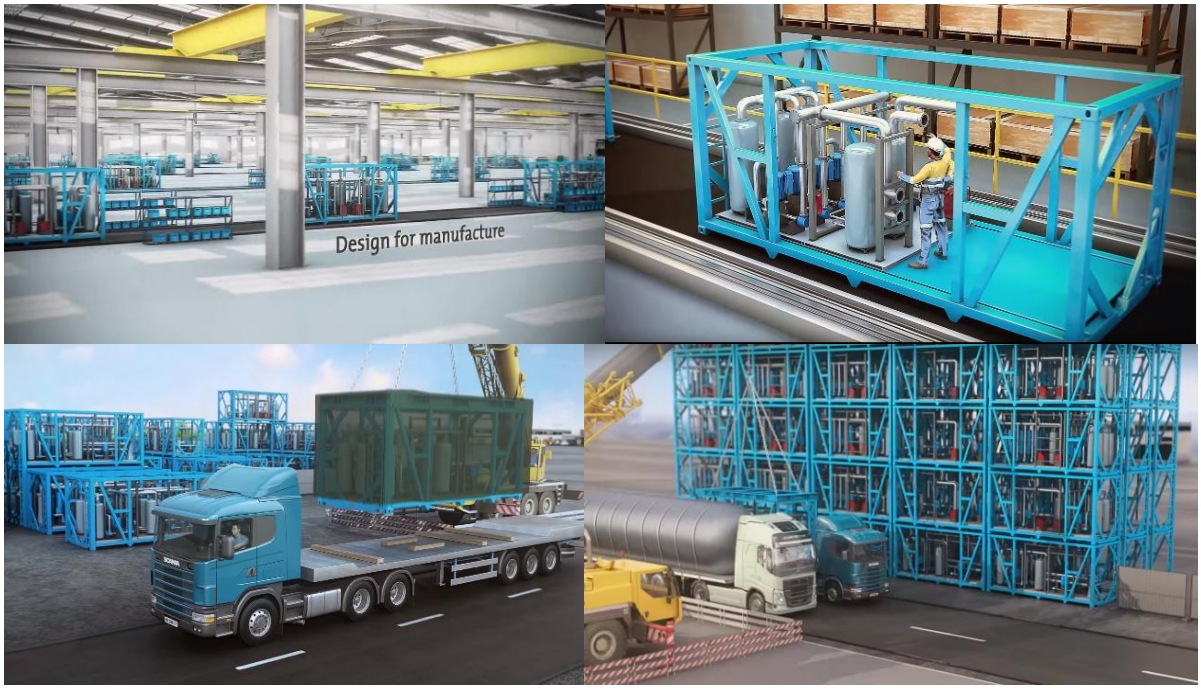


Figure 1-4 – Rolls-Royce factory built SMR module concept and transportation ©Rolls-Royce

1.2.2 Knowledge Gap

Most Small Modular Reactor Designs only consider integrating the Nuclear Steam Supply System (NSSS) and little research has been performed on modularising the rest of the accompanying systems and equipment. This Applied Research Programme considers all the other supporting equipment and systems that may also be designed for off-site manufacture and construction and develops a supporting novel method to aid with this objective. A novel mathematical layout optimisation model was developed to consider modularisation. Mathematical layout optimisation has never been utilised in nuclear power plant design research or for modular industrial process plants. This novel mathematical layout optimisation method will be built upon to analyse modular layouts in this Applied Research Programme to understand if it can aid with designing a complex SMR.

1.3 Aims and Objectives

The aim of this Applied Research Programme is to study how modularisation affects a light water nuclear reactor power plant designed for offsite manufacture, assembly, construction and road transport. Specifically, looking at developing a method whereby a nuclear power plant can be modularised (broken down) into factory-built modules to take work off the critical path (reduce the construction schedule), reduce work on site and increase productivity.

Following this, a method was proposed utilising mathematical optimisation to break down the plant systems and lay them out into standardised modules. The main aim in this work is to develop a tool to help in the design for modularisation of a nuclear power station. This enables more concepts to be analysed, saving engineering and construction time and costs and reducing risk.

It was decided to diverge from investigating modular integrated primary circuits or Nuclear Steam Supply Systems (NSSS) as this is an subject that has received a lot of attention over the past three decades and further considering there are over 50 commercial designs are in development (IAEA, 2020). It was decided to utilise data from a previous modularisation study into on-site assembly (Lapp, 1989) as the data is publicly available.

1.4 Applied Research Programme Aim

The Applied Research Programme aim is to gain an understanding of the state of the art in modularisation in nuclear plant design and the wider plant design industry and to develop a new method to aid in the design of modular industrial plants. Firstly, to achieve this, a literature review was conducted on modularisation in nuclear power, industrial plants and construction. The design process was analysed, identifying a novel layout analysis tool for modularisation as a significant knowledge gap. The new method will be tested to assess performance against current methods and processes.

1.5 Applied Research Programme Objectives

The objectives are stated as follows:

1. Conduct a literature review to understand the state of the art in:
    a. Design process methods and architecture for modular design in nuclear power:
        i. What can small modular reactors learn from understanding the state of the art in current modularisation in nuclear power literature (both large and SMRs)?
        ii. What is the state of the art in modular nuclear design process methods and recommendations?

iii. What are the latest design tools, analysis methods and considerations that may aid modularisation in SMRs?

b. Design process methods in construction and modular industrial plant design.
c. How can knowledge based engineering and automated design help the modular design process?
d. What is the state of the art in mathematical layout optimisation?

2. Investigate the suitability of nuclear power plant component/ equipment sizes (Lapp, 1989) for modular factory build and transport requirements creating new knowledge.
3. Propose a novel method for aiding in the design process of modular process plants and integration with the wider plant design framework.
    a. Develop a mathematical model to arrange modules from existing research.
    b. Develop a mathematical model to layout components in modules.
    c. Develop a mathematical model to divide the plant and group components into modules.
    d. Develop integration within the wider plant design framework and CAD software.
4. Demonstrate the effectiveness of the new method by application to optimisation of modular nuclear balance of plant system (Lapp, 1989) case studies to create new knowledge and new data.
    a. Compare the results to current designs and methods (Lapp, 1989)
        i. Quantitative – Pipe length and module reductions.
        ii. Qualitative – Design time reduction compared to current Rolls-Royce process.

1.6 Thesis Structure

This thesis is structured in the following standard form: Introduction including Aims, Objectives and Scope, Background and Literature Review, Proposal, Method, Results & Discussion and Conclusions.

1.6.1 Chapter 1 - Introduction

The introduction provides an overview of the Applied Research Programme and thesis. It briefly explains the observations that lead to the Applied Research Programme being initiated such as global warming, renewable integration issues, complexities, delays and soaring costs in constructing new large nuclear power plants in the west, where labour is expensive and the industry has lost the construction experience and supply chain. Also discussed is the recent trend to move work off-site via modular construction that may be a solution to reducing cost.

It discusses the Aims, Objectives and Scope for the Applied Research Programme. The thesis structure is also discussed to provide an overview of the thesis content.

1.6.2 Chapter 2 - State of the Art in Nuclear Power Technology

Chapter 2 provides a background explanation to nuclear power. It also provides literature on previous attempts to reduce construction costs in nuclear power and why current new nuclear power plants are so expensive. Also outlined is the literature and multiple economic analyses which identify that smaller factory built nuclear power plants may be at least cost competitive with large nuclear power plants.

The literature review defines current theory and practice to present a deep understanding of the state of the art in off-site modular design and construction literature. After understanding the state of the art in modularisation design and construction, a proposal was then formulated to develop on mathematical layout optimisation research literature to consider modularisation, which has not previously been studied. A brief introduction to the mathematical layout optimisation method is described to adequately understand the mathematical optimisation literature review. A section justifying choice of method, advantages and disadvantages of each method is presented. The literature review offers the state of the art in mathematical layout optimisation literature. Described in Appendix B is the method behind the systematic literature review and the modularisation literature.

1.6.3 Chapter 3: Proposed Novel Mathematical Optimisation and Design Process Research Framework

The literature review highlighted that layout optimisation has not been utilised in nuclear research previously or in modular industrial plants. It was proposed to develop a novel mathematical layout optimisation method to consider off-site construction, specifically small nuclear power plants, but the process could be applied to any modular industrial process plant. The proposal is to take a Systems Engineering approach to breaking down the problem into three case studies for modularisation.

- Case Study 1 - Optimising module layout from the Shearon Harris plant, *Model (A)*
- Case Study 2 - Optimising components layout within module, *Model (Bi)*
- Case Study 3 – Extension to assign equipment to modules, Model (Bii)
- Finally, the link between Plant Design CAD software will be explored to understand the impact on plant design engineering

Also discussed in detail is the data to be utilised from a previous nuclear modularisation study considering shipbuilding methods (Lapp, 1989). This includes the data source, equipment data, the Piping and Instrumentation Diagram (P&IDs), equipment connections and Dependency Structure Matrix (DSM) to be utilised in each of the three case studies.

1.6.4 Chapter 4 – Novel Modular Layout Optimisation Methods – Model Formulations

Chapter 4 discusses the development of the novel optimisation model formulations starting with Chapter 4.1 where *Model (A)* for case study 1 is presented, analysing the optimal arrangement of previously designed modules from prior research (Lapp, 1989). Chapter 7.2 presents *Model (Bi)* for case study 2, optimal arrangement of equipment items within modules. It also includes the novel extension for *Model (Bii)* for case study 3 to consider the optimal arrangement of equipment and modules combined.

1.6.5 Chapter 5 - Results and Discussion

In this chapter, the results are discussed for the layout of modules, *Model (A)*, the layout of equipment within a single module, *Model (Bi),* and the novel extension to consider the allocation of equipment to modules *Model (Bii).* The results are compared against the previous research designs and layouts (Lapp, 1989). Furthermore, the link to plant design is presented and explored along with general observations from the optimisation. Also discussed are the limitations of the study such as the limited data available and the lack of a qualified layout design engineer to obtain expert heuristic knowledge to advise on the arrangements.

1.6.6 Chapter 6 – Conclusions, Major Findings, Recommendations and Future Work

Chapter 6 discusses the conclusions for the Applied Research Programme relating back to the Applied Research Programme aims and objectives. It then provides a summary for future improvements and work outside of the scope of this Applied Research Programme.

1.6.7 Thesis structure and research flowchart

Figure 1-5 shows the thesis structure and research methodology flowchart which is detailed in section 1.6.

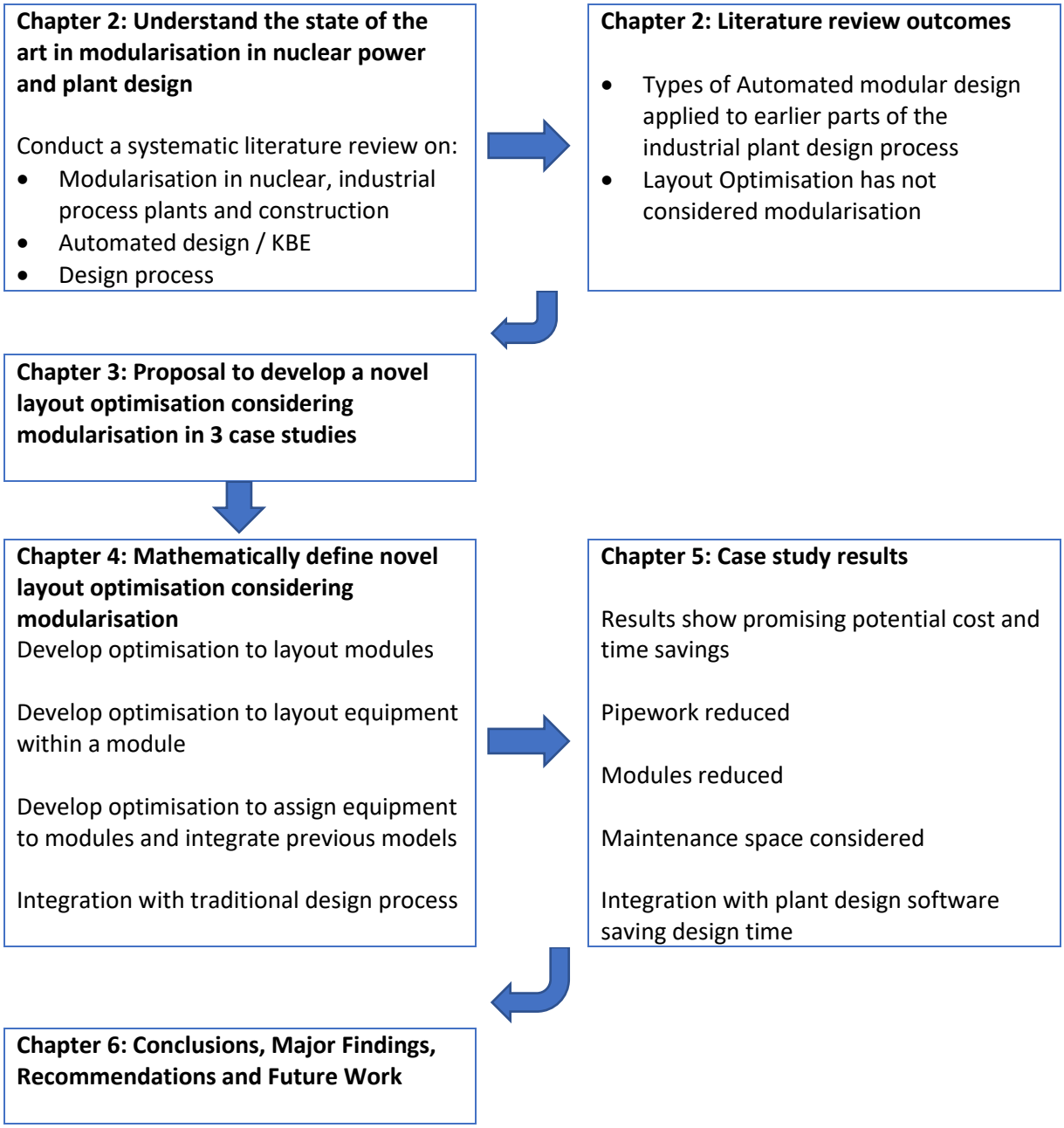


Figure 1-5 - Thesis structure and research methodology flowchart

2 CHAPTER 2
State of the Art in Nuclear Power Technology and modular industrial plant design

Chapter 2 firstly provides a background explanation to Nuclear Power. It also provides literature on previous attempts to reduce construction costs in nuclear power and why current new nuclear power plants are so expensive. It also discusses why smaller factory built nuclear power plants may be a lower cost solution.

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

Conduct a literature review to understand the state of the art in:

a. Design process methods and architecture for modular design in nuclear power:
    iii. What can small modular reactors learn from understanding the state of the art in current modularisation in nuclear power literature (both large and SMRs)?
    iv. What is the state of the art in modular nuclear design process methods and recommendations?
    v. What are the latest design tools, analysis methods and considerations that may aid modularisation in SMRs?
b. Design process methods in construction and modular industrial plant design
c. How can knowledge based engineering and automated design help the modular design process?
d. What is the state of the art in mathematical layout optimisation?

It reviews current theory and practice to provide a deep understanding of the state of the art in off-site modular design and construction literature. It highlighted that layout optimisation has not been utilised in nuclear research previously or considered modularisation. After understanding the state of the art in modularisation design and construction, it was proposed to use mathematical layout optimisation to aid in the design of off-site constructed modular nuclear power plants. *Appendix A – Literature search papers and method*, discusses the method behind the systematic literature review and the modularisation literature.

2.1 Nuclear Energy

Low carbon, Nuclear energy may be a useful tool in the fight against climate change along with renewable technologies. The source of energy for nuclear power comes from radiogenic heating due to the release of heat energy from radioactive decay. The uranium formed naturally in supernovae

provides the radiogenic heating process that powers about half the Earth's core heat flux (Anuta, 2006 and Williams, 2019) and occurs naturally in the sun (Odenwald, 2019). This is then mined for use in nuclear reactors.

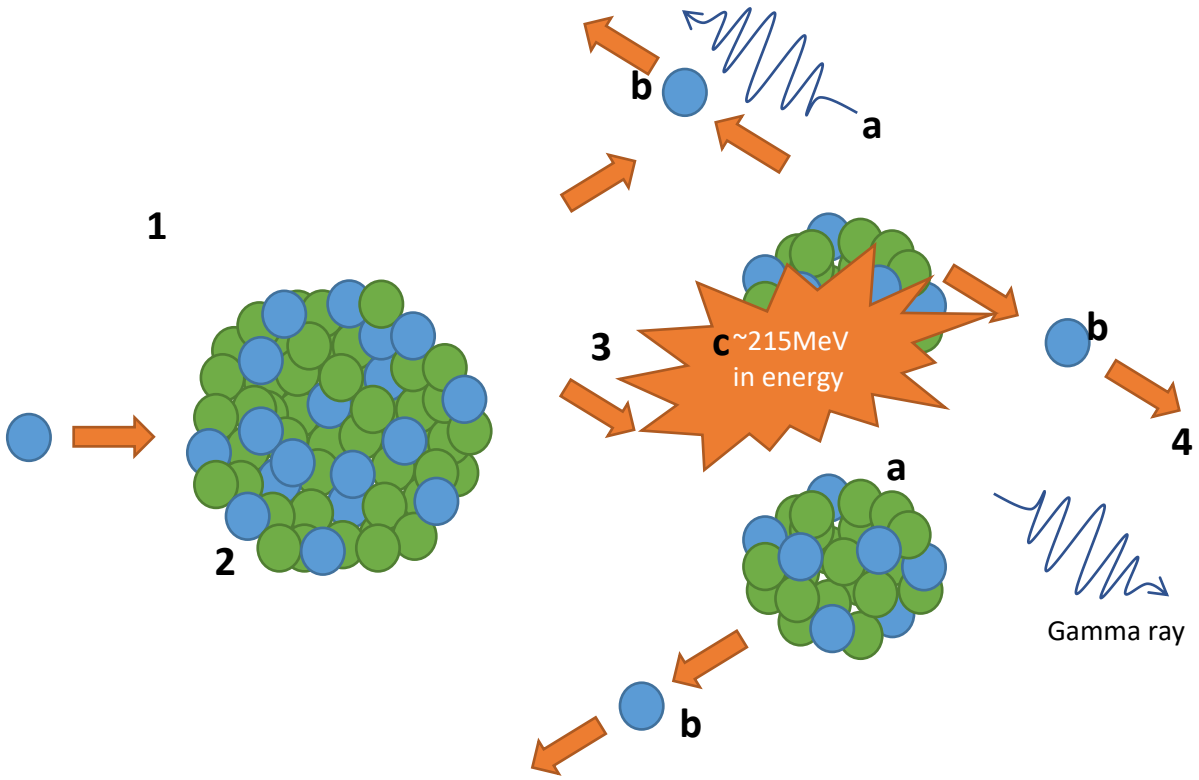


Figure 2-1 – Uranium fission process (MIT, 2020)

The uranium fission process (MIT, 2020) is outlined in Figure 2 1

1. Impact by slow neutron with energy on the order of an electron Volt (eV).
2. Uranium atom becomes unstable
3. Fission occurs (atom splits) yielding:
    a. Fragments of intermediate-mass
    b. An average of neutrons
    c. Average energy of about 215MeV (gamma rays).
4. Neutrons can initiate a chain reaction by going back to 1 in the process cycle.

The energy is used to heat water (Figure 2-2) in the nuclear steam supply system (1), to provide steam for the turbine and generator (2) to create electricity (3), the water is then condensed back to a liquid in a condenser (4) and sent back to the nuclear steam supply system.

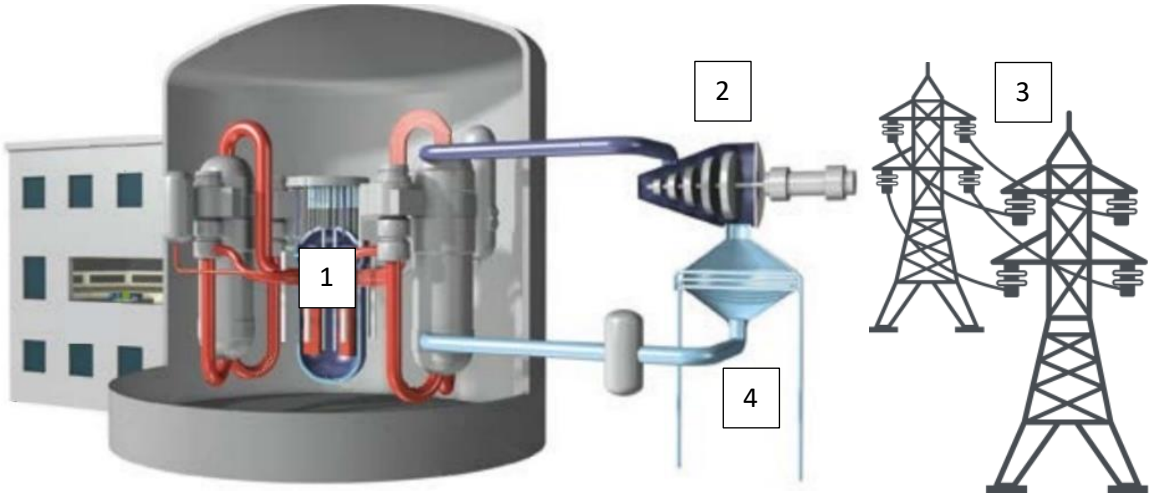


Figure 2-2 –(©Rolls-Royce) Diagram of a Light Water Reactor Design (Rolls-Royce, 2018)

There are many different technologies in nuclear power (World Nuclear Association, 2018) however, Light Water Reactors (Figure 2-2) make up 91% of the World's nuclear capacity (World Nuclear Association, 2018). Light Water Reactors have become the prominent market share in nuclear power mainly due to the development of reactors for submarines (Cowan, 1990).

2.1.1 Pressurised Light Water Reactors

A Pressurised Water Reactor (PWR) encompasses a water filled primary cooling/ Nuclear Steam Supply System/ heat transfer circuit which is heated by the nuclear core, shown as (1) in Figure 2-3, to over 300°C. The water is under pressure ensuring it remains liquid throughout the primary circuit. This heat is then transferred to a secondary circuit through Steam Generator (2) heat exchangers (Figure 2-3) to generate steam which is then sent to drive a turbine (3 red pipes) to create electricity. The steam is then condensed back to a liquid using a condenser and returned to the system (4 blue pipes) using a pump.

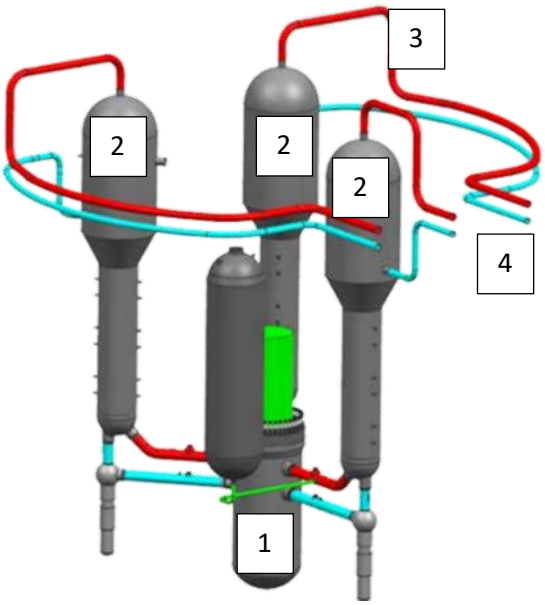


Figure 2-3 – ©Rolls-Royce Nuclear Steam Supply System (Rolls-Royce, 2018)

2.1.2 Other Nuclear Technologies

There have been other types of reactor technology in development over the years. Two of the main technologies are heavy water (CANDU Reactor) and Advanced Gas Cooled (UK). The UK's gas cooled reactors use different technology to most of the World's PWRs (World Nuclear Association, 2018).

The Generation IV International Forum encompasses several countries with the common goal to develop generation IV reactors for commercial deployment such as molten salt, liquid metal, fast reactors or high temperature gas reactors. Generation IV reactors offer various advantages over generation III Light Water Reactors (Generation IV International Forum, 2020) such as better safety, reprocessing spent nuclear fuel and reduced nuclear proliferation risks (Locatelli, Mancini, & Todeschini, 2013).

These reactors have the disadvantage of needing to prove their performance over the product lifetime (60 years for new light water reactors) as none are currently operating commercially. They are all in the research and development phase, proving the concept. This is a long development process and advanced reactors may not be proven economically and technically for decades.

2.1.3 History of Nuclear Power Construction

In 1954, Lewis L. Strauss, chairman of the U.S. Atomic Energy Commission, told the National Association of Science Writers in New York that nuclear electricity would be "too cheap to meter". The first commercial nuclear power plant was opened in 1956 at Calder Hall, England with an initial capacity of 50 Megawatts Electricity (MWe) later rising to 200 MWe. The theme since the 1950s has been to increase the size and output of nuclear power plants to realise economies of scale. Nuclear

power plants developed in the 1960s at around 250 MWe, increasing to over 1500 MWe for the current third generation of nuclear power plants (World Nuclear Association, 2014).

Nuclear power experienced a construction boom up until 1979 (Figure 2-4). However, the three biggest nuclear incidents: Three-Mile Island (1979), Chernobyl (1986) and Fukushima (2011) caused a decline. The high cost of safety improvements after each incident and cheap gas in the 1990s has led to a decline in the world's nuclear reactor construction since the 1980s (shown in Figure 2-4). A steady increase was developing in the 2000s due to concerns over climate change, but construction declined again after the Fukushima accident.

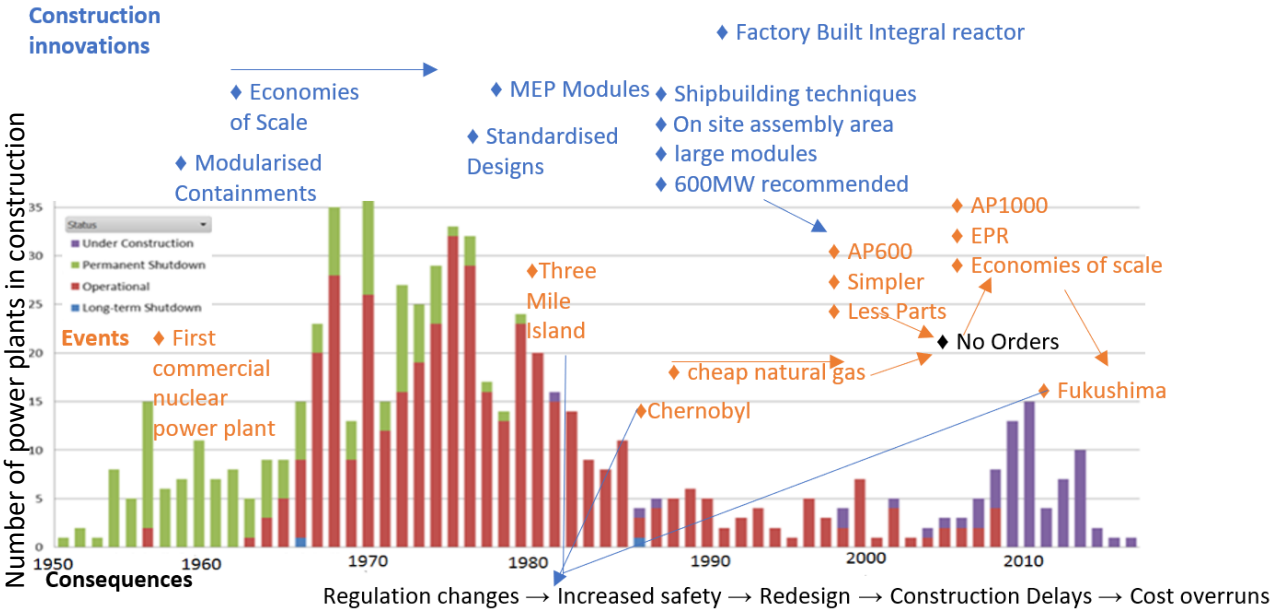


Figure 2-4 – Graph showing the trend of Construction of Nuclear Reactors by year ((Stones, 2014))

Although nuclear safety is hard to measure, most countries have an extremely good safety record with two thirds of nuclear incidents occurring in the US (IAEA, 2018). Benjamin K Sovacool concludes there is no such thing as a 'safe' energy system (Sovacool, 2011) as there is a risk associated with any energy infrastructure (Sovacool, 2009) and showed there is a high risk to life in any energy sector. The nuclear incidents led to the halting of projects and redesign while under construction. The increased safety and resulting construction delays have led to the increasing costs of nuclear construction (Figure 2-5). This decline and the typical design life of over 40 years for a nuclear power plant leaves much of today's capacity reaching the end of their design life. The number of reactors starting construction in the USA in the mid- 1970s experienced dramatically increased construction costs ($1.5/MW to 3-11$/MW).

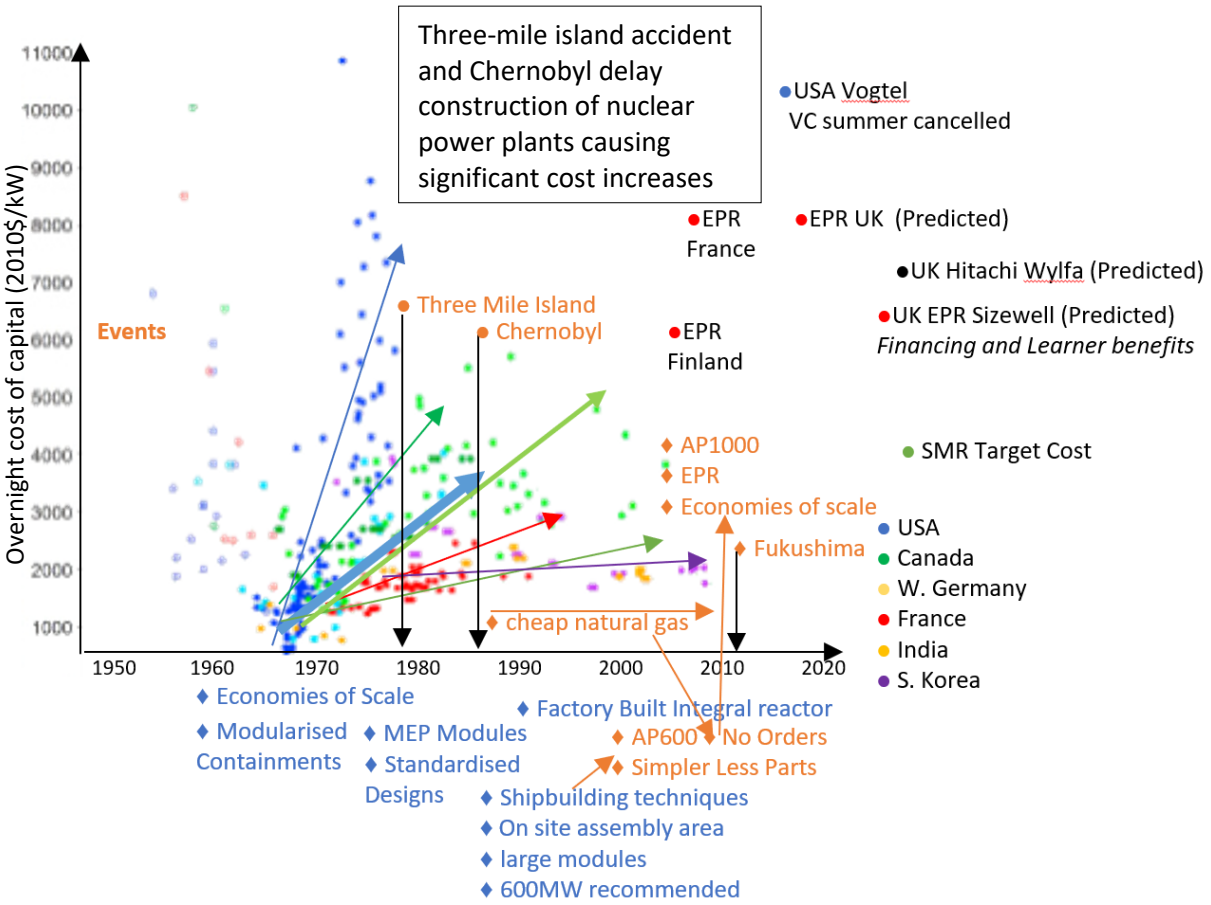


Figure 2-5 – Overnight reactor construction cost Adapted from (Lovering et al., 2016)

2.1.4 Reducing Nuclear Construction Costs

There have been many investigations exploring reducing the cost of nuclear power. The construction costs have been analysed extensively throughout the past four decades.

Containment rings were first "modularised" in the 1950s to reduce schedule and enable assembly away from in situ work (Presley et al., 2009).

A close coupled design stems from the early development of marine reactors for commercial use (World Nuclear Association, 2020a). A close coupled design is more compact than a large nuclear power plant and is more easily factory manufactured. The compact design would also enable smaller containments.

Mandel, (1976) showed that as the size of nuclear power plants increase, construction costs decrease due to economies of scale. This is the basis for the increasing size of nuclear power plants. It also highlighted the need for standardisation to reduce costs, a competitive nuclear industry, delays in licencing increasing costs and construction cost overruns. The construction cost overruns identified in the report (Mandel, 1976) were caused by:

- Adjustment in licensing and regulatory restrictions
- Delayed supply of parts and materials
- Lack or immobility of specialist labour workers
- Inefficient productivity of workers
- Lack of engineers and technical support workers
- Standardisation, regulation, modularisation, on-site labour costs and increased quality and regulation

Baker & Boyd, (1983) highlighted some methods to improve nuclear power plant construction:

- Nuclear Power Construction Stabilisation Agreement
- Construction planning methods (varying four 10-hour day rotas)
- Workforce management programme
- Three phase Change control

Krautmann & Solow, (1988), however, found no evidence of economies of scale in Nuclear Power Generation.

Cantor & Hewlett, (1988) suggest large units may be too large to be effectively overseen by the constructors, and smaller multi-unit plants may be the most economical to construct. They suggest some growth in costs is due to rises in interest and inflation. They advise future efforts to manage costs should also concentrate on regulatory factors. Also highlighting that utilities that oversaw construction, developed projects at reduced rates than those using outside constructors and benefited from a greater learning experience.

Jones & Woite, (1990) analyse past nuclear power projects and cite the following reasons for project cost escalation: variations in project management; regulatory procedure; location specific considerations (e.g. multi-unit, seismic requirements, infrastructure); plant design (including the extent of standardisation); unit prices (e.g. of nearby accessible materials and workers); and accounting (e.g. addition or omission of interest throughout construction, cost reference date supplies of fuel and water, currency exchange prices).

They highlighted 5 points for more cost-effective nuclear power:

1. Learner benefits from replication, standardisation and multi units.
2. Technical improvements in design and construction methods
3. Increase project management quality and quantity
    a. Complete the detailed design before construction starts
    b. Resolve political and regulatory concerns before beginning construction
4. Enhance programme management in scheduling and budget management
5. Attain high operating performance

Hewlett, (1996) assessed data on 69 plants over the 1975-1992 period with an economic model. They claimed that the increased regulatory activity by the US Nuclear Regularity Commission was largely to blame for non-fuel Operation and Maintenance (O&M) input costs escalation from approximately $23 to near $97/kW over the period 1974-93. There was also evidence suggesting that the incentive to improve plant performance by improving maintenance expenses was stronger than the price of replacement power.

OECD, (2000) reported about 12-13% costs savings have been achieved by Canada and France as a result of economies of scale. They also outlined construction methods that have reduced schedule and costs, however, the report does not outline the method it utilised to come to these conclusions:

- Open top access delivers a 15% reduction in construction schedule with potential cost savings of 2.4% of the total cost.
- Modularisation has potential cost savings of 1.4 – 4.0 % of the total cost.
- Sequencing of contractors delivers 6.0 – 8.0% potential total cost savings.
- Slip-forming has a 5% potential reduction in the construction schedule.
- Parallel construction; Better cabling, instrumentation and control; formed elbows for pipes and decrease costs in weld checks can also deliver savings.
- Potential construction methods for better programme management.
    - Advanced engineering techniques and processes.
    - Simplified reactor base construction.
    - Modularisation practices.
    - Prefabrication (reactor liner, primary and secondary shield walls).
    - Deployment of heavy lift cranes.
    - Up-front engineering and licensing.
    - Efficient change control through project scheduling, monitoring, feedback & control.
    - Better training and development for the workforce.
    - Efficiently maximise construction time through shift rotation.
    - Robust industrial relations strategy.
    - Improved transportation across site.
    - Enhancing construction interfaces and integration.
    - Use of advanced project management scheduling software.
    - Plan for contingency in procurement.
    - Inspection services.
    - Simplifying and decreasing quality assurance and quality control documentation.
    - Design enhancement in plant layout, accessibility, simplification, simulation and modelling using improved computational techniques.
- Improved procurement, organisation and contractual aspects.
    - Standardisation and multiple unit cost savings are reported to range from 15% to 40%.

- Multiple unit construction.
    - Siting.
    - Licensing costs.
    - Site labour.
    - Common facilities.
- Better Regulation and policy measures.

Although another study found no evidence of economies of scale in the nuclear and fossil fuel power generation sectors (Rhine, 2001).

Tolley & Jones, (2004) estimate First-of-a-kind (FOAK) costs for new nuclear designs might raise capital costs by 35%, impinging on nuclear energy's desirability, something which has been demonstrated over the past two decades. They also estimated Levelised Cost of Electricity (LCOE), the minimum constant price at which electricity is offered to be cost effective throughout the project lifetime for a range of different scenarios.

Mitenkov, Averbakh, & Antyufeeva, (2007) looked at several construction factors such as serially produced stations where equipment costs can decrease by 30–35%, Labour-Intensiveness, Research and Development (R&D) Costs, and highlighted assembly and manufacture at shipyards is 20–40% lower.

Other studies found that the economy of scale principle is not applicable "as is" (Carelli et al., 2007 and Carelli et al., 2010).

Abu-Khader, (2009) performed a literature review on safety, nuclear economics, spent fuel processing and waste management and nuclear reactor design. They commented on the better safety aspects of recent nuclear power plant designs.

In the literature review of Marques, (2010), they examine technical aspects of gen 3 and 4 reactors.

Grubler, (2010) analyses the French nuclear power programme and theorises the main component of its comparatively short reactor construction successes was an institutional functional support structure that permitted for centralised guidance, regulatory steadiness and a high level of standardisation.

Carelli et al., (2010) showed that the adverse impacts of economies of scale may be offset by the integral and modular design by performing an analysis of capital and O&M costs.

Davis, (2012) analyses and summarises the state of the economics in nuclear power saying that construction is too expensive to be competitive with natural gas.

Harris, Heptonstall, Gross, & Handley, (2013) of Renewable Energy Systems Limited, state that previous nuclear power construction experiences a cost escalation of 5.4% a year. They present a simple analysis, applying some construction delay factors to the expected LCOE on a new nuclear UK power plant. They highlight if the delays happen, more policy support than envisaged may be required as the LCOE would be higher.

The theme across the papers for increasing costs are the increased cost of safety structures due to increased regulation; on-site labour costs and increased quality and regulation; poor management; and no learner curve experience for multiple projects. The improving costs focus on schedule reductions, better site management, regulatory improvements, and standardisation

2.1.5 Current Gen III construction delays and cost overruns in the west

The AP600 and A1000 nuclear plant designs 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, Corletti, & Thompson, 2001) and 1000 $/kW for the AP1000. 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 (E. Ingersoll, Gogan, & Locatelli, 2020). 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).

The EPR encountered manufacturing and construction problems (Garnsey, Joyce, & Nickson, 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%.

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.

2.2 Modularisation in Nuclear Power Design and Construction

Modularisation is a sustainable and innovative approach for breaking down a system by organising complex products and processes efficiently for easy design, assembly and reuse (IGI Global, 2020).

The first notable use of modular assembly stemmed from USA Liberty ships and U-boats during the Second World War which utilised assembly-based modularisation to reduce time in the docks by reducing the construction schedule. The German U-boats were modularised to build components in hidden locations to assemble at the dockyard as fast as possible to ensure minimum dock time to minimise the risk of bombing.

In the 1960s, the Bauhaus school considered the functional requirements of the users and those of industrial production in building construction. The module was connected to the concept of a building block. It was soon found that prefabricating building components increased productivity in construction. This enabled the mass-production of some building blocks and to achieve economies of scale (Hellström & Wikström, 2005). Functional modularity was described by Ernst & Hubka as the "arrangement of functional elements and their interconnections" (Ernst & Hubka, 1988). Whereas Pahl and Beitz describe modular products as "machines, assemblies and components that fulfil various overall functions through the combination of distinct building blocks or modules" (Pahl, Beitz, Feldhusen, & Grote, 2007).

The move to modularity in construction is due to the ability to move work off the critical path to an assembly area for parallel working. Construction modularisation brings about the following advantages: better quality, improved customer satisfaction, quicker implementation, reduced on site workers and increased factory productivity, generating more regional jobs away from large urban areas, superior health and safety practices, safety advantages through quality assurance standards, improvement to sustainability of buildings and infrastructure and reduced disruption to the local community during construction.

The UK Government predicts off-site manufacture for construction can increase construction productivity as the industry is facing a labour shortage (UK GOV Science and Technology Select Committee, 2018)

2.2.1 Modularisation in nuclear

Modularisation has been utilised in nuclear power plant construction assembling parts in offsite assembly areas or in factories to take work off the critical path starting with containment rings in the 1950s (Presley et al., 2009). 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 2-6).

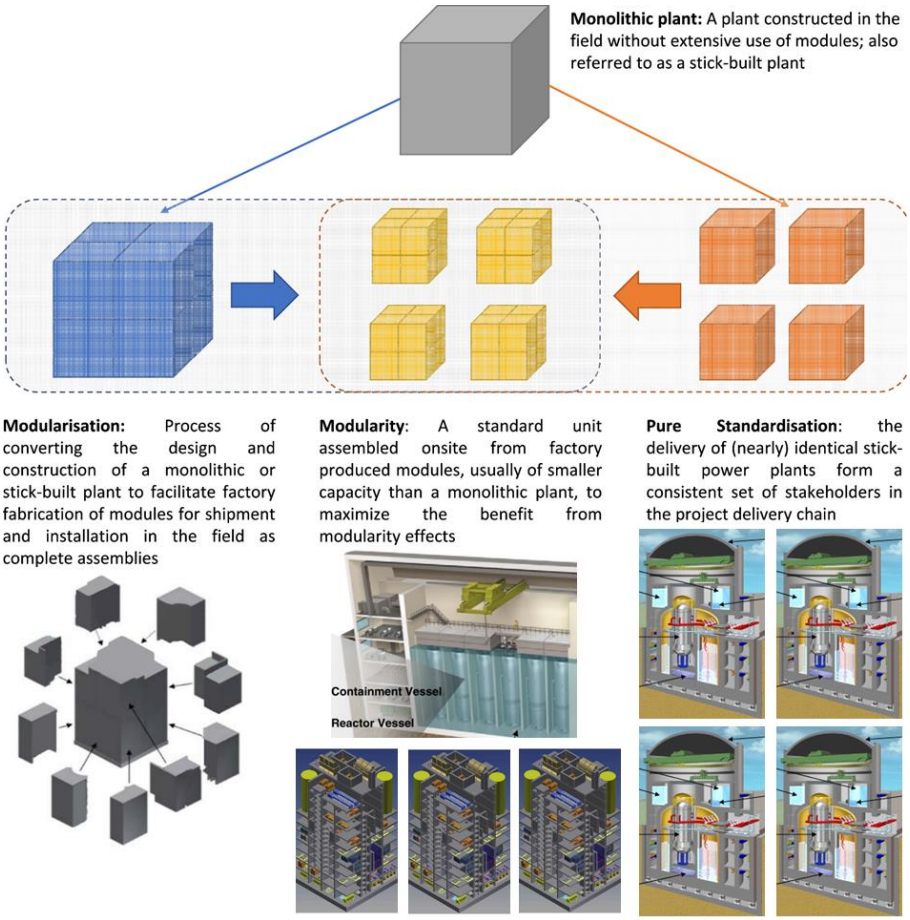


Figure 2-6 – (top) Definitions of Modularisation, Modularity and Standardisation (B. Mignacca & Locatelli, 2020)

(Left) Partitioned large nuclear steam supply system (AP1000),

(Middle top) Nuscale combined integrated modules (D. T. Ingersoll et al., 2014)

(Middle bottom) Integrated Westinghouse SMR NSSS modules (Giovanni Maronati et al., 2018)

Standardisation see Hanul Nuclear Power Plant (AB1600 plant in right picture (Arai, Murase, Hamazaki, & Kuroki, 2008)*)* (P. Wrigley, Wood, O’Neill, Hall, & Robertson, 2021)

2.2.2 Current Large Gen III nuclear power modularisation

Fang et al., (2012) defined the “Modularity Degree” as 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. The method is simple and requires most of the plant to already be designed.

Although not designed to be a “modular design” EDF, (2020) highlight increasing use of prefabrication in factories as a success factor in the on time construction delivery of Hinkley Point C.

However, (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. Although this study is only uses high level and limited data, possibly because of commercial restrictions, but is more of a policy recommendation tool.

Multiple studies maintain SMRs can be cost competitive with large reactors, offsetting economies of scale through reduced finance, standardisation, co-location, learning by doing (B. Mignacca & Locatelli, 2020). 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).

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.

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 modules. The APR1400 is designing and testing composite SC, mechanical & electrical modules (Y. Il Lee, Lee, & Kim, 2010).

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.

2.2.2.1 Current Large Gen III nuclear power modularisation summary

The nuclear industry in America and Europe has lost vital experience in construction, management and the supply chain meaning reactors are often 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). European Pressurised water Reactor (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 and Russian 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 should be taken into consideration when designing small modular reactor plants.

2.2.3 Economics of SMRs

Small modular reactors offer multiple benefits such as reduced finance and risk, economies of mass production through factory work, whereas integral reactors offer better safety. 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 (B. Mignacca & Locatelli, 2020) (Lovering & McBride, 2020) shown in Figure 2-7. A. Roulstone, (2015) hinted that

smaller reactors could benefit from economies of learning and mass production instead of economies of scale.

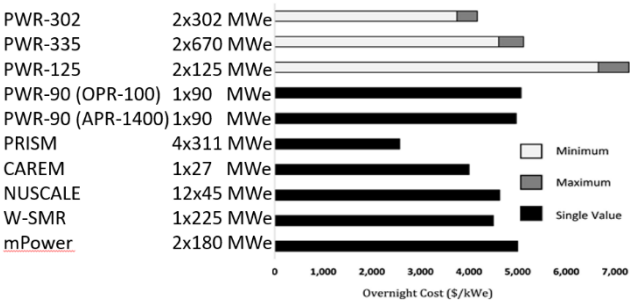


Figure 2-7 -SMR Overnight Cost Estimations (B. Mignacca & Locatelli, 2020)

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 analysis 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 (Figure 2-8) more productive (Barry, 2009) than stick building at site, useful for when considering what parts of the plant to modularise, with more congested areas gaining the most benefit.

Figure 2-8 – 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 2-1), 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 – N(ext)OAK 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 (P. Wrigley, Stewart, Hall, Wood, & Robertson, 2018)		2% of the resultant module total cost.	0	2

Table 2-1 - Comparison of stick-built and modular plant features (Generation IV International Forum, 2007)

2.2.4 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 2-9). 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, Mutyala, Vijuk, & Mishra, 2011) shown in Figure 2-9 (left).

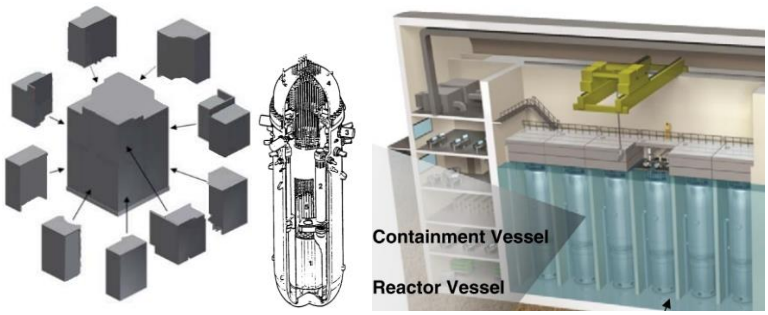


Figure 2-9 – Partitioned nuclear steam supply system (left), integrated modules and combined integrated modules (right)

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).

2.2.5 Balance of plant/ secondary systems modules analysis

With the nuclear island taking up 28% of the whole plant costs (World Nuclear Association, 2020b), 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 2-10 shows the modules for Residual Heat Removal heat exchanger and Chemical Volume and Control System (CVCS) module layout.

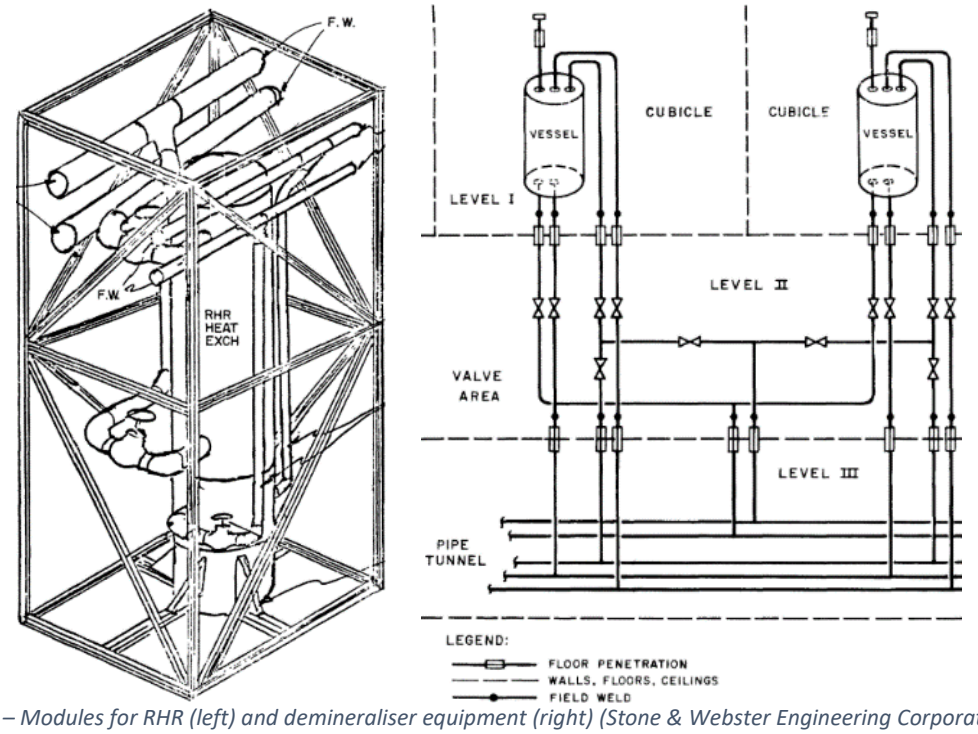


Figure 2-10 – Modules for RHR (left) and demineraliser equipment (right) (Stone & Webster Engineering Corporation, 1977)

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, using component module space frames (Figure 2-11) was introduced by 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, where learning rates and additional capital costs would be more than the additional site costs.

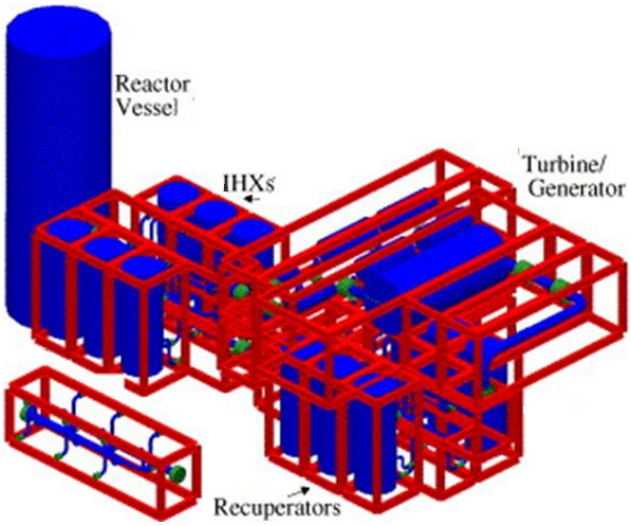


Figure 2-11 - Modular pebble bed reactor designed with space frames and a "virtual Factory" (Kadak & Berte, 2006)

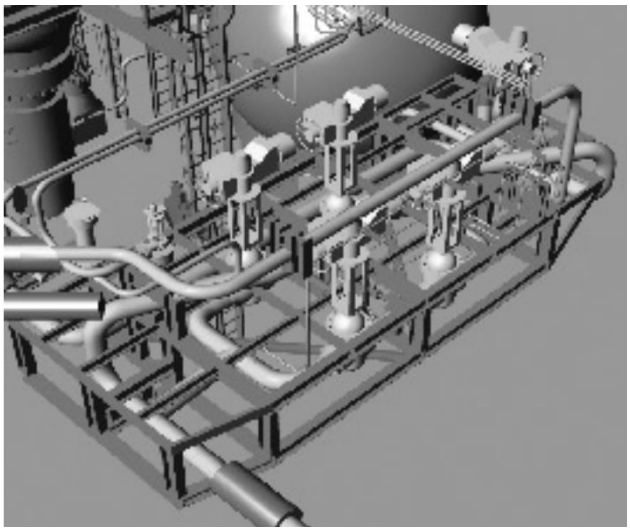


Figure 2-12 – AP1000 piping module (Sutharshan et al., 2011)

AP600/AP1000 plants uses over 270 modules including piping (Figure 2-12) structural, and valve modules (Figure 2-13), 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).

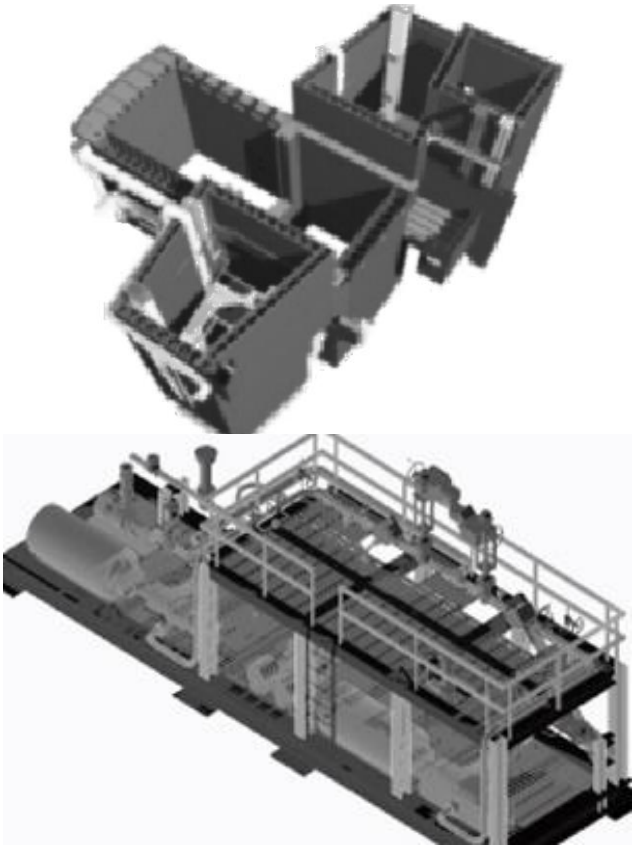


Figure 2-13 - Structural and valve modules (Sutharshan et al., 2011)

2.2.6 Modular 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 Lifting Industry. The report also highlighted several smaller, advanced modular reactors that were in development and suggested a 600MWe Light Water Reactor (LWR) plant for modularisation results in total capital costs which are 12 percent lower and a reduction in the overall schedule from 8 years to 6 years. New projects should consider new 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.

2.2.6.1 Systems Matrix Reordering (Lapp, 1989) and on-site assembly

Lapp, (1989) studied an onsite assembly area technique, similar to shipbuilding and highlighted a 15% reduction in total capital cost using this method. 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 method highlighted efficiency savings lending to lowering costs, higher quality and minimising the construction timetable.

This approach is used on the latest large gen 3 plants such as the Westinghouse AP1000, involving breaking down the nuclear steam supply system into 9 large modules to be assembled in an on-site factory utilising one of the world's largest cranes.

A Design (or Dependency) Structure Matrix (Eppinger & 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 & Ben-Asher, 2005) was implemented to reorder and cluster highly linked systems (Figure 2-14).

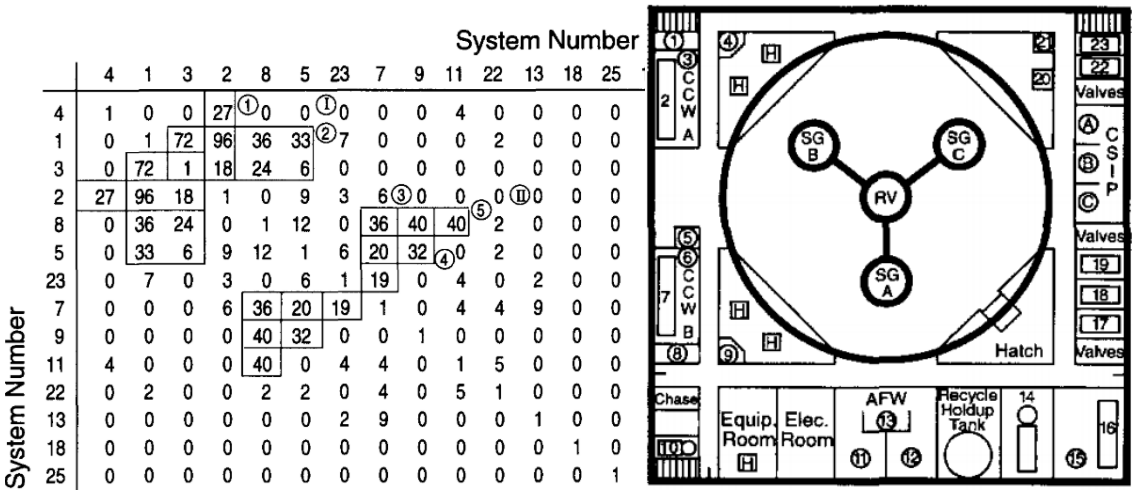


Figure 2-14 – Reordered systems matrix (left) from (Lapp, 1989) and equipment assigned to plant areas (right)

The matrix reordering technique from Lapp, (1989) is described in the following sections. The equipment data is then analysed for transport requirements and the data for each of the 3 case studies considered.

The prior on-site modularisation technique, clustered systems and equipment utilising a matrix rearranging method. This method enabled prospective capital cost reductions of 15% in comparison to a conventional construction method. The matrix rearranging method is summarised in Figure 2-15.

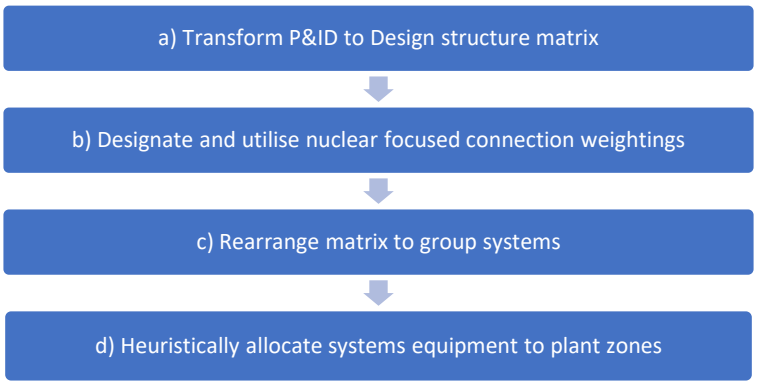


Figure 2-15 - Lapp (1989) technique for clustering systems

2.2.6.2 Step A - Transform P&ID to Design Structure Matrix

Initially, the Process and Instrumentation Diagram (P&ID) is transformed to a Design (Dependency) Structure Matrix (DSM).

The DSM (or connections weightings matrix) amongst two equipment items or systems is typically established from a P&ID like the case in Figure 2-16. Using Equation (1), (Jayakumar and Reklaitis, 1994) the relationship between one equipment item or system to the following is allocated to an *n* by *m* matrix.

$$DSM(i,j) = \begin{cases} 1, & if\ flow\ is\ from\ unit\ i\ to\ j \\ 0, & otherwise \end{cases} \qquad \text{Equation (1)}$$

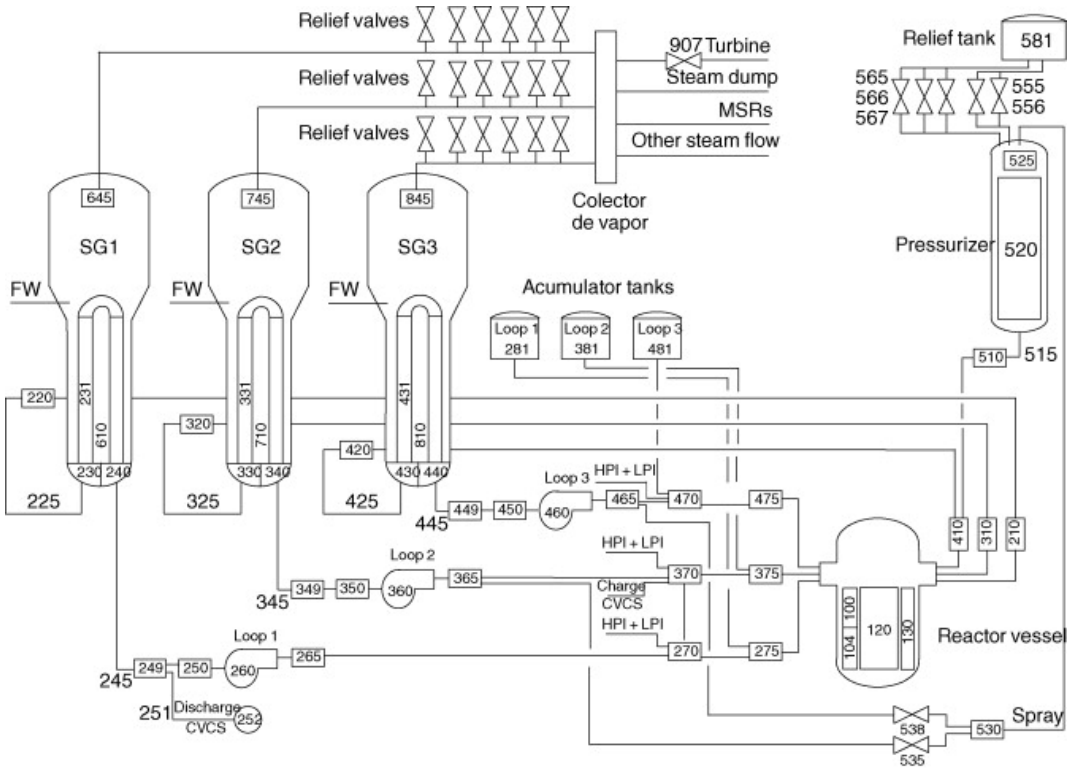


Figure 2-16 - Example of a 3-loop-2940 MWth Westinghouse PWR (Ascó-2) P&ID (©Elsevier) (Freixa, Reventós, Pretel, Batet, & Sol, 2009)

2.2.6.3 Step B - Designate and Utilise Nuclear Focused Connection Weightings

Step B in the matrix rearranging method (Figure 2-15) is to designate the nuclear focused connections weightings from Table 2-2 to the system relationships in the design structure matrix.

Class	Safety Class Penalty (SCP) Explanation	SCP	PSP
1	In-containment primary coolant system equipment and associated systems	6	-
2	Emergency functional equipment requirements.	4	-
3	Equipment assisting Class 1 or 2 systems	2	-
NNS	Non-safety, balance of plant associated systems	1	-

Class	Pipe Size Penalty (PSP) – Diameter of outer pipe	SCP	PSP
S	Small ≤ 10 cm	-	1
M	Medium ≤ 5 cm	-	3

L	Large	≤ ≥46 cm	-	5
Xl	Extra Large	≥46 cm	-	7

Table 2-2 - Pipe Safety Class And Size Penalty Values adapted from (Lapp, 1989)

The connections penalty (CP) matrix (Figure 2-17) for every link is evaluated with equation (2) utilising the prior links from the DSM, Pipe Size Penalty (PSP) and Safety Class Penalty (SCP) shown in Table 2-2. The PSP and SCP weightings of Lapp, (1989), Appendix C are employed. These are then transferred into the *n* by *m* connections penalty matrix.

$$CP_{ij} = DSM_{ij}\ x\ PSP_{ij}\ x\ SCP_{ij}$$

Equation (2)

2.2.6.4 Step C - Matrix Rearranging

The n by m DSM system matrix is rearranged to cluster equipment, presuming that the matrix's weightings are positive numbers. The objective function is to maximize the degree of effectiveness (ME), which is described in Equation (*3*).

$$ME = \sum_{i,j}^{n,m} CP_{ij} \times \left[CP_{i,j-1} + CP_{i,j+1} + CP_{i-1,j} + CP_{i+1,j}\right]$$

Equation (3)

The rearranging algorithm is accomplished by:

- Multiplying every part of the CP_{ij} matrix with the components adjacent to it
- The lines or columns are added to develop the bond energy algorithm (BEA) cost.
- The lines and columns are rearranged while the value of the BEA is maximised.

The finalised grouped matrix is displayed in Figure 2-17 with 4 categorised groupings.

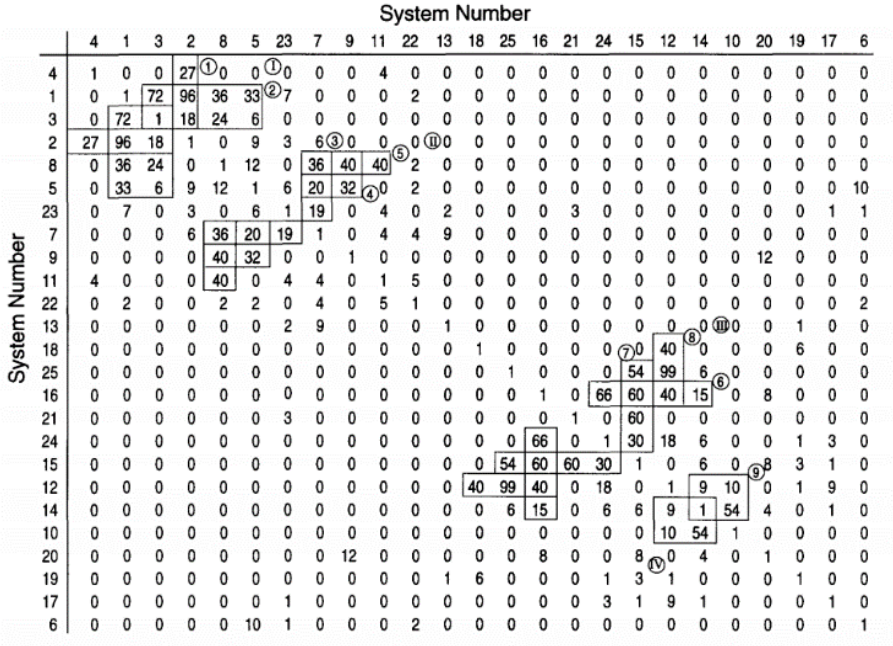


Figure 2-17 – Reordered system matrix to cluster components (Lapp, 1989)

The clustered systems are heuristically designated to closely defined modules (Figure 2-18). The components were then heuristically assigned to plant areas (shown in Figure 2-14 and Appendix B).

2.2.6.5 Altered Shearon Harris Nuclear Plant Outcomes (Lapp, 1989)

Possible capital cost reductions of 15% were emphasised with the assembly area on-site construction technique. The associated safety systems in the plant are clustered in the upper left two groups (Figure 2-17):

- Safety Injection System (SIS)
- Residual Heat Removal (RHR) /Containment Spray (CS)
- Component Cooling Water (CCW) / Emergency Service Water (ESW)
- Auxiliary Feedwater (AFW)

The 2D organisation of the plant layout (Lapp, 1989), (pages 212-244 and figures 6.3a-6.9d) were mapped into an 3D figure using the MATLAB graphing function (Figure 2-18). The Reactor Cooling System (RCS) can be observed within the nuclear island (translucent grey containment) (Figure 2-18). The RCS consists of the Reactor Pressure Vessel (RPV), Reactor Cooling Pumps (RCP) and Steam Generators (SG). The Safety Injection System module (SIS), Containment Spray module and Residual Heat Removal (RHRCS) are situated nearby containment owing to the increased grouping amongst these systems and the systems within containment (RCS). Situated nearby the Containment Spray (CS)/ Residual Heat Removal (RHR) (combined RHRCS) are the Component Cooling Water (CCW) modules. The Chemical and Volume Control System (CVCS) is positioned nearby the waste process treatment complex owing to the high connectivity. Non-attached systems such as the electrical and heating and ventilation modules have been excluded for transparency because the data is not available so they are not considered in the optimisation.

Module i	Module/ System	Description	Floor	Key
1	RCS	Reactor Coolant System	1	
2	RHRCSA	Residual Heat Removal A	1	
3	RHRCSB	Residual Heat Removal B	1	
4	SGBD	Steam Generator Blow down	1	
5	CSS	Chemistry Sampling System	1	
6	CCWA	Component Cooling Water A	2	
7	CCWB	Component Cooling Water B	2	
8	RHRCSA	Residual Heat Removal A	2	
9	RHRCSB	Residual Heat Removal B	2	
10	AFW	Auxiliary Feed Water System	2	
11	BRS	Boron Recycle System	2	
12	BRTS1	Boron Thermal Regeneration A	2	
13	BRTS2	Boron Thermal Regeneration B	2	
14	SIS	Safety Injection System	2	
15	CVCS	Chemical and Volume Control	2	
16	Boric Acid	Boric Acid	3	
17	BTRS	Boron Thermal Regeneration	3	
18	CVCS	Chemical and Volume Control	3	
19	CCWST	CCW Surge Tank	4	

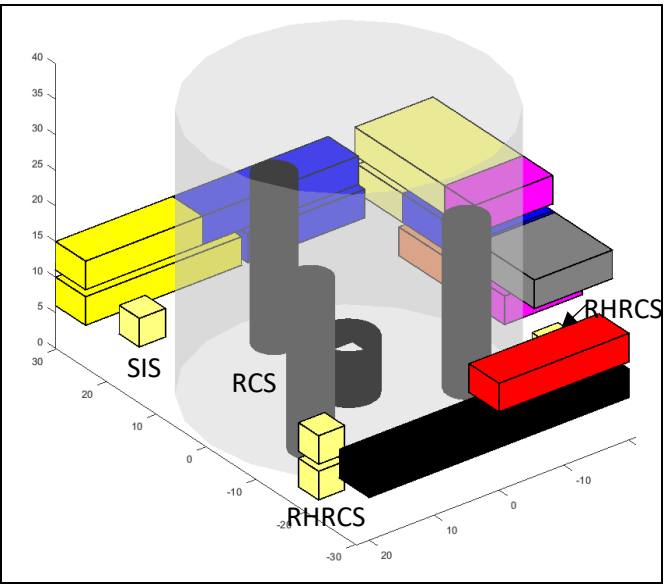


Figure 2-18 –Shearon Harris Power Plant associated systems shown in a MATLAB graphics figure (P. A. Wrigley, Wood, Stewart, Hall, & Robertson, 2019)

The balance of plant systems (listed in Figure 2-18) are placed on three sides of the nuclear island in this arrangement. If systems are linked, as the CVCS is linked to the CCW and RHRCS systems, the pipework journeys circumferentially around the containment for the nuclear island, increasing pipework and adding considerable expenses to construction. Generally, in a fluid-process plant, up to 20% of the fixed capital investment can be attributed to piping and installation costs (Peters et al., 2003).

The limitation the utilising the DSM in representing the inter-module constraints, is that it only considers one connection parameter. There might be multiple connections, which are only added together, limiting its usefulness.

2.2.6.6 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. There was a large drop off in degree of modularisation from 450MWe (Figure 2-19) for mechanical modules, therefore they recommended a 60% Degree of Modularisation to provide considerable construction cost savings and to be cost competitive with a large plant. It also revealed that the (Generation IV International Forum, 2007) report highlighted cost reductions of between 155-295% for factory-produced modular units. It suggested most of the benefits of modularisation are resultant in the field indirect accounts, reduced construction schedule, and financing costs. Further savings could be realised through the future potential of Robotics and automation and Autonomous Electric Transport (Wrigley et al., 2018).

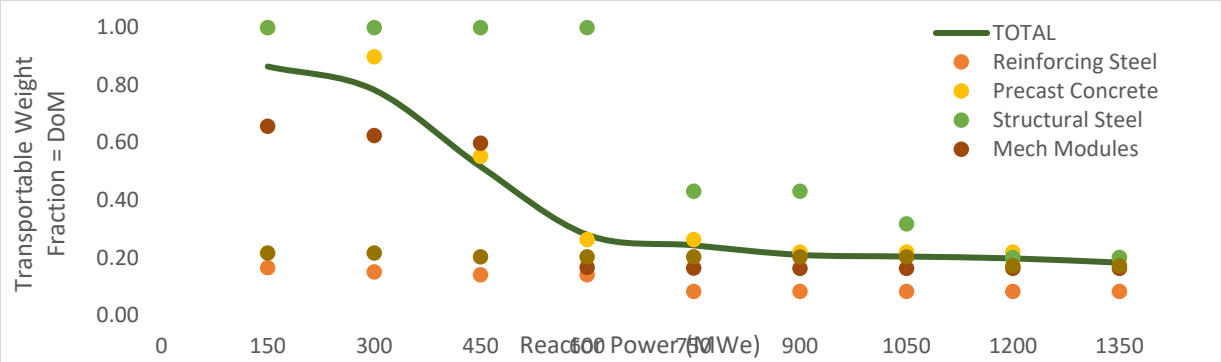


Figure 2-19 - Degree of modularisation concept developed by (Lloyd & Roulstone, 2018b) (Lloyd & Roulstone, 2018b)

2.2.6.7 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.

2.2.6.8 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.

2.2.6.9 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).

2.2.6.10 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 & Townsend, 2003).

2.2.6.11 Systems description

Memmott et al., (2012) discuss the balance of plant (BOP) systems designs for the Westinghouse Small Modular Reactor. The design 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, Van Wyk, & Memmott, 2012).

2.2.6.12 Modular Retrofit designs

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

2.2.6.13 Module decision tool

A decision-making tool comprising of a screening and weighting criteria was developed in order to aid module selection (Y. Il 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 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)

2.2.7 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 2-20).

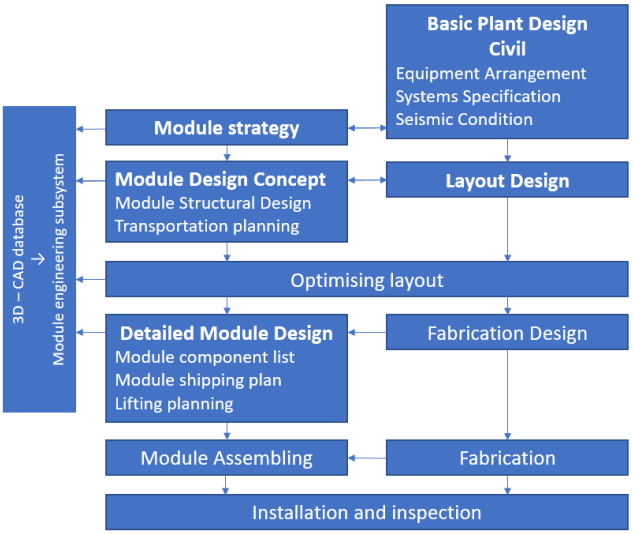


Figure 2-20 – Hitachi's parallel module design process (Akagi et al., 2002)

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 2-21).

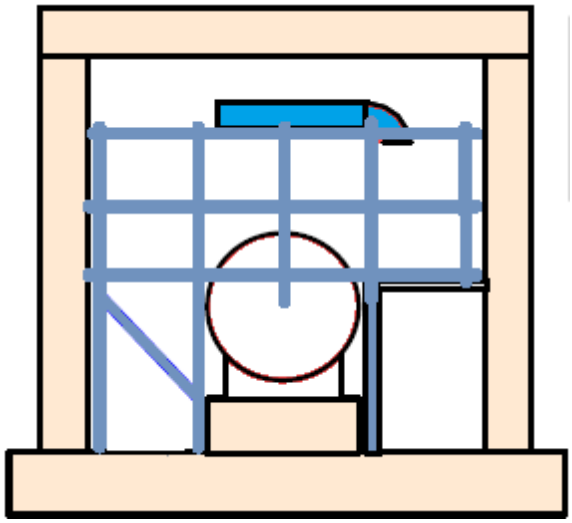


Figure 2-21 - open top construction for modules (Yotsuya et al., 2004) (Lapp & Golay, 1997)

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 plant modular design process (Figure 2-22), 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).

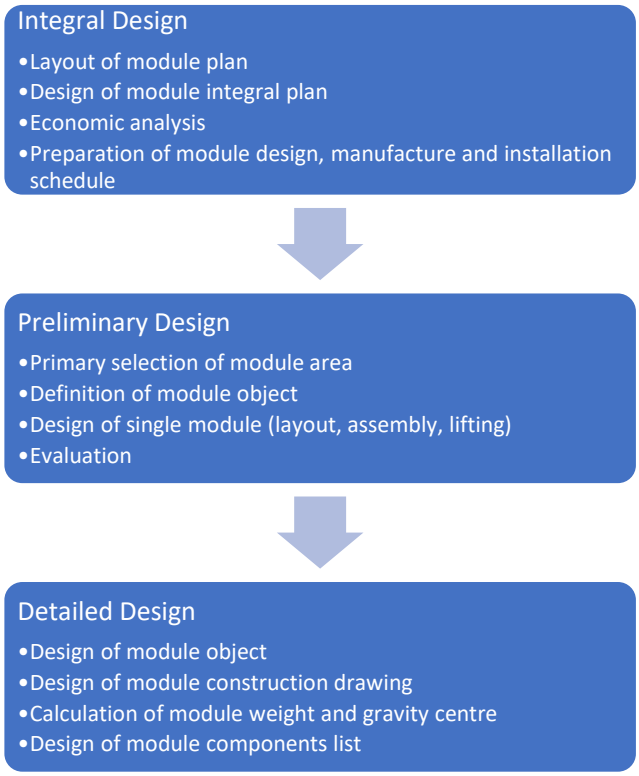


Figure 2-22 - Modular design process Adapted from (Lu et al., 2013)

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 2-20) 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.

2.2.8 "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.

2.2.8.1 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 (Y. Il Lee et al., 2010). They detail a mock-up test of a composite module and provide recommendations for future research. Discussing 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).

2.2.8.2 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.

2.3 Industrial Plant Modularisation

Oil and Gas Modularisation has mainly focused on large transportable modules (Figure 2-23) in remote and weather adverse locations.

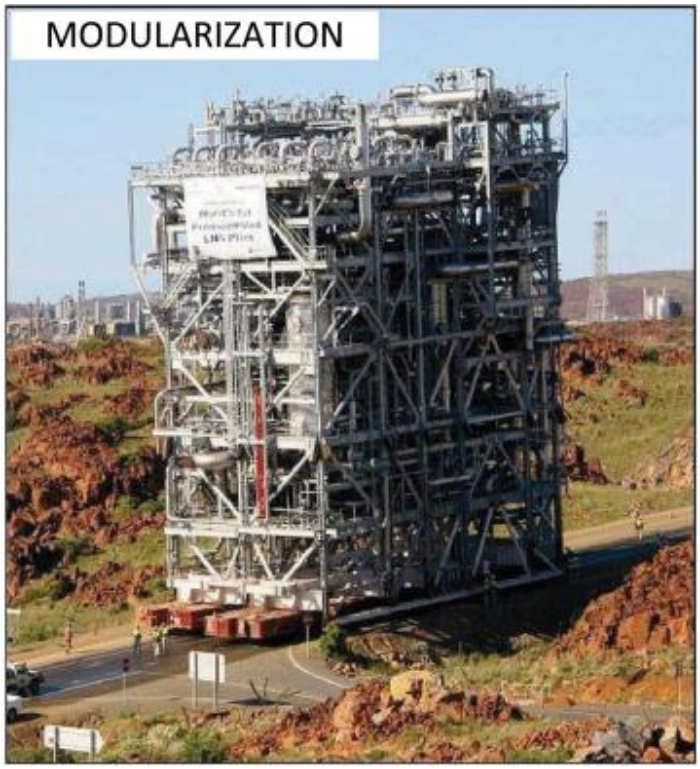


Figure 2-23 - Very Large modules designed for remote and weather adverse locations (Mokhatab, Mak, Valappil, & Wood, 2013)

2.3.1 Economics of Industrial Plant Modularisation

Glaser, Kramer, & Causey, (1979) state that a Modular construction project can expect to see design and engineering costs increase by around 10%, the procurement cost associated with evaluating and selecting vendors, fabricators, and factory manufacture and assembly and to administer contracts increases by 20%, fabrication by 17% and transportation by 13%. Kliewer, (1983) cites an engineering cost increase of 15% for a Modular construction project.

Hesler, (1990) underlines that capital cost savings of 20 % or more can be achieved with modular design. Although engineering costs can be 12% more the total installed cost compared to stick-built designs. Shelley, (1990) reveals a 20% reduction in capital costs is possible. Modular design could decrease the land use by 10% to 50%, total price of a plant by 10% and minimise on-site labour by 25% (Tatum, Vanegas, Williams, & Construction Industry Institute (Austin, 1987)). At the Sullom Voe Oil process terminal facilities in the Shetland Islands, using large modular construction saw reductions of at least 7% of the total contract figure (Parkingson & Short, 1982). Jameson, (2007) showed a cost saving of 17.8% could be obtained on a gasoil hydrotreater modular project situated in North America.

Merrow, (2012) highlighted that the majority of megaprojects in the world seem to complete the projects far behind schedule and over budget and could be seen as failures. Although, it was emphasized that the World's largest Liquid Natural Gas project, Yamal, was completed to the timeframe and on budget (Benito Mignacca, Locatelli, Alaassar, & Invernizzi, 2018).

2.3.2 Construction Schedule reductions

Shelley, (1990) shows that modular construction time can be shortened by 50%. Hesler, (1990) states that modular power plants show schedule savings approaching 40%. Eftimie, (2016) states that modular construction reduced schedule up to 25-50% in offshore facilities. Modular Building Institute, (2013) shows modular construction time can be shortened by 50%. Song & Choi, (2014) approximate a schedule saving of 22.2% for construction of modular underground machine room in a high-rise residential building. General Dynamics, (2020) showed the construction schedule could be reduced by 28% in its electric boat.

2.3.3 Modular design methods in industrial plant design

Recently, chemical process plant research has seen increased interest in smaller plant designs, designed to be manufactured in factories, which are faster, cheaper and provide more flexibility in production.

The capability of modules as reusable items were discussed and a module documentation internet administration software tool was produced for quality and assurance (Hady & Wozny, 2011). Student evaluation showed approval and acceptance of the technique.

It was estimated that small modular plants could decrease the construction schedule by over 2 years (66%) and improve value by 35%. Changing to a continuous process rather than batch could also achieve 30% better value (Seifert, Sievers, Bramsiepe, & Schembecker, 2012).

A real options framework methodology for plant growth regarding capability bottlenecks and multiproduct situations was presented (Seifert, Schreider, Sievers, Schembecker, & Bramsiepe, 2015)

A new cluster analysis approach was produced for the creation of an electronic storage tool for heat exchanger modules from previous industrial applications (Eilermann, 2016). The generated heat exchanger modules could cover 59% of the contemplated engineering functions (Eilermann et al., 2017). Eilermann et al. then presented a method for plant design via module election and outline. The requisite design responsibility modules are chosen from records and configured for all tasks in the design process from Process Flow Diagrams (PFD), P&ID, equipment set and 3D layout tasks (Eilermann, Post, Radatz, Bramsiepe, & Schembecker, 2018). They improve the method to cover more

requirements while being more computationally efficient (Eilermann, Schach, Sander, Bramsiepe, & Schembecker, 2019).

Chemical and food production (Figure 2-24) was assessed to determine how it can be affected by small and (Zeton factory-built (Zeton, 2019)) modular process units (Bramsiepe et al., 2012).

Figure 2-24 - Factory-built process plant modules (Bramsiepe et al., 2012) by ((Zeton, 2019))

The EU Research and Development into Industrial technologies platform ran a €30 million project on modular production methods (EU Community Research and Development Information Service, 2013a). The F^3 Factory project enabled a method to introduce a new synthetic process at low capital cost (up to -40%). The industrial processes have been intensified by a substantial factor of up to 500, the project brought about:

- Improved space-time-yield up by 100x
- 20% Enhanced capability
- 20% Expanded fabrication yield
- Solvent usage decreased by up to 100%
- 50% site decrease
- 60% decreased equipment demand

- Decrease of reaction/processing period by 10x
- Decrease of reaction and processing actions up to 30%

A computer-assisted selection methodology was created for reactor equipment. It returns favourable technical equipment and configuration in the early phases of the design (Krasberg, Hohmann, Bieringer, Bramsiepe, & Kockmann, 2014).

An approach for assessing modular & non-modular fabrication situations was developed. The "F3" factory concept (Figure 2-25) was utilised as an example assessing different production methods as well as the supply chain (Sievers, Seifert, Schembecker, & Bramsiepe, 2016). This included a set of design guidelines for the process plant. (EU Community Research and Development Information Service, 2013b).

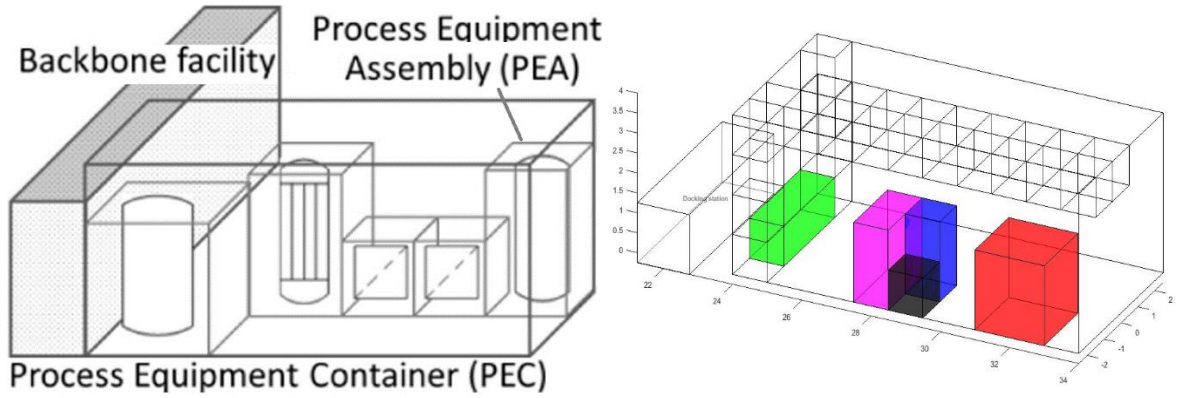


Figure 2-25 -Illustration of F3 factory modular elements (left) (Sievers et al., 2016) *and F3 Factory design procedures and specifications for modular, module-based fabrication units characterised and applied in various process component modules (EU Community Research and Development Information Service, 2013b)*

The revision of process component designs from previous projects were utilised to create appropriate results for new projects (Fleischer-Trebes, Krasberg, Bramsiepe, & Kockmann, 2017).

A theory for data processing during the whole life cycle of the process industry from laboratory to production was defined (Hohmann, Kössl, Kockmann, Schembecker, & Bramsiepe, 2017). Reusable modules, organised module databases, and innovative techniques for module election and configuration were analysed. They highlighted it can lessen the engineering effort, development period and budget.

Modular fabrication was evaluated and modular fabrication designs are appraised based on the value concentration of feedstock assets, an innovative system of measurement and markets (Baldea, Edgar, Stanley, & Kiss, 2017). Also discussed are the links amongst modularisation and process intensification. Barriers to implementation and future work are highlighted through numerous industrial examples.

A method where a modular P&ID is formed via 'simple and supplementary components: equipment, P&ID' was developed. Modular P&IDs are formed by employing a knowledge-based decision tree technique centred on design questions (Uzuner, 2017).

The deduction of heuristics and a global sensitivity analysis are applied to the flexible design of a liquid heat exchanger (Radatz, Elischewski, Heitmann, Schembecker, & Bramsiepe, 2017). The design is compared to the original design and it is shown that a 4X operational period can be achieved for 14% increased yearly costs.

A multi-objective evolutionary algorithm was developed to choose component modules for an adaptable modular manufacturing plant with minimal investment costs (Radatz, Schröder, Becker, Bramsiepe, & Schembecker, 2019). They highlighted for 50% greater investment costs an 11 times expanded working period can be achieved.

Developments in US process intensification and modular construction (Figure 2-26) were summarised in various industries: pulp & paper handling, chemical manufacture, gas processing and fuels refining (Bielenberg & Palou-Rivera, 2019). They stress that in future, the two methods could also have a significant impact in water usability processes and carbon capture and utilisation.

Figure 2-26 – Modular process plant (Bielenberg & Palou-Rivera, 2019)

2.4 Offsite Modular Construction

Off-site modular construction has been an increasing area of research over the past few decades as productivity in construction has declined. Mechanical Electrical and Plumbing (MEP) systems are a vital component of building services. A search for MEP modules was conducted to understand if similarities between modular MEP design and industrial plants exist.

2.4.1 Offsite Modular Construction literature reviews

The Scientometric literature review analysis performed by Hosseini et al., (2018) and Jin et al., (2018) found that Off-Site Modular Construction (OSMC) has only seen significant consideration in the preceding few decades, as construction productivity has steadily decreased. They both found that the most significant areas in OSMC research were precast concrete, BIM, prefabrication and production planning with less focus on operational and management and very few research articles on industrial buildings.

In the literature review by Yin, Liu, Chen, & Al-Hussein, (2019), it was found that a large focus was on BIM research, whereas OSMC research concentrated on the management of the construction process and component design and operation. They highlighted an area for further OSMC research could be BIM-based generative design for prefabrication.

A Scientometric analysis and critical review highlighted computer vision for offsite production remain under-researched (Martinez, Al-Hussein, & Ahmad, 2019).

A literature review into construction automation highlights automation in construction is still in the early phases and is yet to experience larger adoption. They find Single-Task Construction Robots approaches, construction automation technology, other microsystems technology and service robot systems are currently uniting with BIM (Bock, 2015).

Yang et al., analyse how robotics and off site modular construction (Figure 2-27) can be integrated with case studies from Hong Kong (Y. Yang, Pan, & Pan, 2019).

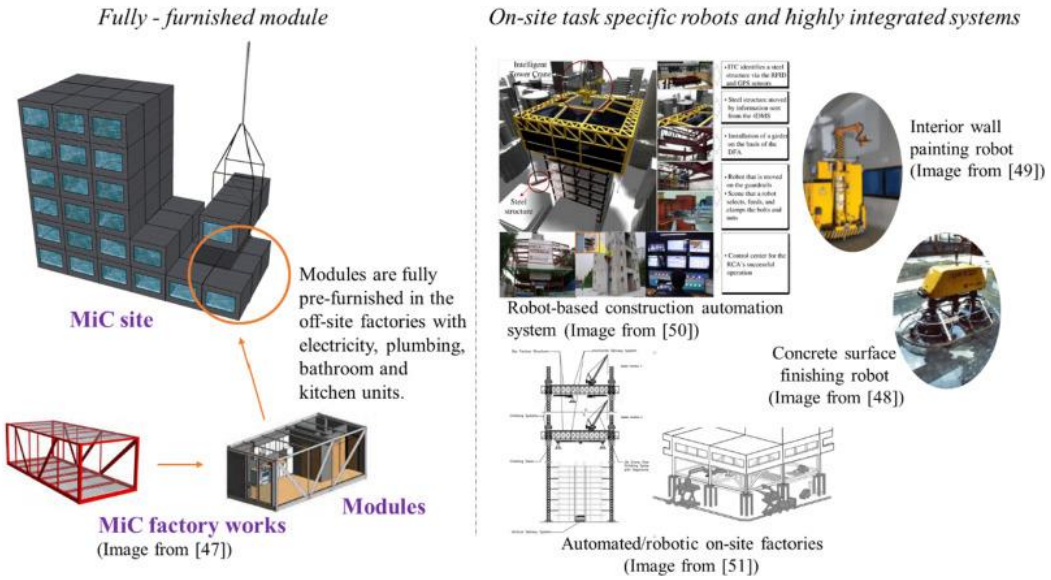


Figure 2-27 - How robotics and off-site modular construction can be integrated (Y. Yang et al., 2019)

2.4.2 MEP module design

Tserng et al. found that modularising a MEP module (Figure 2-28) using planning algorithms reduced costs from $66,030 to $19,566 and saved 12 days in the construction schedule (Tserng, Yin, Jaselskis, Hung, & Lin, 2011).

Figure 2-28 - Fire suppression system decomposition, motor, foam tank and Generator (Tserng et al., 2011)

Modular offsite production of fluid systems were analysed, identifying barriers and recommendations for successful implementation (Li, Li, & Wu, 2017), these should be considered in the modular design process.

An automated efficient modularisation algorithm combining a DSM, fuzzy logic and Hierarchical Clustering (HC) methods was developed (Samarasinghe, Gunawardena, Mendis, Sofi, & Aye, 2019). The algorithm identifies the ideal amount of modules and separation places centred on assembly expenditure and the processing cost of every module to accomplish the lowest total fabrication cost (Figure 2-29).

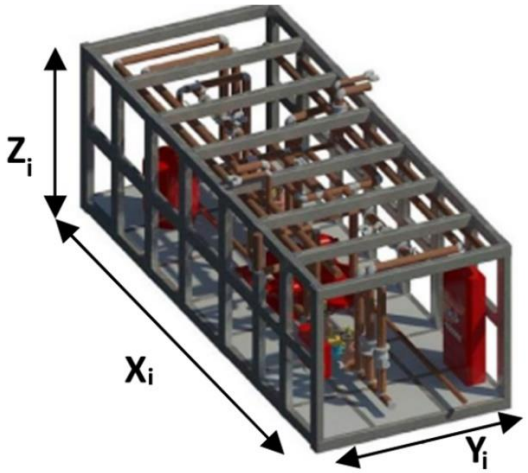


Figure 2-29 – Technique utilised to calculate dimensions of MEP modules using the equipment coordinates (Samarasinghe et al., 2019)

A design structure matrix method of calculating a near ideal option of module arrangement using 5 indicators was proposed: shipment of prefabricated modules to the construction assembly site, connections of modules onsite, related cost, project concrete foundation and crane operating condition (Salama, Salah, Moselhi, & Al-Hussein, 2017). The method showed efficient results in a residential construction project (Figure 2-30).

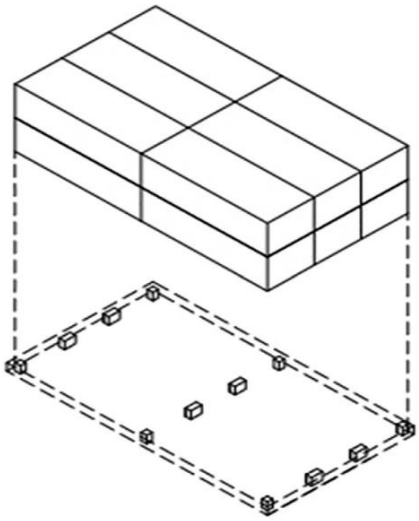


Figure 2-30 - Modules' foundation design in residential construction by Salama et al., (Salama et al., 2017)

Object-based CAD constraint logic programming to aid in the design of a low-pressure hot water plant room (Figure 2-31) was developed, considering selection, sizing, layout and pipe routing (Medjdoub, Richens, & Barnard, 2003). Design time was estimated to be reduced by around 10–20%. This was then improved in later works (Medjdoub & Chenini, 2015) (Medjdoub & Bi, 2018).

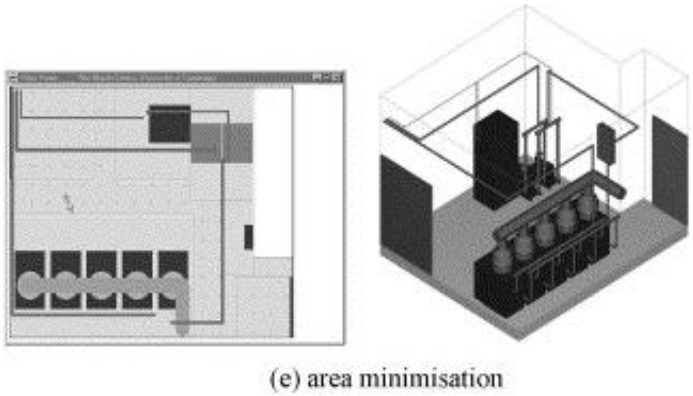


Figure 2-31 - Production of variational essential plant room solutions (Medjdoub et al., 2003)

Medjdoub applied a similar technique to a ceiling mounted fan coil system via designing, sizing and layout planning (Medjdoub, 2009).

A Monte Carlo tolerance simulation was applied to a preassembled building (Figure 2-32), highlighting that using this method to improve tolerances, a major rework probability can be reduced from 100% to 34% likelihood of slight alterations (Rausch, Nahangi, Haas, & Liang, 2019).

Figure 2-32 - Monte Carlo tolerance simulation on a preassembled building to improve tolerances to reduce rework probability (Rausch et al., 2019)

2.4.3 Design and planning process

A modularisation business case evaluation model was established to help businesses consider off site construction for industrial projects (Choi, O'Connor, Kwak, & Shrestha, 2019). They summarise Modularisation Decision-Making Tools, which are useful for considering modularisation and to integrate into the design and planning process.

A research framework for stakeholders in off-site manufacturing was developed for future practice and improvement (X. Hu, Chong, Wang, & London, 2019).

Modular projects in different industries (bridge, industrial, light industrial/commercial, prison, residential, and ship) were assessed and highlighted several techniques to apply to ensure success (De La Torre, Sause, Slaughter, & Hendricks, 1994).

A multi-objective particle swarm algorithm was proposed to minimise the total cost of site layout; and maximise safety for the Longtan hydropower construction project (J. Xu & Li, 2012).

A schedule saving of 22.2% was approximated for construction of a modular underground machine room in a tall residential building (H. Song & Choi, 2014) and discuss considerations in the design process

2.4.4 BIM integration

A pragmatic Building Information Modelling (BIM) outline for assimilating the MEP layout across all levels of the design was developed, highlighting early detection of errors, saving schedule and costs (J. Wang, Wang, Shou, Chong, & Guo, 2016).

Machine learning algorithms for MEP equipment based on BIM and the Internet of Things were implemented via a data predictive maintenance scheduling scheme, highlighting effective maintenance prediction and scheduling (Cheng, Chen, Chen, & Wang, 2020).

The BIM implementation for the Italian Public Pilot Project developed an interoperable Industry Foundation Classes based process, achieving sophisticated model and code checking and evaluating the 4D BIM construction phase. It showed a shared stakeholder BIM management is required with collaboration needing to be improved for effective implementation (Ciribini, Mastrolembo Ventura, & Paneroni, 2016).

Another study found that a sequential BIM coordination approach was about 3x more efficient than a parallel method in a pharmaceutical MEP building (Figure 2-33) case study (G. Lee & Kim, 2014).

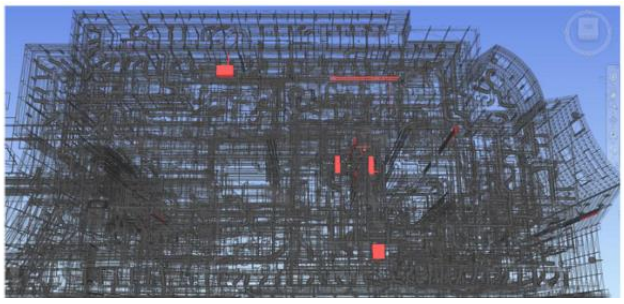


Figure 2-33 - Pharmaceutical MEP building case study (G. Lee & Kim, 2014).

2.4.4.1 Logistics planning and optimisation

A two-stage stochastic programming model was applied for logistics planning in a residential construction sector project (Hsu, Angeloudis, & Aurisicchio, 2018). They then add the selection of optimal warehouse locations and apply the technique to a school dormitory construction project and show significant efficiency savings (Hsu, Aurisicchio, & Angeloudis, 2019).

2.4.4.2 Scheduling optimisation

A multi-objective Genetic Algorithm for the scheduling of precast construction for manufacturing, transportation and assembly intending to minimise time and cost while maximising safety was developed (Anvari, Angeloudis, & Ochieng, 2016).

2.4.4.3 Crane planning and optimisation

A method to automate and optimise crane planning and configuration (Figure 2-34) was conceived and applied to modular projects in Alberta, Canada (Taghaddos, Hermann, & Abbasi, 2018).

Figure 2-34 - Optimised crane planning and configuration for a modular project in Alberta, Canada (Taghaddos et al., 2018)

2.5 Knowledge Based Engineering/ Automating Design

Since the conception of the personal computer in the 1980s, software has sought to improve processes by making tasks more efficient and easier to accomplish. The increase in computing power of personal computing developed applications for Computer Aided Software (CAx) and Artificial Intelligence (Figure 2-35). The storage capability improved knowledge management access.

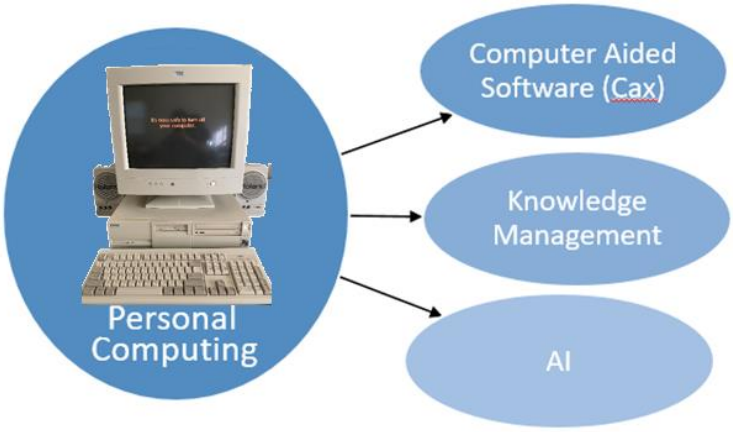


Figure 2-35 – Development of computer software to support engineering operations

CAx software's include (a not extensive list) of Computer Aided Design (CAD), Computer Aided Manufacturing (CAM), Modelling and Analysis Software: Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD), Nuclear reactor physics codes (NRC, 2018)

CAD replaced the drafting room, effectively allowing a handful of engineers to do the job of a team of draftsmen. CAD also allowed quick modifications and manufacturing drawings to be produced easily.

FEA, CFD and nuclear reactor physics codes allowed the modelling and analysis of different scenarios to predict situations which would have required extensive testing without computers, saving time, money and increasing accuracy due to less chance of human error. Today, combining and integrating the different codes available (De Haas et al., 2018) can again speed up the process for modern digital reactor design (Lindley et al., 2018).

Knowledge management software also enabled further process improvements, allowing knowledge to be stored and accessed easily, facilitating fewer errors, as the design engineers would not make the same mistake twice as knowledge and lessons learned had already been documented.

Artificial intelligence allowed the use of programmable computers to make human like decisions, increasing the speed at which decisions could be made. The processing speed significantly increased the speed at which calculations could be performed, reducing the time taken to search for a solution.

2.5.1 Automated design techniques

Knowledge Based Engineering (KBE) is a type of automated design. Whereas (Penoyer, Burnett, Fawcett, & Liou, 2000) describes generative design as a part of KBE, Krish, (2011) believed generative design is to be utilised more in the concept design stage, whereas "design optimisation" using FEA and CFD is utilised in the detailed design stage.

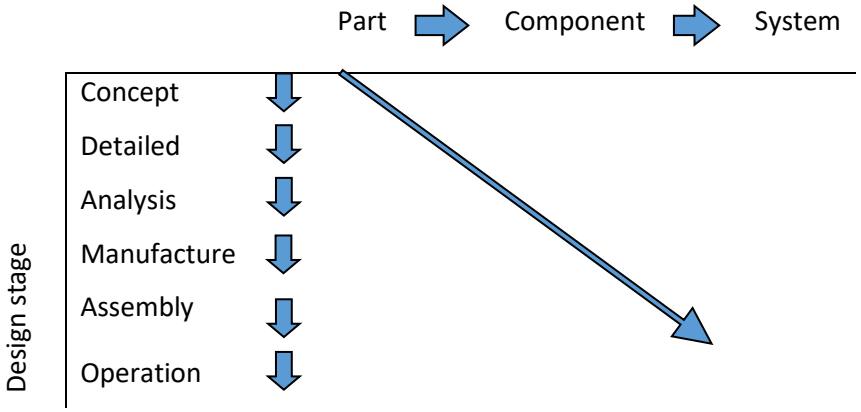


Figure 2-36 – Automated design can be applied to any part of the design process

The KBE definition is "to capture and re-use product and process engineering knowledge by automating parts of the design process" (Skarka, (2007) and V Holla, (2018)). Figure 2-36 shows how KBE can be applied over any part of the design process. KBE grew out of the increase in PC's and computer power in the 1980s, which facilitated the technology growth of CAx software, Knowledge management and Artificial intelligence growth. Knowledge Based Engineering takes the stored knowledge, along with decision making AI to automate parts of the design process (Figure 2-37).

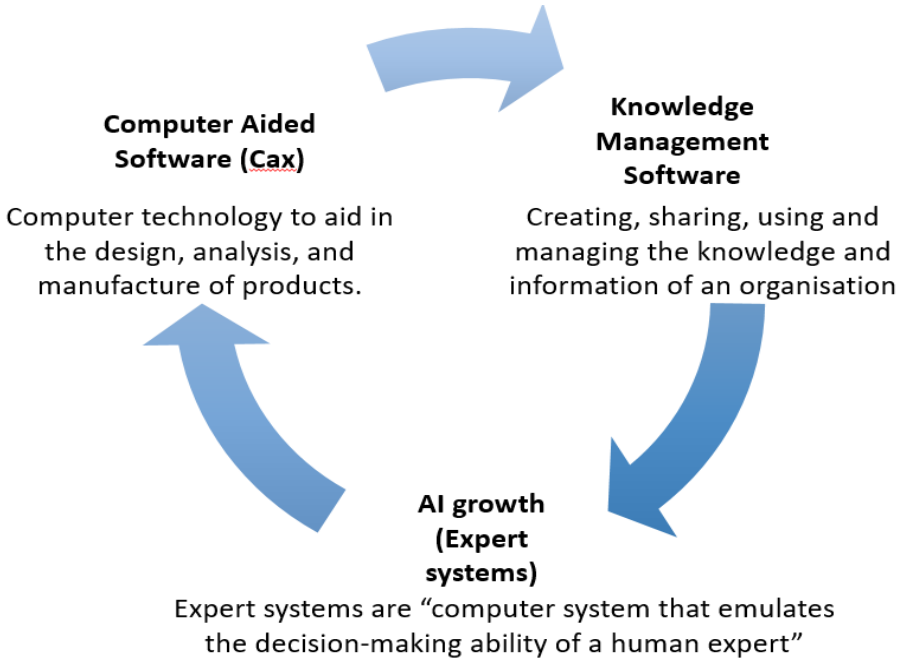


Figure 2-37 - KBE developed from technology progress in other fields

KBE is subject to a variety of interpretations and related definitions. This is mainly due to the broad definition of KBE and the fact that it may be applied to any part of the design process. Automated design tools can cut down the routine design tasks for design engineers, speeding up the design process or increasing the time for creative design (Figure 2-38).

2.5.2 How KBE can affect the design process

In the typical linear product design process, KBE can reduce the 80% routine design time and increase innovative design time (Figure 2-38).

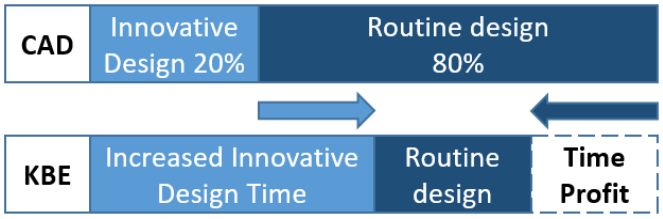


Figure 2-38 - How KBE affects the typical design process (Skarka, 2007)

In the systems engineering V-model of the design process, KBE can also shorten development time. KBE for systems design is a step up from Model-Based Systems Engineering (MBSE) (See Figure 2-39). MBSE is a methodology that utilises models instead of the traditional documents based systems engineering process. KBE for systems design utilises the same knowledge reuse method as KBE for product design.

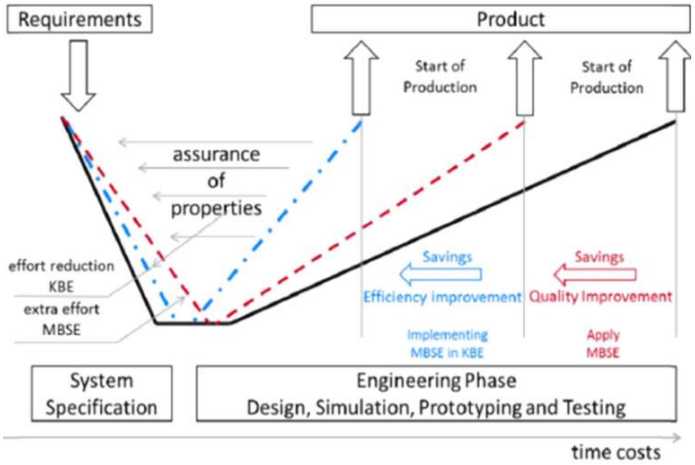


Figure 2-39 - Effect of MBSE and KBE on the development process according to the V-model (Dietz, 2015)

2.5.3 Types of KBE

There are four types of KBE System suggested (Penoyer et al., 2000), shown in Table 2-3.

Type	Description
Generative	Rules are set up to generate an output
Selection	Several options are suggested to the user of the KBE-system

Type	Description
Advisory	These systems analyse the current model, and present recommendations for improvement or search for irregularities
Innovative	The KBE system explores a large solution space. The objective is to optimise desired parameters. The technique uses artificial intelligence search methods from a simple search for a global minimum to more complex approaches like genetic algorithms or deep learning.

Table 2-3 - Types of KBE system (Penoyer et al., 2000)

Selecting a KBE system depends on the type of problem to be solved. It is proposed that the capabilities within KBE can be categorised into 4 levels depending on the level of engineering definition (Table 2-4).

KBE Level	Description
1	**Part/ component based**
	Traditional CAD Automation of repetitive and non-creative design tasks but utilising: spreadsheets, handbooks, engineering formulas, drawings and documents, rules of thumb into parts of the design
1.5	**Integration of Component based KBE**
	Multi-discipline analysis using workflow automation and iteration, structural, thermal, vibration, cost) to quickly optimise design
2	**Component/ Product based**
	Product configurators - Traditional CAD plug in overlay. Defining parameters with standard components to automatically generate a component/ product design
3	**Systems based design**
	Utilising a model based systems engineering approach and artificial intelligence to perform KBE.

Table 2-4 – KBE classified as models based on parts, components or systems

2.5.4 Rule Based Expert systems

The decision making AI, a part of KBE systems, are normally based on a Rule Based Expert Systems (RBES). RBES are a branch of artificial intelligence. They were developed to mimic the human decision-making process. Figure 2-40 outlines a generic architecture for an Expert System. Knowledge engineers input rules into the system, the RBES then generates constraints from the rules. The rules are stored in the knowledge base and run through the inference engine using a Rete Algorithm. Rete is a very efficient mechanism for solving the difficult many-to-many matching problem (Forgy, 1982).

Jess is based on Java and has many unique features including backwards chaining and working memory queries, whereas PYKE is based on python.

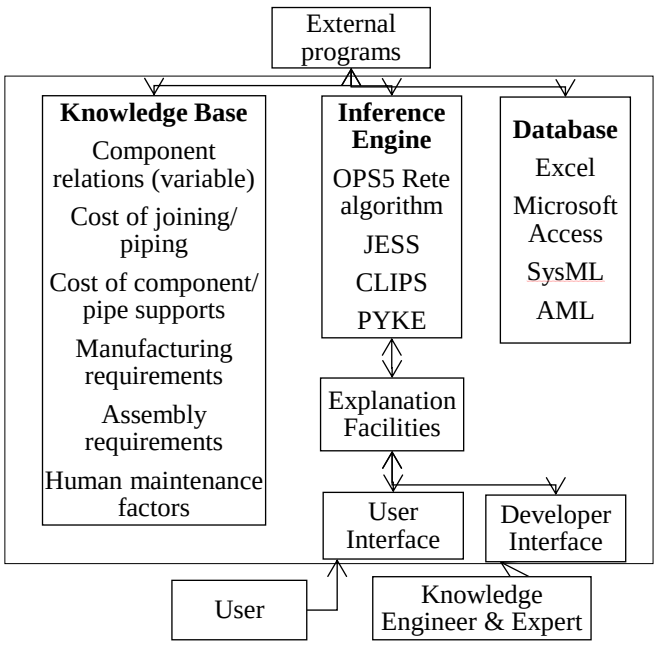


Figure 2-40 - Generic Rule Based Expert System architecture

2.5.5 Automated Component / product design (levels 1-2)

KBE for product and component design is a step up from parametric modelling. Parametric modelling uses feature definition and dimension control defined by design intent from the design engineer. KBE uses a knowledge base and design rules to create a design subject to constraints.

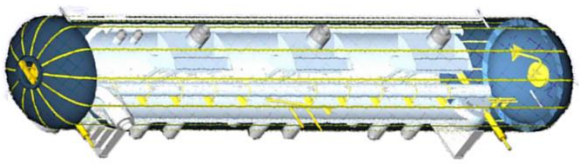
Product configurator software packages could be utilised to quickly design components within the power plant in the concept design stage such as:

- Pumps,
- Tanks,
- Pressure vessels,
- Heat exchangers,

Combine this with a workflow integrator to perform FEA and CFD, concepts could be analysed and developed quickly.

The different types of components that have been designed using KBE are shown in Figure 2-41.

HEAT EXCHANGERS



(Technosoft, 2018a) AML

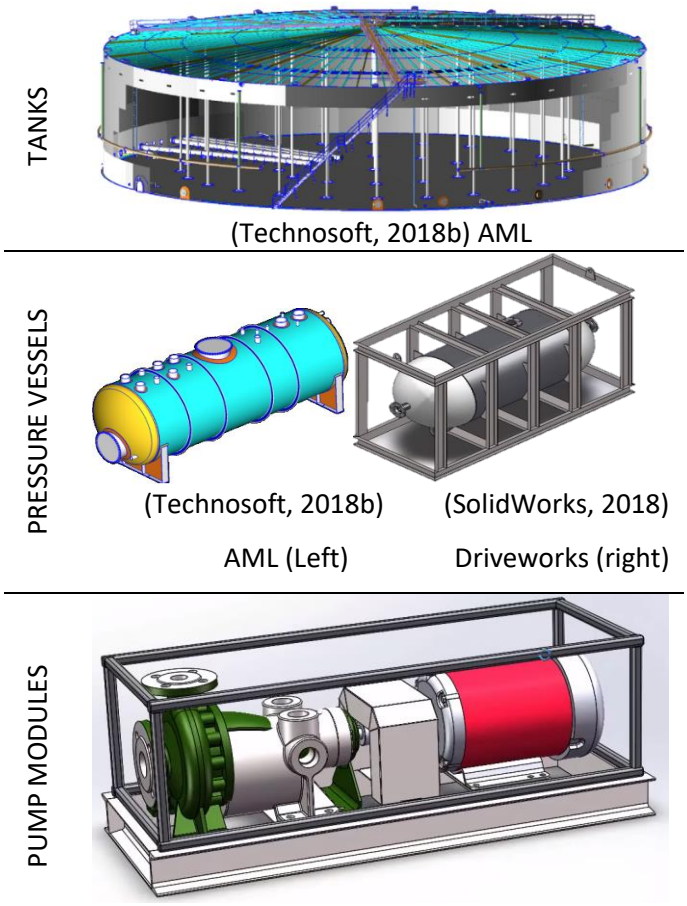


Figure 2-41 – Components/ Products designed using KBE from Technosoft, (2018a) AML and SolidWorks, (2018) Driveworks

Some types of KBE design in literature are Pansare and Palsodkar, (2017) who studied design automation on a centrifugal pump. Surve, (2017) proposed a knowledge based graphical method to design an inlet port with flow simulation. Nowakova and Pokorny, (2012) used a Knowledge Based Fuzzy System to Design a PID Controller.

2.5.6 Automation for systems design

It has been established that KBE implementation is largely product based but some examples for systems engineering do exist.

KBE for systems engineering is a step up from MBSE (Figure 2-39). It utilises the database and storage structure from MBSE to perform KBE/ AD. MBSE has become a bigger topic for research as system modelling has gained prevalence in designing systems. MBSE is a methodology for structuring data. Pihlanko et al., (2013) utilised SysML to modernize a nuclear automation project.

Schlagenhaufer et al., (2010) proposed a parametric design study of the HPLWR safety system advances in nuclear power plants. Wang et al., (2017) studied the parametric optimization of steam cycle in PWR nuclear power plant using an improved genetic-simplex algorithm.

Other types of design problem solved using knowledge-based automation include:

A fuel lattice design in a boiling water reactor (Tung, Lee, Kuo, & Yaur, 2015). kbe systems to monitor a nuclear fuel manufacturing plant advances in instrumentation and control (Harper, 1995). Knowledge-based software design for Defence-in-Depth risk monitor system and application for AP1000 (Ma, Yoshikawa, Nakagawa, & Yang, 2017)

Knowledge based engineering has also been utilised in the design of fuel lattices for boiling water reactors (Tung et al., 2015), inlet port designs (Surve, 2017) and centrifugal pump designs (Pansare & Palsodkar, 2017). Parametric design and knowledge-based CAD software automation techniques can aid with equipment design.

However, for 3D plant design, unlike mechanical systems which are usually coupled in one degree of freedom, fluid systems offer the flexibility to be connected in 3 degrees of freedom. Therefore, 3D plant design requires level 4 “Innovative” Knowledge based engineering which is defined as where the KBE system investigates a large resolution area (Penoyer et al., 2000). The objective is to optimise the requested parameters. The method uses artificial intelligence exploration approaches from a straightforward search method for a global minimum to complicated methodologies such as genetic algorithms or deep learning.

Fujita et al., (1994) employed a rule based expert system to generate constraints and develop a preliminary layout of a nuclear plant using constraint directed search. The distances were then fixed using Mixed Integer Linear Programming (MILP). The resulting plant layout was split across 5 floors with equipment arranged around the circular containment (Figure 2-42).

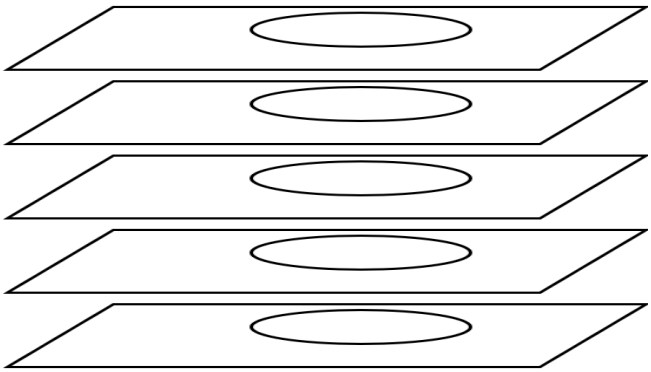


Figure 2-42 - Rule Based Expert System design of a nuclear power plant (adapeted from Fujita et al., 1994)

A project with Aker Solutions and The University of Norway utilised Technosoft’s AML to perform layout optimisation of equipment on an oil rig using a bin packing algorithm (Marthinusen, 2016).

Figure 2-43 shows an offshore rig layout developed using KBE through Technosofts AML, (2018a)

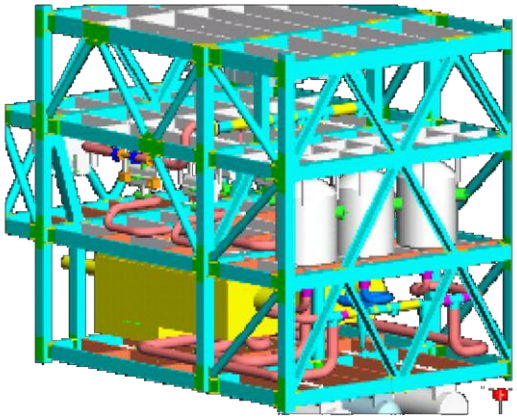


Figure 2-43 – Offshore Equipment layout performed using KBE through ©Technosoft, (2018a) AML

Kim and Roh, (2016) developed an expert system to arrange a submarine with a multistage optimisation. They also applied this process to an offshore oil rig design (S.-K. Kim, Roh, & Kim, 2017), and a surface naval shop (S. K. Jung, Roh, & Kim, 2018).

2.6 Mathematical Layout Optimisation

This section discusses the background information required to understand mathematical layout optimisation. A section justifying choice of method, advantages and disadvantages of each method is presented. The literature review provides the state of the art in mathematical layout optimisation literature.

2.6.1 Mathematical Optimisation Background

Upon understanding the plant design process, a literature search for plant layout discovered plant layout optimisation literature utilising mathematical optimisation. To support the advancement of a layout approach for modular plant design, a literature review on the current state of layout optimisation in plant design was conducted.

Mathematical optimisation is concerned with finding the best solution (minima or optimum) of an objective function from various feasible solutions (variables) considering:

- Set design parameters and decisions as optimisation variables
- Optimisation problem variables can be discrete or continuous
- Use integer constraints to limit variables to discrete values only
- Use the optimisation variables in defining an objective function
- Use constraint equations to define the mathematical problem (Equation 5 to Equation 7) (Stanford University, 2020)

The general formulation is shown in equations 4-7 to minimize the objective function:

$$\min_x f^T x \qquad \text{(objective function)} \tag{Equation 4}$$

Subject to the constraints:

$$Ax \leq b \qquad \text{(inequality constraints)} \tag{Equation 5}$$

$$Aeqx = beq \qquad \text{(equality constraints)} \tag{Equation 6}$$

$$lb \leq x \leq ub \qquad \text{(bound constraints)} \tag{Equation 7}$$

Figure 2-44 shows a representational graphical example (Hammond, 2020) of a simple optimisation problem to maximize the objective function *y* subject to the inequality constraints:

$$-x + y \leq 1$$
$$2x + 3y \leq 12$$
$$3x + 2y \leq 12$$

If x and y are restricted to integers, only the red integer solutions can be utilised.

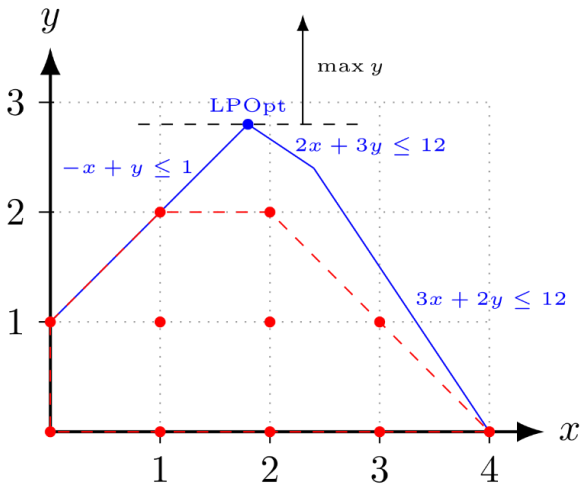


Figure 2-44 - Graphical representation of a simple optimisation problem

2.6.2 Algorithm Types

Depending on the types of objectives and constraints in the optimisation problem (Table 2-5), the optimisation problems are either solved through deterministic, iterative, stochastic / heuristic methods and a different method based on rule based expert systems. X. S. Yang, (2010) presented the following classification of optimisation algorithms (Figure 2-45).

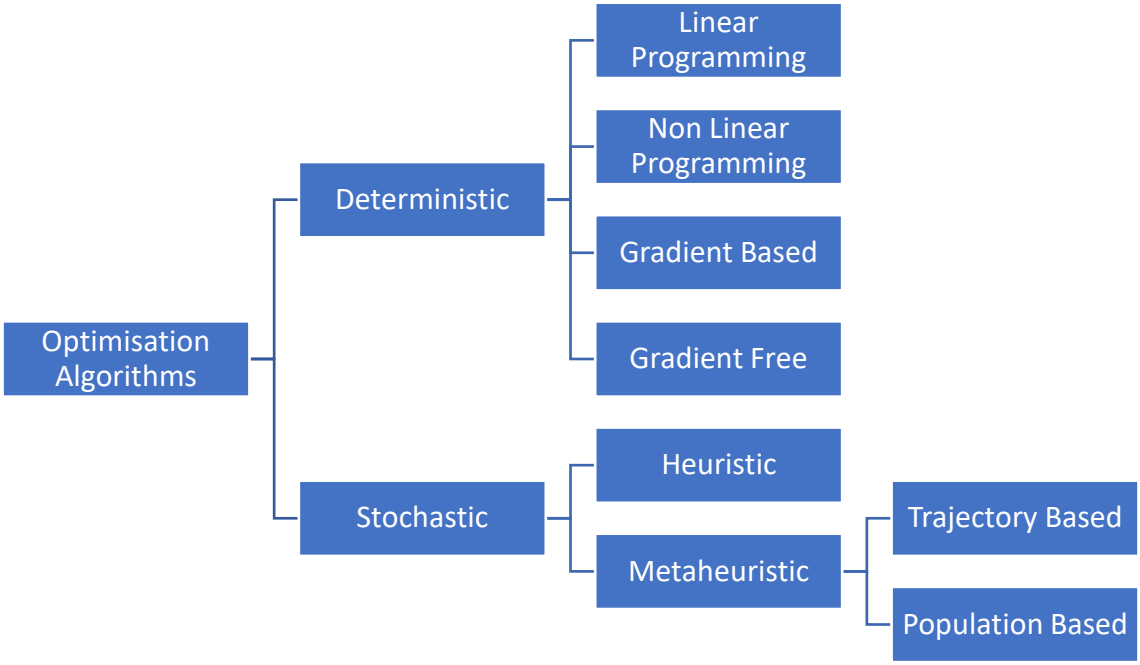


Figure 2-45 - Classification of optimisation algorithms (X. S. Yang, 2010)

2.6.2.1 Deterministic methods

Deterministic, direct or exact methods (Figure 2-45) are normally used to solve linear or quadratic problems solved through a form, variation or extension of the simplex algorithm. A deterministic algorithm will always find an exact (the optimum) value. However, they can become exponentially large with an increasing number of variables.

Iterative methods (Figure 2-45) evaluate hessians, gradients, approximate gradients, or function values and are often the only method for nonlinear equations. Iterative methods are also useful for linear problems with many variables, where deterministic methods are excessively computationally expensive due to combinatorial exponentiality.

2.6.2.2 Stochastic/ Approximate Methods

Stochastic methods (Figure 2-45) involve randomness/ probability to solve an optimisation problem. Heuristic methods are designed for solving a problem more quickly when deterministic or Iterative methods fail to find any exact solution or are too computationally time intensive to solve in a reasonable amount of time.

CONSTRAINT TYPE	**OBJECTIVE**	**TYPE**	**ALGORITHM**		
	Linear	Quadratic	Least Squares	Smooth Nonlinear	Nonsmooth
NONE	n/a (f = const, or min = −∞)	quadprog	mldivide, lsqcurvefit lsqnonlin,	fminsearch, fminunc,	fminsearch, Global Optim
BOUND	linprog	quadprog	lsqcurvefit, lsqlin, lsqnonlin, lsqnonneg,	fminbnd, fmincon, fseminf,	fminbnd, Global Optim
LINEAR	linprog	quadprog,	lsqlin,	fmincon, fseminf,	Global Optim
GENERAL SMOOTH	fmincon,	fmincon,	fmincon,	fmincon, fseminf,	Global Optim
DISCRETE, WITH BOUND OR LINEAR	intlinprog,	Global Optim	Global Optim	Global Optim	Global Optim

Table 2-5 - Matlab Optimisation Decision Table

2.6.3 Mathematical Optimisation Research

Plant layout is a significant part of plant design and mistakes can require rework, either in design or construction, leading to cost escalations and accidents (Moran, 2016b). Facility layout planning is a vastly combinatorial problem and is defined as Non-Polynomial hard. A plant layout problem is a type of Facility Layout Problem (FLP) which is concerned with the location of facilities in a plant zone, with the objective of realising the most effective layout in compliance with conditions or objectives under

certain constraints, such as size, shape, connections and orientation and evaluating flows amongst manufacturing and assembly lines or office departments.(Drira, Pierreval, & Hajri-Gabouj, 2007) (Anjos & Vieira, 2017) (Hosseini-Nasab, Fereidouni, Fatemi Ghomi, & Fakhrzad, 2018).

Plant layout problems and Facility layout problem (FLP) have integer variables due to the logic operator. A Mixed Integer Linear Programming (MILP) solver is most appropriate until a large enough number of variables are added where the solution space becomes too computationally time intensive to solve in a reasonable time. This would require either iterative or heuristic methods to determine an accurate solution in a reasonable time.

Initial research in this discipline contains Rosenblatt, (1979) who integrate the initial study of assigning facilities quantitatively utilising material processing costs (E.S Buffa, 1964) and qualitative work on heuristic proximity rankings (Seehof, Evans, Friederichs, & Quigley, 1966). Further studies have expanded this to augment further abilities such as contemplating multi-floor layouts (Bozer, Erlebacher, & Meller, 1991). Francis and White, (1974) supplied a broad ranging director to the facility layout and problem for production facilities; analysing location, storage, material flows, single and multi-planar problems and networks.

Anjos and Vieira, (2017) studied three key facility layout problems: row layout, unequal-areas layout, and multi-floor layout. They suggested a universal formulation for multi-floor layouts and outline that symmetry continues to be a significant issue in facility layout problems.

2.6.3.1 Heuristics for Plant Layouts

Heuristics (intuitive judgment, rules of thumb and common sense) for plant layouts were initially generated to support plant design. Amorese et al. (1977), originally researched using an adaptive technique to arrange a chemical process plant to reduce costs of the plant. They established that numerical experimentation produces prevalent principles for suitable rules to create the learning process. Kern, (1977) created procedures to administer and arrange distinct equipment in a plant.

2.6.3.2 Mathematical Programming Approaches

Mathematical programming techniques were then developed for the plant layout problem. They examine quantitative data such as pipe distance, safety length, quantity of connections and land extent.

Gunn and Al-Asadi, (1987) focused on a modular layout of a chemical plant using a hill climb and Mathematical Nonlinear Programming (NLP) method. The objective function analysed piping and building costs.

Jayakumar and Reklaitis, (1994) pioneered graph partitioning for the creation of cosmetic grade isopropyl alcohol. They applied an objective function to decrease connections among equipment.

Barbosa-Póvoa and Macchietto, (1994) study a Mixed Integer Non-Linear Programming (MILP) formulation to determine the best choice of both the apparatus units and the network of connections to fulfil the yield specifications in a multipurpose batch plant. The objective function was to maximize the plant return on investment and minimize capital costs.

Penteado and Ciric, (1996) presented a Mixed Integer Non-Linear Programming (MINLP) technique for safe process plant layouts, using an objective function to minimise the cost of piping, land cost, financial risk, and device safety cost.

Georgiadis and Macchietto, (1997) employed MILP for the chemical process plant layout problem by assessing the assignment of equipment to equivalent area positions and designation of equipment to non-equal zones (Michael C. Georgiadis, Schilling, Rotstein, & MacChietto, 1999). The objective function evaluates pipe, land and pumping costs.

Papageorgiou and Rotstein, (1998) enhanced this model to study a continuous domain single floor MILP model. Patsiatzis & Papageorgiou then broaden the scope to multi floor (Dimitrios I. Patsiatzis & Papageorgiou, 2002a) and generate a decomposition and an iterative method (Dimitrios I. Patsiatzis & Papageorgiou, 2003). The decomposition method is principally more exact but more costly in processing time, whereas the iterative method is the opposite. Furthermore, recommending an MINLP model by implementing rectangular shapes and rectilinear distances (Dimitrios I. Patsiatzis & Papageorgiou, 2002b) and alternative system similarly assessing safety (D. I. Patsiatzis, Knight, & Papageorgiou, 2004).

Guirardello and Swaney, (2005) considered MILP optimisation of process plant arrangements and further developed the inclusion and evaluation of pipe routings.

Park et al., (2011) used MILP to examine safety aspects in a multi-floor plant arrangement issue.

Han et al., (2013) used MILP to express a process layout optimisation problem with hazard areas. The objective function comprised pipeline joining costs, land price and installation cost of the extra protective equipment.

Other MILP models expanded on the Domino Hazard index (Tugnoli, Khan, Amyotte, & Cozzani, 2008) (López-Molina, Vázquez-Román, Mannan, & Félix-Flores, 2013) (J. De Lira-Flores, Vázquez-Román, López-Molina, & Mannan, 2014) (Brunoro Ahumada, Quddus, & Mannan, 2018).

Martinez-Gomez et al., (2015) presented a MILP problem considering subsequent developments with a multi-year framework as well as accounting for financial and safety objectives.

J. A. de Lira-Flores, Gutiérrez-Antonio, & Vázquez-Román, (2018) introduced the quantitative risk analysis methodology and the safety instrumented system design methodology (J. A. de Lira-Flores, López-Molina, Gutiérrez-Antonio, & Vázquez-Román, 2019).

Ejeh, Liu, & Papageorgiou, (2018) added new features such as large component items with an elevation greater than the average building level elevation in chemical process plants, with connection locations at a design-stipulated level for every piece component item.

Ejeh et al., (2018) expand the optimisation model with considerations for large component items that bridge through building levels and the availability of predefined production segments.

Ejeh, Liu, & Papageorgiou, (2019a) present an updated model accounting for fire and explosion risk.

Ejeh, Liu, & Papageorgiou, (2019b) adds 3 improvements over the previous methods: an extension for multi-floor equipment items to extend above the maximum possible number of levels, the choice of an available number of floors fewer than the maximum amount essential for any equipment item and Integer cuts to improve the efficiency. The P&ID and resulting layout are shown in Figure 2-46.

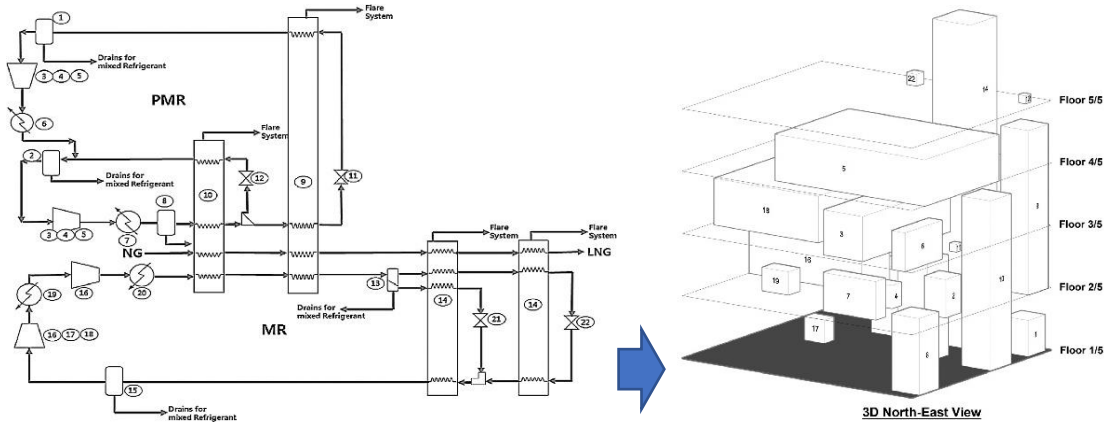


Figure 2-46 – P&ID and Resulting layout for (Ejeh et al., 2019b)

Blast wall protection was also considered within an optimisation (B. Jung & Lee, 2019).

2.6.3.3 Metaheuristic Approaches

Metaheuristic techniques have been developed to offer different operation to the capabilities of mathematical programming. A metaheuristic is a higher-level process or heuristic which was created to find a close to optimum solution but in a quicker time than linear programming. It explores the solution space only partially, ideal in a situation which would be too computationally time exhaustive to explore completely.

Suzuki et al. (1991) generated an evolutionary algorithm method for plant layouts as it is problematic to resolve costs and preferences concurrently with MILP. Piping and site costs are analysed in the objective function as weighted preferences. Equipment is clustered in modules to reduce calculation effort.

Genetic Algorithm methods have been developed for large facility layout problems that might deliver a sub optimal solution although they can be more efficient in computation (Balakrishnan, Cheng, Conway, & Lau, 2003).

Xu et al., (2013) enhanced the genetic algorithm through a hybrid technique and included toxic gas diffusion limits to the layout problem.

Alves et al., (2016) contemplate using Monte Carlo simulation combined with simulated annealing to find the optimum for process units in industrial installations to decrease hazards to the adjacent neighbourhoods. The Monte Carlo simulation examines constraints and assesses the objective while the simulated annealing executes the optimisation. The objective function analyses the significance of accidents close to nearby built-up locations.

Latifi et al., (2017) presented a metaheuristic algorithm developed from bat behaviour to resolve an MINLP process plant layout problem with the observation of toxic release danger and conceivable situations of fire and explosions.

Palomo-Romero et al., (2017) suggest an Island Model for the genetic algorithm to arrive at a solution to the complications of early convergence, lack of diversity, or high computational effort from other approaches.

Ruiqi Wang et al., (2017) integrate efforts of R. Wang, Wu, Wang, & Feng, (2017), who extend the investigation on the Dow's Fire and Explosion Index technique to an industrial location arrangement optimisation technique through a genetic algorithm. Accompanied by Yan Wu & Wang, (2017) which studies a piping application for location extensive arrangement, employing Kruskal's algorithm for resolving the multi-branch pipe system of material flow. The resultant objective function assesses explosion and toxic release safety distances, material and steam piping cost concurrently with joining cost. Y. Wu, Wang, Wang, & Feng, (2017) enhance the location-wide arrangement plan technique by assessing piecewise steam piping.

Ruiqi Wang, Zhao, et al., (2018) integrate an additional quadrilateral packing algorithm assisted by a genetic algorithm to solve the plant design problem. The objective function contains piping outlay cost, pump power cost, land price, and flooring erection cost.

Lee, (2018) created the most up to date assessment of genetic algorithms in operations management and proposes areas for continued study.

J. S. Yang & Lee, (2019) utilise particle swarm optimisation to optimise a propane precooling mixed refrigerant plant.

He, Ji, Zhou, & Dang, (2019) utilise a 4 step optimisation process. Firstly, heuristic expert knowledge is applied to reduce the search space, then a stochastically generated layout is determined. A detailed process layout is acquired using a commercial optimisation solver and then the second and third step are repeated using Simulated Annealing. This builds on work by Ejeh et al., (2018).

2.6.4 Rule Based Expert Systems

Rule based expert systems try to program the qualitative heuristic information of design engineers into a form that can be utilised to arrange different parts of the plant. Expert systems are an initial format of AI and use a succession of IF-THEN instructions and an inference engine to generate intelligent decisions comparable to a person.

Fujita et al., (1994) created a rule based expert system to produce constraints and attain an initial arrangement of a nuclear plant by a constraint-directed search exploration using a depth first search process in common LISP with object-oriented programming. The locations are then determined using MILP. The objective function was to reduce the size of the building.

Kim and Roh, (2016) produced an expert system for the layout of equipment in a submarine using a template model to save the layout information. A genetic algorithm was used to accomplish the optimisation. They then implemented this same technique to an offshore oil rig design (S.-K. Kim et al., 2017), and a surface naval plant (S. K. Jung et al., 2018).

2.7 Findings of the Literature Review Summary

The systematic literature review analysed modular design and construction in nuclear power, industrial process plants and in the construction industry. Automated design analysis and development methods were investigated in knowledge-based engineering. Finally, the state of the art in industrial plant layout optimisation was explored, highlighting modularisation has not been considered in this field previously and is a significant gap in the knowledge.

2.7.1 Modular design in nuclear power

Current large nuclear power is too large, complex and expensive for it to be built efficiently in America and Europe. Cost reduction in nuclear power is critical for it to play a part in reducing carbon emissions. Small Modular reactors have been proposed as a method of reducing costs by moving work off the critical path, into highly productive factories.

Reduced build programmes may be enabled via this factory manufactured method through productivity enhancements and parallel working (Locatelli, Bingham, & Mancini, 2014). Standardisation through utilisation of standard supply chain equipment facilitates direct cost decreases as equipment is not specially designed which incurs increased costs. Less capital investment is required in contrast to large reactors with reduced size plants. Energy firms might be more likely to expend on these projects due to the lesser risk.

The objective for SMRs is “shop fabricated and then transported as modules to the sites for installation” (IAEA, 2020). Factory-built modules require less rework, increase productivity and quality, assisting to reduce the construction schedule. To maximise work off site, modules should be designed for maximum limits of unrestricted road transport. Mignacca et al., (2019) suggest the site location of SMR modules is important for transport and should be selected before other factors can be decided (special equipment, insurance, licences, possible incidents and obstructions, quality control and management, environment, etc).

However, only a few research articles consider the modularisation of equipment and systems in nuclear power:

Modularising equipment and systems in nuclear power was first considered by the Stone & Webster Engineering Corporation, (1977). Small modular “packaging of the nuclear primary circuit/ nuclear steam supply system (NSSS) for shop fabrication” technologies were introduced slightly later (Technology Transfer Modularization Task team. DOE, 1985), with several small modular nuclear plants discussed at the 1983 ASME Joint Power Generation Conference in Indianapolis. The Safe Integral Reactor (SIR) integral design emerged in 1991 (Hayns & Shepherd, 1991), (Matzie, Longo,

Bradbury, Teare, & Hayns, 1992) which focused on modularising the nuclear steam supply system into an integrated module. This had the advantage of the elimination of Loss of Coolant Accident (LOCA) enhancing safety, while factory production of the nuclear steam supply system could reduce costs. Kadak & 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. 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) depending on the analysis method.

Most studies focus on the economics of integral designs. This has led to two main design differences in power plant design, with integral reactor designs and several partitioned reactor designs (Figure 2-47).

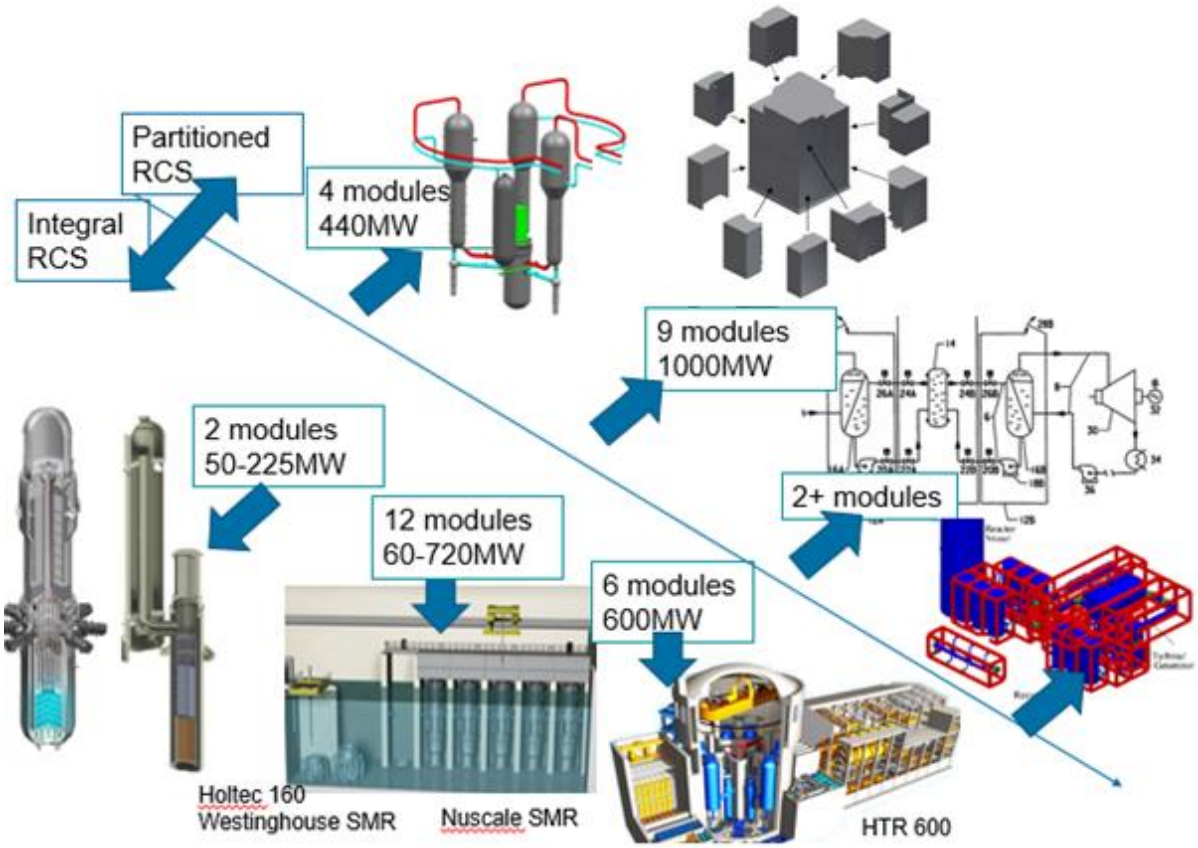


Figure 2-47 - (Liu & Fan, 2014) (D. T. Ingersoll et al., 2014) *(Kadak & Berte, 2006)* (Dong, Pan, Zhang, Dong, & Huang, 2018)

However, very little research focuses on layout design for the balance of plant systems which account for 18% of nuclear power plant costs, shown in Figure 2-48 (World Nuclear Association, 2020b). This percentage would increase if other nuclear island systems could be included in the modular construction scope, but more analysis and data would be needed to assess this.

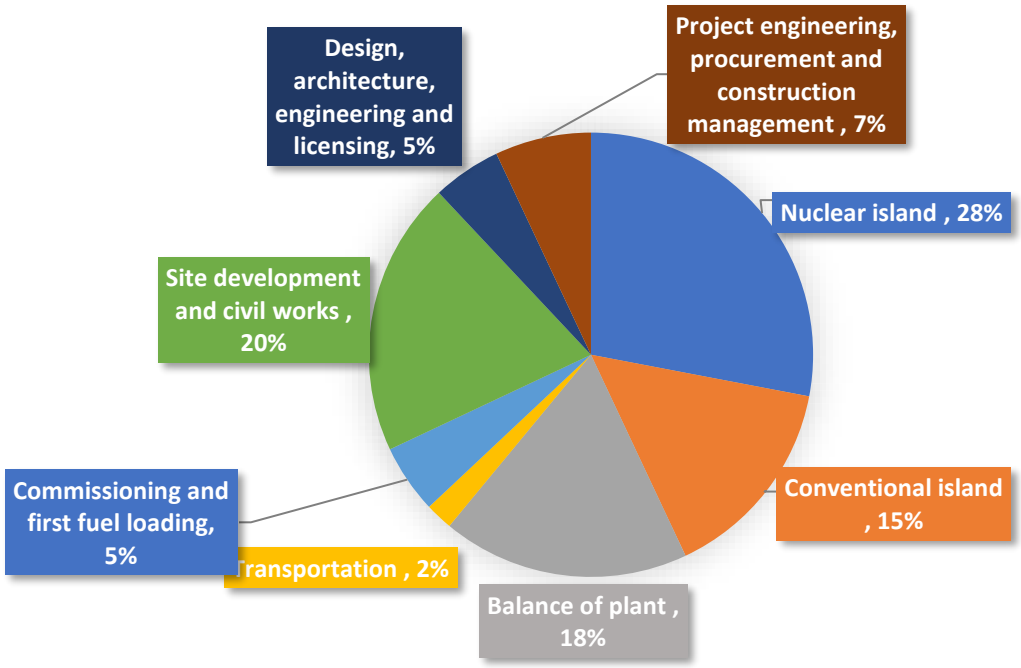


Figure 2-48 - The balance of plant accounts for 18% of the cost of construction (World Nuclear Association, 2020b)

Research suggests a 450MW plant is optimal (Lloyd & Roulstone, 2018a) (Lloyd & Roulstone, 2018b), striking a balance between economics and maximising scale for factory-built, road transportable SMR equipment modules

2.7.2 Designing the Modules to Fit the System

There have been a number of studies considering designing the module to fit the system.

Stone & Webster Engineering Corporation, (1977) studied modularisation of different aspects of a nuclear plant. Lapp, (1989) introduced a matrix reordering technique to cluster highly linked systems. A possible 15% capital cost reduction was highlighted for an onsite assembly. The virtual factory module space frames (Kadak & Berte, 2006) method. These are all methods for configuring the modules to encompass the system (Figure 2-49).

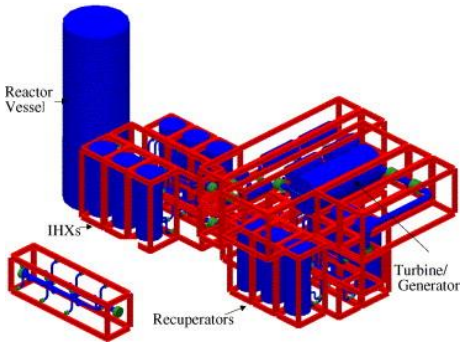


Figure 2-49 –Containers intended to locate the equipment, MIT pebble bed reactor (Kadak & Berte, 2006)

These methods are more suited to one off projects such as prototypes, as more work is required to connect the modules at site, increasing costs.

2.7.3 Design Systems to Modules

The other technique is to configure the system to the modules as suggested by Wrigley et al., (2018) in the concept of standardised modules shown in Figure 2-50. Increased equipment is able to fit in standardised modules maximising volume capacity designed for transportation. Fitting more equipment into a module reduces the amount of work on-site. Another benefit is the economies of volume production of one type of module. Cost-effective supply, production, operation and learner effects are all benefits of standardisation (Benito Mignacca et al., 2018). The off site construction technique will take advantage of additional cost reductions if forthcoming advances in electrified autonomous vehicles come to fruition, which are predicted to be 2-10x cheaper than current logistics (PWC, 2020) of utilising oil and human labour.

However, more capital investment is necessary in early engineering design and manufacturing plants in comparison to on site methods, or the virtual factory methodology. When planning and constructing multiple projects it would be advantageous to utilise this method to realise the economies of volume production.

As stated in section 1.2.1 (Cost Reduction Methods in Nuclear), Rolls-Royce has opted for a three loop SMR rather than an integral reactor design (Rolls-Royce, 2018) and believe the cost of electricity can be reduced through 4 main factors (Figure 2-50): reduced finance, off-site construction, digital through life management and modularised balance of plant.

Figure 2-50 - factory-built and road transportable modules

The move to factory-built modules and their transport (Figure 2-51) could become even more economical as the world moves towards a future of electric, driverless vehicles (P. Wrigley et al., 2018).

Figure 2-51 – Systems devised for the standardised modules idea (Rolls-Royce, 2017)

Modularisation is concerned with the breaking down of a complex system. In this regard, breaking down nuclear plant systems to fit into standardised, factory-built, road transportable modules. A few methods were utilised previously such as the N^2 systems engineering matrix or the virtual factory method, but these are simple and outdated. New, modern, efficient design tools are required to help with the design of these new nuclear power plant designs.

2.8 Summary and Research gap

Section 2.2 found that very little work has been performed on analysing the modular design of nuclear power plants other than integrated nuclear steam supply systems.

Section 2.3 in this thesis found that although recent process plant research has focused on automation in earlier parts of the design process (PFDs, equipment databases, modular P&ID) but not on layout design. Section 2.5 showed that level 4 “innovative” knowledge based engineering, able to search a large solution space, is required for complex systems. Section 2.6.3 highlighted that a layout optimisation method has not been applied to OSMC of process plant modules or nuclear power plants. This requires a different model to those used previously on large process plants which have focused on reducing pipe length and operational costs and increasing safety.

A novel mathematical optimisation model should therefore be developed, building upon previous layout optimisation research literature, to consider modularisation. Integration with the wider plant design process should be considered to analyse the impacts of the new process against the previous design methods.

3 CHAPTER 3
Proposed Novel Mathematical Optimisation for Modularisation and Design Process Framework

The literature review in Chapter 2 highlighted that industrial plant research on modular design methods has focused on automation in earlier parts of the design process (PFDs, equipment databases, modular P&ID) but not on layout design. Furthermore, it was found that layout optimisation has not been utilised in nuclear research previously or in modular industrial plants. It is proposed to develop on previous mathematical layout optimisation research to consider off-site modular construction, specifically small nuclear power plants, but the process could be applied to any modular industrial process plant. The proposal is to take a Systems Engineering approach to breaking down the problem into three case studies for modularisation.

- Case Study 1 - Optimising module layout from the Shearon Harris plant *Model (A)*, creating new knowledge and data
- Case Study 2 - Optimising components layout within module, *Model (Bi)*, creating new knowledge and data
- Case Study 3 – Extension to assign equipment to modules, *Model (Bii)*, creating new knowledge and data
- Finally, the link between Plant Design CAD software will be explored to understand the impact on plant design engineering, creating new knowledge and data

Also discussed in this chapter is the data to be utilised from a previous nuclear modularisation study considering shipbuilding methods (Lapp, 1989). This includes the data source, equipment data, the Piping and Instrumentation Diagram (P&IDs), equipment connections and Dependency Structure Matrix (DSM) to be utilised in each of the three case studies.

3.1 Introduction

The literature review highlighted earlier parts of the plant design process have studied modularisation and that layout optimisation research has not considered modularisation. Therefore, this study will focus on optimising modular 3D plant layout design (Moran, 2016a).

The definition of the layout of process plants is the “layout of process equipment and pipework, plots, plants, sites, and their corresponding environmental features in a safe, economical way” (Moran, 2016a). The process of layout may either be accomplished through the heuristic knowledge of an expert plant designer, with the support of codes of practices and standards and/or with the aid of an optimisation tool (Moran, 2016a) (Moran, 2017). The creation and development of design tools to optimise system modules layout enables:

- Assessment of concepts and layouts quickly

- Reduction of design time
- Cost savings
- Continuous development of the model as new requirements are established

3.2 Research Methodology

The modularisation of a process plant with regards to 3D layout is concerned with how to modularise plant equipment and systems into modules for off-site construction to reduce schedule and costs. Using the systems methodology of breaking down the problem, this modularisation problem is broken into three stages to be able to develop the required aspects in order to achieve the applied research programme aims and objectives. The literature review highlighted the development of layout optimisation research. This research and mathematical models will be utilised and built upon to develop a novel mathematical layout optimisation for modularisation. Three aims were identified and will be decomposed (Figure 3-1) in a system engineering process to develop the necessary capability:

1. Develop a method for system breakdown into modules
2. Develop a method to arrange modules
3. Develop a method to arrange components within the module

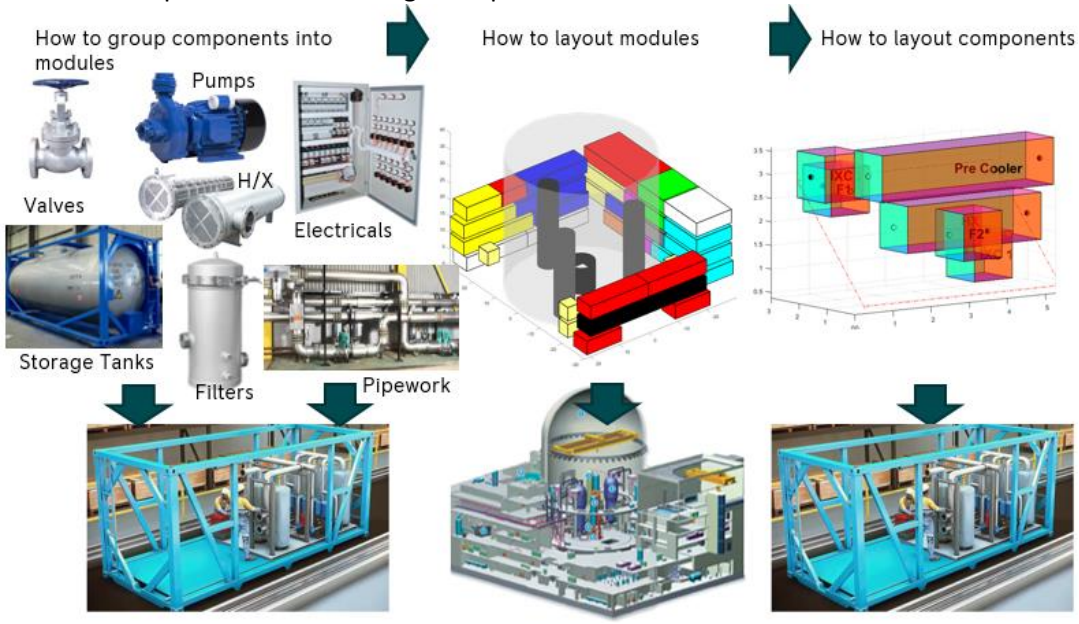


Figure 3-1 – Three steps required for plant modularisation

These three core parts of the optimisation capability will be compared to current designs and processes from (Lapp, 1989) to assess quantitative benefits (pipe length reductions and module reduction) and qualitative benefits such as reduced design time.

3.3 Plant Design Process and System Architecture

During a conventional plant design procedure, the plant design engineer uses a Process and Instrumentation Diagram (P&ID) and, together with a library of equipment, arranges the equipment and pipework using 2D or 3D CAD.

Piping & Instrument Diagrams (Figure 2-16) are communications for design engineers to understand how a system process functions. The flows between equipment are defined as lines along with other possible attributes such as flows, temperatures, pressures and valves. They can then translate this into a 3D layout.

Figure 3-2 shows how the optimisation model may be integrated into the plant design process. As highlighted in the literature review, modular process plant design has already studied developing databases of components, selection tools and modular P&IDs.

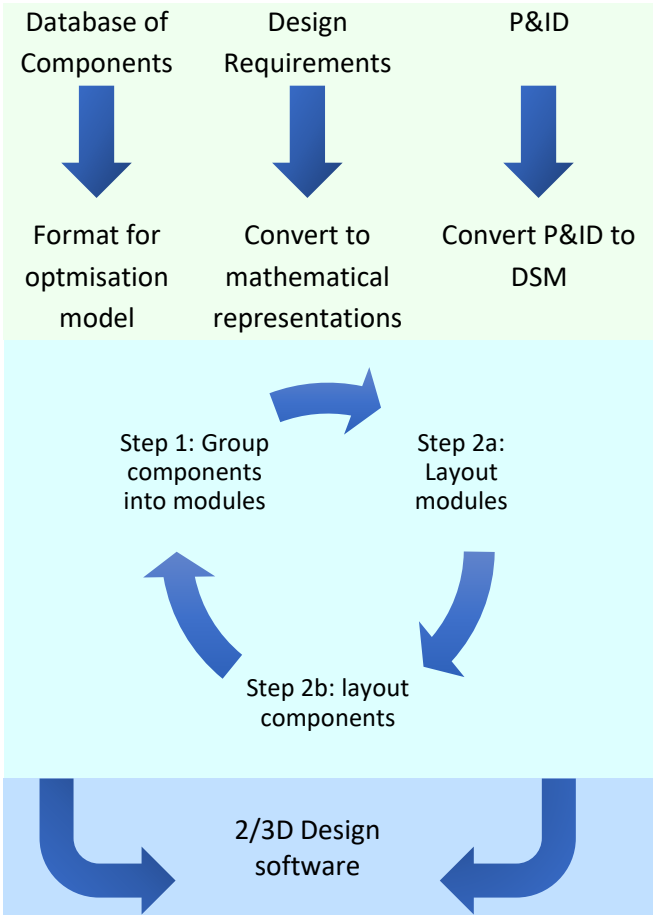


Figure 3-2 – Plant design process for standardised balance of plant modules and grid

Similar to the conventional plant design procedure, in the standardised module grid method, the P&ID is employed in conjunction with the digital archive of equipment in the initial phase. The optimisation process then takes place (Figure 3-2). The result of the optimisation then advises the 2/3D plant layout.

3.3.1 Integration with Plant Design software

Linking the optimisation output with Plant Design Software provides an early estimate for concept engineering studies to enable the design team to understand and learn from changing different parameters. As the model is developed, more constraints and knowledge can be included (Figure 3-2).

The Bentley Plantwise model can be easily revised to include the new equipment positional information and updated with the Bentley AutoRoute function to further enhance engineering studies. In this environment, manufacturing and assembly, operators, maintenance engineers, human factors and safety personnel can interrogate the design to ensure it meets their requirements. The optimisation model can then be updated with additional information in an iterative process (Figure 3-3).

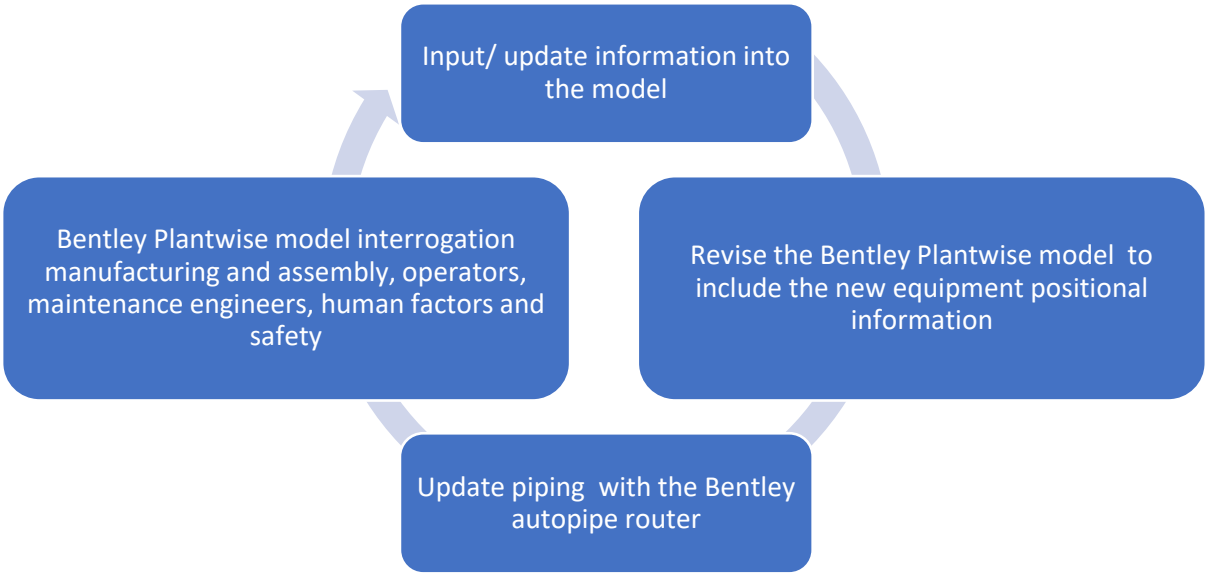


Figure 3-3 – Design process for increasing detailed design and knowledge

3.4 Design Specification

Both the Applied Research Programme and SMRs are required to consider the following:

1. Modularisation project applicability – site locations and workforce (P. Wrigley et al., 2018)
2. Build strategy – site labour cost and equipment availability, transport
3. Module design configuration
4. System breakdown
5. Interfaces and definitions
6. Design tools
7. Equipment layout
    a. Cost, safety, human factors, site location/ equipment/ workforce,
    b. Design
    c. Manufacturing
    d. Assembly
    e. Transport
    f. Construction
    g. Test
    h. Operation
    i. Maintenance
    j. Decommissioning

Future technologies to consider in the Applied Research Programme to possible future implementation:

- Capture full product life cycle data

- Utilise virtual reality/ augmented reality in the design stage for assembly and maintenance considerations
- Next generation automated factories
- Connected sensors for through life monitoring.

3.4.1 Road Transportation Requirements

Transport is an important consideration in modular plant design (B Mignacca et al., 2019) (Salama et al., 2017). Careful consideration should be given to assess SMR site locations and local transport regulations. In the UK no permit is needed for vehicle loads of (Highways England, 2019):

- Width under 3m,
- Length under 18.75m,
- Height under 4.95m,
- Weight under 80 tonnes
- An axle capacity of no more than 10,000kg for an only non-steering axle and 11,500kg for

3.5 Case Study Data

Data from Rolls-Royce is not permitted to be published and the Rolls-Royce SMR plant systems data is at the concept stage and undetailed at the time. Other recent designs for SMRs are also commercially confidential and have not made data available or provided consent to publish data. Therefore, the data that will be used in this research will be from a previous modular on-site assembly area nuclear case study (Lapp, 1989). The preceding research redesigned the Shearon Harris power plant for on-site assembly modularisation. The data for the case study is publicly distributed online. The data for this case study is extracted from (Lapp, 1989), the Shearon Harris plant, a 928 MW Westinghouse 3-loop (DRYAMB) style plant. The previous study heuristically located equipment from a clustered systems matrix reordering technique for on-site assembly shown in Figure 3-4.

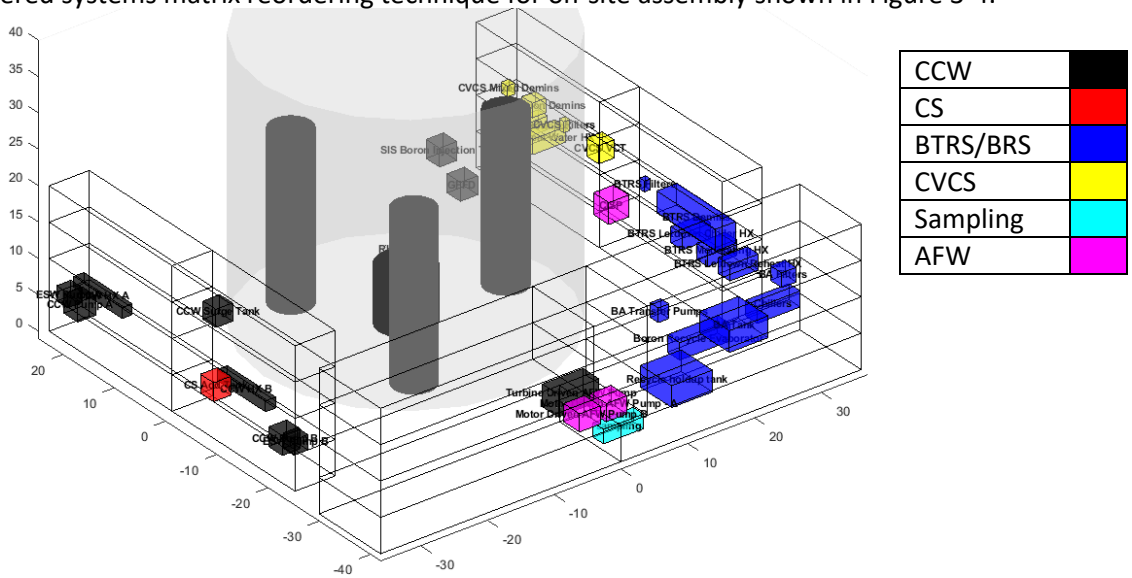


Figure 3-4 – Module layout for the original Shearon Harris plant (Lapp, 1989)

All 29 equipment items from Figure 3-4 are described in Table 3-1. The primary circuit/ nuclear steam supply system can be seen in the circular containment in the centre of the diagram.

3.6 Equipment Data and Transport Analysis

The equipment data was taken from (Lapp, 1989) and the 900Mwe Shearon Harris Plant Equipment is shown in Table 3-1. The scaled equipment for 450 MWe plant is also shown in Table 3-1.

	Equipment	900Mwe Shearon Harris Plant Equipment			Scaled equipment for 450 MWe plant		
#	Description	d (m)	L (m)	h (m)	d (m)	L (m)	h (m)
1	ESW Booster Pump A	2.1	2.1	2.1	1.67	1.67	1.67
2	CCW Pump A	2.7	2.7	2.7	2.14	2.14	2.14
3	CCW HX - A	9.4	1.5	1.5	7.46	1.19	1.19
4	CS Additive Tank	2.6	2.6	2.6	2.06	2.06	2.06
5	CCW Pump B	2.7	2.7	2.7	2.14	2.14	2.14
6	CCW HX - B	9.4	1.5	1.5	7.46	1.19	1.19
7	ESW Booster Pump B	2.1	2.1	2.1	1.67	1.67	1.67
8	Boron Recycle Evaporator	7.5	2.4	2.4	5.95	1.91	1.91
9	Recycle holdup tank	6.1	6.1	3	7.00	2.80	2.80
10	BTRS Letdown Reheat HX	4.3	2.2	2.2	3.41	1.75	1.75
11	BTRS Moderating HX	4.3	2.2	2.2	3.41	1.75	1.75
12	BTRS Letdown Chiller HX	4.3	2.2	2.2	3.41	1.75	1.75
13	CVCS Seal Water HX	4.9	2.1	2.1	3.89	1.67	1.67
14	CVCS Letdown HX	4.9	1.9	1.9	3.89	1.48	1.48
15	Boric Acid Tank	5.8	5.8	3	6.50	2.80	2.80
16	Boric Acid Transfer Pumps	1.6	1.6	2	1.27	1.27	1.59
17	Boric Acid Filters	2.2	2.2	2	1.75	1.75	1.59
18	BTRS Demineralisers	11.5	3	3	9.13	2.38	2.38
19	BTRS Filters	0.9	0.9	1.5	0.71	0.71	1.19
20	CVCS Volume Control Tank	2.3	2.3	2.5	1.86	1.86	1.98
21	CVCS Filters	0.9	0.9	1.5	0.71	0.71	1.19
22	CVCS Cation Bed Demins	2	2	2	1.59	1.59	1.59
23	CVCS Mixed Bed Demins	1.2	1.2	1.5	0.95	0.95	1.19
24	Chillers	6.5	2.2	2.2	5.13	1.75	1.75
25	sampling	6	2	2	4.76	1.59	1.59
26	CISP	3	3	3	2.38	2.38	2.38
27	Gross Failed Fuel Detector	2.6	2.6	2.6	2.06	2.06	2.06
28	SIS Boron Injection Tank	2.6	2.6	2.6	2.06	2.06	2.06
29	CCW Surge Tank	2.5	2.5	2.5	1.98	1.98	1.98
33	Motor Driven AFW Pump A	3.1	3.1	2.5	2.46	2.46	1.98
34	Motor Driven AFW Pump B	3.1	3.1	2.5	2.46	2.46	1.98
35	Turbine Driven AFW Pump	6.1	3.1	3.1	4.84	2.46	2.46

Table 3-1 - 900Mwe Shearon Harris Plant Equipment and Scaled equipment for 450 MWe plant (P. Wrigley, Wood, O'Neill, Robertson, & Hall, 2020)

The equipment that will not fit into the 5m width space (from Section 3.4.1 - Road Transportation Requirements) in any direction envelope (highlighted grey in Table 3-1) are:

9 Recycle holdup tank
15 Boric Acid Tank

The Turbine Driven Auxiliary Feed Water Pump (AFW) Pump (35) does not fit into the 3m width space envelope in any direction as well as the two previously mentioned. The equipment that may only fit into the 3m module space envelope in one direction envelope (also highlighted grey in Table 3-1) are equipment items: 3, 6, 8, 10, 11, 12, 13, 14, 18, 24, 25, 33 and 35.

3.6.1 Scaled 450MWe Plant Equipment

Research suggests a 450MWe plant may be optimal for road transport (Lloyd & Roulstone, 2018b) (Lloyd & Roulstone, 2018a). The equipment data from Lapp, (1989) was scaled linearly by volume to reflect a 450MWe plant and can be found in Table 3-1. The equipment that will not fit into the 3m width space in any direction envelope but may fit into the 5m envelope (highlighted grey in Table 3-1):

9 Recycle holdup tank
15 Boric Acid Tank

The equipment that may only fit into the 3m module space envelope in one direction (also highlighted grey in Table 3-1) are: 3, 6, 8, 10, 11, 12, 13, 14, 18, 24, 25 and 35. Both the recycle holdup tank and boric acid tank may need to be redesigned to fit road transportable factory produced SMR modules.

3.7 Summary

The literature review highlighted that layout optimisation has not been utilised in nuclear research previously or in modular industrial plants. This chapter outlined the proposal to develop on previous mathematical layout optimisation research to consider off-site construction, specifically small nuclear power plants, but the process could be applied to any modular industrial process plant. The proposal is to take a Systems Engineering approach to breaking down the problem into three case studies for modularisation.

- Case Study 1 - *Model (A)* Optimising module layout from previous (Lapp, 1989) module designs
- Case Study 2 - *Model (Bi)* Optimising equipment layout within module
- Case Study 3 - *Model (Bii)* Extension to assign equipment to modules
- Finally, the integration between Plant Design CAD software will be explored to understand the impact on plant design engineering

Also discussed in this chapter is the data to be utilised from a previous nuclear modularisation study considering shipbuilding methods (Lapp, 1989). The data is analysed for road transport envelopes, highlighting some equipment and systems may need redesigning for road transport. The data source, equipment data, the Piping and Instrumentation Diagram (P&IDs), equipment connections and

Dependency Structure Matrix (DSM) to be utilised in each of the three case studies are found in Appendix A – Literature search papers and method.

4 CHAPTER 4
Novel Layout Optimisation Method for Modularisation

The literature review in Chapter 2 in this thesis highlighted that a novel layout optimisation method considering modularisation for factory built industrial process plants and small modular reactors would fill a knowledge gap in current research literature. This section presents the novel layout optimisation methods developed for the optimisation of modular plants. The optimisation is developed with a systems engineering methodology by decomposing the problem into three parts: chapter 4.1 outlines the mathematical model for the layout of modules – *Model (A)*; following this, Section 4.2 describes *Model (Bi)* for the layout of equipment within a single module and also the extension for the equipment to module allocation, *Model (Bii)*.

Facility layout are mostly classified as NP-hard problems i.e. global optimal solutions are difficult or even impossible to solve in a sufficient time (Drira et al., 2007) (Anjos & Vieira, 2017) (Hosseini-Nasab et al., 2018). The question remains on how best to find a "good enough" solution in a reasonable amount of time. Linear programming solutions may therefore be ineffective for large problems. Metaheuristic approaches may offer a "good enough" solution in a quicker time. More research would be required to understand the performance and results benefits to both solutions for the required task.

4.1 Model A - Layout Pre-existing Modules Design (Module to Location Assignment)

Although the modules in this study (6m) would require Highways England Special Order, 5 clear days' notice to the Police and to Road and Bridge Authorities with indemnity. It is envisaged that this model can be redeployed for various module sizes, along with *Model (Bi)/ (Bi)* developed for transport. In future sections, the enhancement of an equipment item assignment and layout algorithm (Step 1, Figure 3-2) would facilitate SMR designers to design balance of plant modules with specific P&IDs and equipment data for factory produced modules and transport constraints.

This case study assesses and considers how the plant might be redesigned for offsite prefabricated construction and transport using standardised modules to maximize productivity of factory labour. Offsite prefabricated modules boost productivity, quality and involve reduced rework, aiding a reduction in the construction period.

Identical equipment to module allocation and size is utilised from the preceding research. The layout optimisation then considers the ideal arrangement of modules in a standardised grid.

The next stage (Figure 3-2, Step C) is to transfer this information into the layout model. This is achieved through developing a method such as those presented in the layout optimisation literature.

The arrangement of modules in a standardised grid problem is created as a quadratic assignment facility layout problem. The considerations concerning layout optimisation of small modular nuclear reactor power plants might comprise of connections cost (on-site), land cost, pumping costs, pipe distance, safety, module size, assembly and maintenance considerations and construction costs. The only information offered for this case study was for piping factors. Minimising the piping amongst the modules is therefore the objective function for this initial standardised module concept problem.

The ultimate action is to enter the figures into the optimisation algorithm. Figure 2-18 illustrates the 13 modules that are required to be allocated to places within the standardised grid concept of Figure 2-50.

4.1.1 Provided to the Layout Optimisation Model

- Standardised grid module locations (width, height, depth)
- Directed connections between modules
- Costs of connections
- Margin between modules for walkways

4.1.2 Determined by the Model

- Positions of modules

4.1.3 Assumptions

- Module connection is from the centre of one side of the module

4.1.4 Model A Formulation

A binary optimisation variable y_{ik} matrix is employed comprising of the quantity of modules *i* and the amount of positions *k*. It permits the modules to be allocated to positions in the standardised grid. The binary optimisation variable restriction in Equation (8) stipulates that every module *i* is required to be allotted in one of the provided positions *k* (Mathworks, 2018a) (Mathworks, 2018b):

$$\sum_{k=1}^{K} Yik = 1 \qquad \textit{Equation (8)}$$

The constraint in Equation (9) denotes every position might inhabit at most a single module (Mathworks, 2018a):

$$\sum_{i=1}^{N} Yik \leq 1$$ Equation (9)

Variable expressions are utilised to ascertain the positions of the modules:

$$X_i = \sum_{i=1}^{N} Xlocations \times y_{ik}$$ Equation (10)

$$Y_i = \sum_{i=1}^{N} Ylocations \times y_{ik}$$ Equation (11)

$$Z_i = \sum_{i=1}^{N} Zlocations \times y_{ik}$$ Equation (12)

The subsequent constraints are employed to evaluate the distances amongst the modules.

$$H_{ij} = \sum_{i=1}^{N} X \times (y_{ik} - y_{jk})$$ Equation (13)

$$F_{ij} = \sum_{i=1}^{N} \mathrm{Y} \times (y_{ik} - y_{jk})$$ Equation (14)

$$V_{ij} = \sum_{i=1}^{N} \mathrm{Z} \times (y_{ik} - y_{jk})$$ Equation (15)

$$`(For\ i = 1, \dots, N-1, j = i+1, \dots, N)$$

Minimising piping distance amongst the modules is the objective function for this case study.

$$minOF = \sum_{i,j,i<j} \left[CP_{ij} \cdot \left(\mathrm{H}_{ij} + V_{ij} + F_{ij} \right) \right]$$ Equation (16)

The model was executed in MATLAB 2018a using a genetic algorithm (Mathworks, 2018c) default parameters (Table 4-1). Explanations of the genetic algorithm options are provided in Appendix D – MATLAB Genetic algorithm options.

Genetic algorithm parameter	**value**
Elite Count	3
Crossover Fraction	0.55
T Size	4
Pop Size	22
Sub Pop	4
Migration Interval	5
Stall Gen Limit	100
Tol Fun	1e-7
Tol Con	1e-7
Generations	500
Stall limit	300

Table 4-1 - Genetic algorithm default parameter values from (Mathworks, 2018c)

Two situations were investigated. Firstly, where the 6m across balance of plant modules are situated on two sides of the nuclear island. The other is where the modules are located on one side in a standardised grid format. Distances are evaluated from the centre of the module as singular locations utilising rectilinear distances. The point positions are provided in Table 0-1. A 3m space is included in amongst modules to permit worker admission and shielding obligations in the standardised grid situation, equivalent to Lapp, (1989). In relation to the RPV, the grid for the assignment of modules was located at -27m in the y direction. Building elevation levels for the Z direction were at 3m, 8m, 13m and 18m.

4.2 How to Layout Equipment within a Module (Model Bi) and Novel Equipment to Module Assignment Extension (Model Bii)

In this section, the layout of equipment within modules utilising non overlapping constraints will be considered. Both MILP formulations and utilising soft constraints within a Genetic Algorithm function were developed. An extension will then be considered to the optimisation model with the addition of equipment to module assignment variables.

4.2.1 Provided to the Model

- Item size (width, height, depth)
- Module size (width, height, depth)
- Directed connections between items
- Connection points on items
- Costs of connections and modules
- Additional margin space between items
- Module positions (fixed)

4.2.2 Determined by the Model

- Positions of items
- Rotations of items
- No of modules used (for Model Bii)
- Cost of connections

Nomenclature

Binary Variables	
m_{vk}	Item v in module k
r_{vi}	Item v is rotated by [0◦, 90◦, 180◦, 270◦]
x_{uv}, y_{uv}, z_{uv}	Set of logical variables used to prevent overlapping of items *u* and *v*

Constants	
cij	Unit cost of connection (i, j) ∈ E
Dx_{ij} , Dy_{ij} , Dz_{ij}	Rectilinear distance in the x, y, z axes respectively, between connected items (i, j) ∈ E
g_k	Cost of a module k ∈ K
L	Margin between items
M	A sufficiently large number
mx_k, my_k, mz_k	Fixed position of module k with reference to the x, y, z axes respectively
Wk, Hk, Dk	Width, height and depth of a module k with reference to the x, y, z axes respectively
Continuous Variables	
R_{ij} , B_{ij} , F_{ij}	The absolute value of the rectilinear distance between connected items (i, j) ∈ E, in the x, y, z axes respectively
w_v, h_v, d_v	Width, height and depth of item v with reference to the x, y, z axes respectively
x_v, y_v, z_v	Position of item v with reference to the x, y, z axes respectively
xs_{ij} , ys_{ij} , zs_{ij}	Nozzle connection location displacement on item i for connection (i, j), measured from the centre point of item i in the x, y, z axes respectively
Sets	
E	Multiset of connections between items (directed edges), {(i, j) : i, j ∈ V ∧ i 6= j}
K	Set of modules
V	Set of items (vertices)
V'	Set of ordered vertices $V' = \{(u, v) \in V^2 : u < v\}$

Table 4-2 – Nomenclature used in the optimisation Model (Bi) & Model (Bii)

4.2.3 Model *(Bi)* & Model *(Bii)* Formulation

Consideration must be given to the following to determine a solution to the problem:

- Items must occupy only one rotation in the x & y axis
- Items must be in one and only one module
- Number of modules used (Model Bii)
- Items within module bounds
- Items must not overlap
- Rectilinear distance between connected items

All other assumptions are assumed to be feasible with respect to the constants supplied to the MILP model. The Layout optimisation model is defined in the following sections.

4.2.4 Determine Design Structure Matrix from P&ID

In the first step, the Process and Instrumentation Diagram (P&ID) (Figure 2-16) is transformed into a Design Structure Matrix (DSM). The DSM between two equipment or systems is established from a P&ID using Equation (1), from Jayakumar and Reklaitis (Jayakumar & Reklaitis, 1994). The connections from one equipment or system to the subsequent equipment can be allocated to an *n* by *m* matrix (as shown in the example in Figure 2-16).

$$DSM_{ij} = \begin{cases} 1, & if\ the\ flow\ is\ from\ unit\ i\ to\ j \\ 0, & otherwise \end{cases} \qquad \text{Equation (1)}$$

4.2.5 Equipment Orientation Constraints

Designation of the equipment unit *i* anti-clockwise horizontal rotation, conveyed in multiples of 90° (respectively: 0°, 90°, 180° and 270°) from the initial equipment illustration.

Each equipment unit can be positioned in four rotations therefore only one binary rotation can be assigned at one time. Let $r_{vi} \in \{0,1\}, i \in \{1,2,3,4\}$ represent if item *v* is rotated by $90(i-1)\circ$, i.e. rv2 = 1 represents a rotation of 90◦. As items only take one rotational position, we have the following constraint:

$$\sum_{i=1}^{4} r_{vi} = 1 \quad \forall\, v \in V \qquad \text{Equation (17)}$$

Each equipment item is allowed rotation (Ana Paula Barbosa-Póvoa, Mateus, & Novais, 2002) (D. I. Patsiatzis et al., 2004) in the x-y plane by 90°.

4.2.6 Model Bii Extension - Items Must be Located in only one Module

Let m_{vk} indicate whether item *v* is within module *k*, then the following constraint is sufficient to ensure that items can only occupy one module:

$$\sum_{k \in K} m_{vk} = 1 \quad \forall\, v \in V \qquad \text{Equation (18)}$$

If the model is only considering items in one module, *Model (Bi)*, m_{vk} takes the value of 1.

4.2.7 Non-Overlapping of Items with Module Bounds

A lower and upper bound must be enforced on the equipment item coordinates to ensure they remain within the module dimensions depending on its current rotation (Michael C. Georgiadis et al., 1999)

(Papageorgiou & Rotstein, 1998) (Ana Paula Barbosa-Póvoa et al., 2002). Assuming that all modules are positioned at the origin and distances are calculated by taking their relative position into account:

$$x_v + (r_{v1} + r_{v3})w_v + (r_{v2} + r_{v4})h_v \leq W_k + M(1 - m_k),\ \forall v \in V, \forall k \in K$$

Equation 19

$$y_v + (r_{v1} + r_{v3})h_v + (r_{v2} + r_{v4})w_v \leq H_k + M(1 - m_k),\ \forall v \in V, \forall k \in K$$

Equation 20

Considering if items can move in the z axis:

$$z_v + dv \leq D_k + M(1 - m_k),\ \forall v \in V, \forall k \in K$$

Equation 21

4.2.8 Model Bii - multiple modules extension Equipment items in the same module check

The binary variable N_{uv} is used to represent whether items *u* and *v* occupy the same module. i.e. N_{uv} = 1 if *u* and *v* share the same module. Equation 22 to Equation 25 are only considered in *Model (Bii)*. The variable n_{uvk} is also included to consider the constraint over all modules:

$$n_{uvk} \geq m_{uk} + m_{vk} - 1,\ \forall (u, v) \in V', k \in K$$

Equation 22

$$n_{uvk} \leq m_{uk},\ \forall (u, v) \in V', k \in K$$

Equation 23

$$n_{uvk} \leq m_{vk},\ \forall (u, v) \in V', k \in K$$

Equation 24

$$N_{uv} = \sum_{k \in K} n_{uvk},\ \forall (u, v) \in V'$$

Equation 25

If items (*u, v*) are positioned in the same module, inequalities (Equation 22 to Equation 24) state that ($n_{uvk} \geq 1$) ∧ ($n_{uvk} \leq 1$) ⟹ n_{uvk} = 1 and then from equation (8), N_{uv} = 1. The values of equation (8) are constrained by equation (2), i.e. for any *k*, N_{uv} = {0, 1}. If (*u, v*) are not located in the same module, either inequality (6), inequality (7) or both will result in inequalities $n_{uvk} \leq 0$, ∀ $k \in$ K, therefore Nuv = 0. Inequalities (4) can then be revised to consider for overlaps within a module by logically considering whether items exist in the same module or not.

4.2.9 Non overlapping equipment items

To guarantee that the equipment items do not overlap, the equations developed by Tsai et al. (1993) (Tsai, Malstrom, & Kuo, 1993), and also studied by Papageorgiou and Rotstein (Papageorgiou &

Rotstein, 1998) and Barbosa-Póvoa et al., (A. P. F. D. Barbosa-Póvoa, Pinto, & Novais, 2001), are adopted to formulate this constraint:

$$x_u + (r_{u1} + r_{u3})w_u + (r_{u2} + r_{u4})h_u + L \leq x_v + M(x_{uv} + y_{uv} + z_{uv}) + (1 - N_{uv}), \forall (u, v) \in V'$$

Equation 26

$$x_v + (r_{j1} + r_{j3})w_v + (r_{j2} + r_{j4})h_j + L \leq x_u + M(1 - x_{uv} + y_{uv} + z_{uv}) + (1 - N_{uv}), \forall (u, v) \in V'$$

Equation 27

$$y_u + (r_{u1} + r_{u3})h_u + (r_{u2} + r_{u4})w_u + L \leq y_v + M(1 + x_{uv} - y_{uv} + z_{uv}) + (1 - N_{uv}), \forall (u, v) \in V'$$

Equation 28

$$y_v + (r_{j1} + r_{j3})w_v + (r_{j2} + r_{j4})w_v + L \leq y_u + M(2 - x_{uv} - y_{uv} + z_{uv}) + (1 - N_{uv}), \forall (u, v) \in V'$$

Equation 29

For considering overlap in the z axis:

$$z_u + d_u + L \leq z_v + M(2 - x_{uv} + y_{uv} - z_{uv}) + (1 - N_{uv}), \forall (u, v) \in V'$$

Equation 30

$$z_v + d_v + L \leq z_u + M(2 + x_{uv} - y_{uv} - z_{uv}) + (1 - N_{uv}), \forall (u, v) \in V'$$

Equation 31

At least one of these constraints needs to be maintained and to only consider the placement of u relative to v and not vice versa. To ensure we consider all pairs only once, define the set of ordered pairs V' = {(u, v) ∈ V ^{2} : u < v}, were the cardinality of the set |V'| =|V |2. Let x_{uv}, y_{uv} ∈ {0, 1}, then for a sufficiently large M, we have:

Eight permutations are permitted with these variables. So that only six are present and also so that only one equation is active, the subsequent equations from (Ana Paula Barbosa-Póvoa et al., 2002) are included:

The introduction of the additional binary variable z_{uv} results in 2^3 = 8 possible binary sums, to restrict this to a choice of 6 requires the addition of the constraints

$$x_{uv} + y_{uv} + z_{uv} + d_v \leq 2, \ \forall (u, v) \in V'$$

Equation 32

$$x_{uv} + y_{uv} + M(1 - z_{uv}) \geq 1, \ \forall (u, v) \in V'$$

Equation 33

Inequalities (20) and (21) forbid x_{uv}, y_{uv}, z_{uv} from taking the values (x_{uv}, y_{uv}, z_{uv}) = (1, 1, 1) and (x_{uv}, y_{uv}, z_{uv}) = (0, 0, 1) respectively.

4.2.10 Model Bii extension - Number of modules used

Let $m_k \in \{0, 1\}$ denote whether a module k has at least one item. If the module is empty, $m_k = 0$, else $m_k = 1$. Using a logical OR we have,

$$m_k \geq m_{vk}, \ \forall \mathrm{v} \in \mathrm{V}, \forall \mathrm{k} \in \mathrm{K}$$

Equation 34

$$m_k \leq m_{vk}, \ \forall \mathrm{k} \in \mathrm{K}$$

Equation 35

Thus, by inequality (11), (mvk = 0, ∀v) ⟹ (mk ≤ 0, ∀i) ⟹ (mk = 0). Also by inequality (10), if any mvk = 1, say p, then (mpk = 1) ⟹ (mk ≥ 1) ⟹ (mk = 1). Therefore, the total number of modules used is:

$$\sum_{k \epsilon K} m_k$$

Equation 36

4.2.11 Rectilinear Distance Between Connected Items

The rectilinear distance in the x-axis between item i and j can be calculated by the absolute value of Dxij and is considered for the set of connected items, f(i; j) 2 Eg, where Dxij is defined by:

$$Dx_{ij} = \left[x_i + (r_{i1} + r_{i3}) \frac{w_i}{2} + (r_{i2} + r_{i4}) \frac{h_i}{2} + \sum_{k \epsilon K} m_{ik} \, mx_k \right] - \left[x_j + (r_{j1} + r_{j3}) \frac{w_j}{2} + (r_{j2} + r_{j4}) \frac{h_j}{2} + \sum_{k \epsilon K} m_{jk} \, mx_k \right], \qquad \forall (i, j) \in E$$

Equation 37

$$Dy_{ij} = \left[y_i + (r_{i1} + r_{i3}) \frac{h_i}{2} + (r_{i2} + r_{i4}) \frac{w_i}{2} + \sum_{k \epsilon K} m_{ik} \, my_k \right] - \left[y_j + (r_{j1} + r_{j3}) \frac{h_j}{2} + (r_{j2} + r_{j4}) \frac{w_j}{2} + \sum_{k \epsilon K} m_{jk} \, my_k \right], \qquad \forall (i, j) \in E$$

Equation 38

Considering the rectilinear in the z-axis, Fij is given by,

$$Dz_{ij} = \left[z_i + \sum_{k \epsilon K} m_{ik} \, mz_k \right] - \left[z_j + \sum_{k \epsilon K} m_{jk} \, mz_k \right], \qquad \forall (i, j) \in E$$

Equation 39

$$D_{zij} =\leq F_{ij}, \qquad \forall (i, j) \in E$$

Equation 40

$$-D_{zij} =\leq F_{ij}, \qquad \forall (i,j) \in E$$ Equation 41

4.2.12 Nozzle Locations

To model the nozzle locations first considered by Ana Paula Barbosa-Póvoa et al., (2002), for the connection (i; j) ∈ E, let the nozzle connection position displacement of the connection point measured from the centre point of item i be given by xs_{ij} ; ys_{ij} ; zs_{ij} . Modelling of the nozzle connection position displacement is achieved by amending Equation 37, Equation 38 and Equation 39 to give Equation 42, Equation 43 and Equation 44 respectively.

$$Dx'_{ij} = \left[x_i + (r_{i1} + r_{i3})\frac{w_i}{2} + (r_{i2} + r_{i4})\frac{h_i}{2} + \sum_{k\epsilon K} m_{ik}\, mx_k\right] - \left[x_j + (r_{j1} + r_{j3})\frac{w_j}{2} + (r_{j2} + r_{j4})\frac{h_j}{2} + \sum_{k\epsilon K} m_{jk}\, mx_k\right] + (r_{i1}xs_{ij} - r_{i2}y\, s_{ij} - r_{i3}xs_{ij} + r_{i4}ys_{ij}) - (r_{j1}xs_{ji} - r_{j2}ys_{ji} - r_{j3}xs_{ji} + r_{j4}ys_{ji}), \quad \forall (i,j) \in E$$

Equation 42

$$Dy'_{ij} = \left[y_i + (r_{i1} + r_{i3})\frac{h_i}{2} + (r_{i2} + r_{i4})\frac{w_i}{2} + \sum_{k\epsilon K} m_{ik}\, my_k\right] - \left[y_j + (r_{j1} + r_{j3})\frac{h_j}{2} + (r_{j2} + r_{j4})\frac{w_j}{2} + \sum_{k\epsilon K} m_{jk}\, my_k\right] + (r_{i1}ys_{ij} - r_{i2}xs_{ij} - r_{i3}ys_{ij} + r_{i4x}s_{ij}) - (r_{j1}ys_{ji} - r_{j2}xs_{ji} - r_{j3}ys_{ji} + r_{j4}xs_{ji}), \quad \forall (i,j) \in E$$

Equation 43

$$Dz_{ij} = \left[z_i + \sum_{k\epsilon K} m_{ik}\, mz_k\right] - \left[z_j + \sum_{k\epsilon K} m_{jk}\, mz_k\right] zs_{ij} - zs_{ji}, \qquad \forall (i,j) \in E$$

Equation 44

4.2.13 Objective function

Equation 45 defines the objective function to reduce pipe length, highlighted previously as a major labour and cost factor (up to 20%) in industrial plants (Peters et al., 2003). Rij and Bij are absolute value of the rectilinear distance between connected items (i, j) ∈ E, in the x, y, z axes respectively. Given that the unit cost of a connection between i and j is cij and the cost of a module is given by gk, minimise the following objective function to minimise pipelengths and number of modules utilised:

$$MinOf = \sum_{(i,j)\in E} c_{ij}\,(R_{ij} + B_{ij}) + \sum_{k\epsilon K} g_k\, m_k$$

Equation 45

For formulation Bi - multiple modules, mk would equal 1.

The pipe installation costs are calculated with Equation (46) using pipe cost ($926.29/m) and installation data (14.04/m) from (Generation IV International Forum (appendix G), 2007). The construction method is 1 for the on-site assembly method, and 3 for the factory-built method (Barry, 2009).

$$Pipe\ cost = Pipe\ Length\left(Pipe\ Cost + \frac{(Pipe\ Labour)}{Construction\ method}\right)$$

Equation (46)

4.3 Relation to Plant Design

This section relates to how the optimisation output links to the plant design software. The Bentley PlantWise model was developed with the aid of the online Bentley Plantwise Help Documentation (Bentley, 2020). The attributes of equipment and nozzles would ordinarily come from the supply chain or in-house equipment design teams, however, in this case, as the information is not available, assumptions must be made to the equipment information. To create a 3D PlantWise model, first projects and models must be created within PlantWise. A process model is then built starting with adding equipment items in the Equipment editor, defining equipment attributes and locations such as those shown in Figure 4-1.

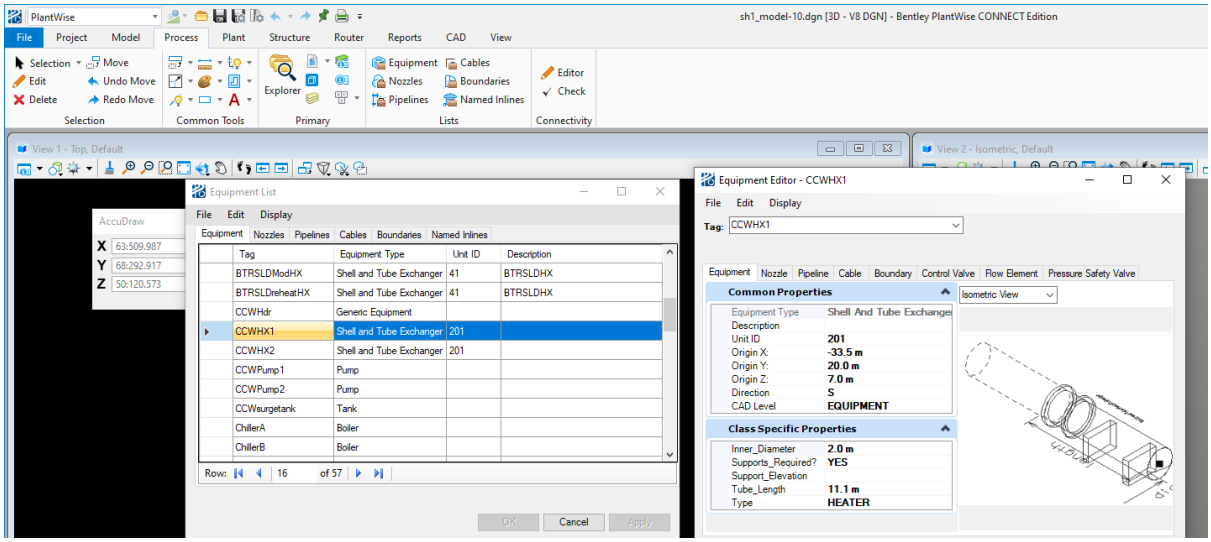


Figure 4-1 – Creating and defining equipment items in Bentley PlantWise (CCW example)

Each Equipment's Nozzles are then defined in the model through the Nozzle List and edited in the Nozzle Editor (Figure 4-2).

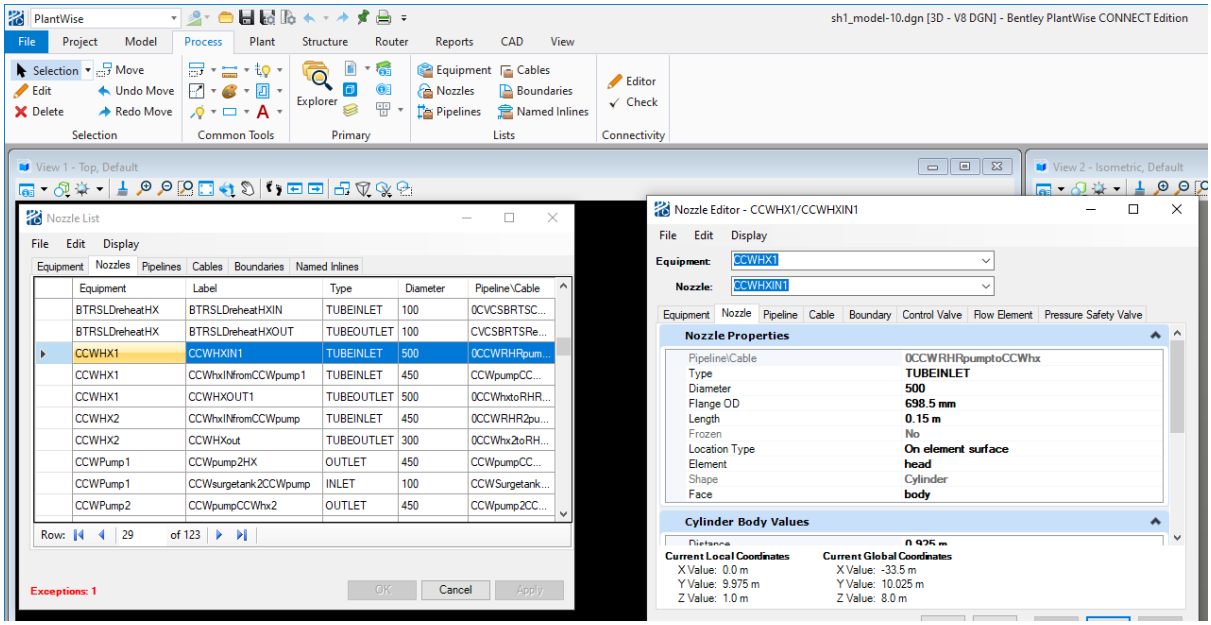


Figure 4-2 – Defining equipment Nozzles in the Nozzle editor (CCW example)

Next, the connection between two equipment items is defined using the Pipeline Editor and Connectivity Editor (Figure 4-3). The pipeline information such as Diameter, Unit ID, Pipe Class, Commodity, Insulation Code, Operating Temperature and the origin and terminus of the pipeline connection is defined.

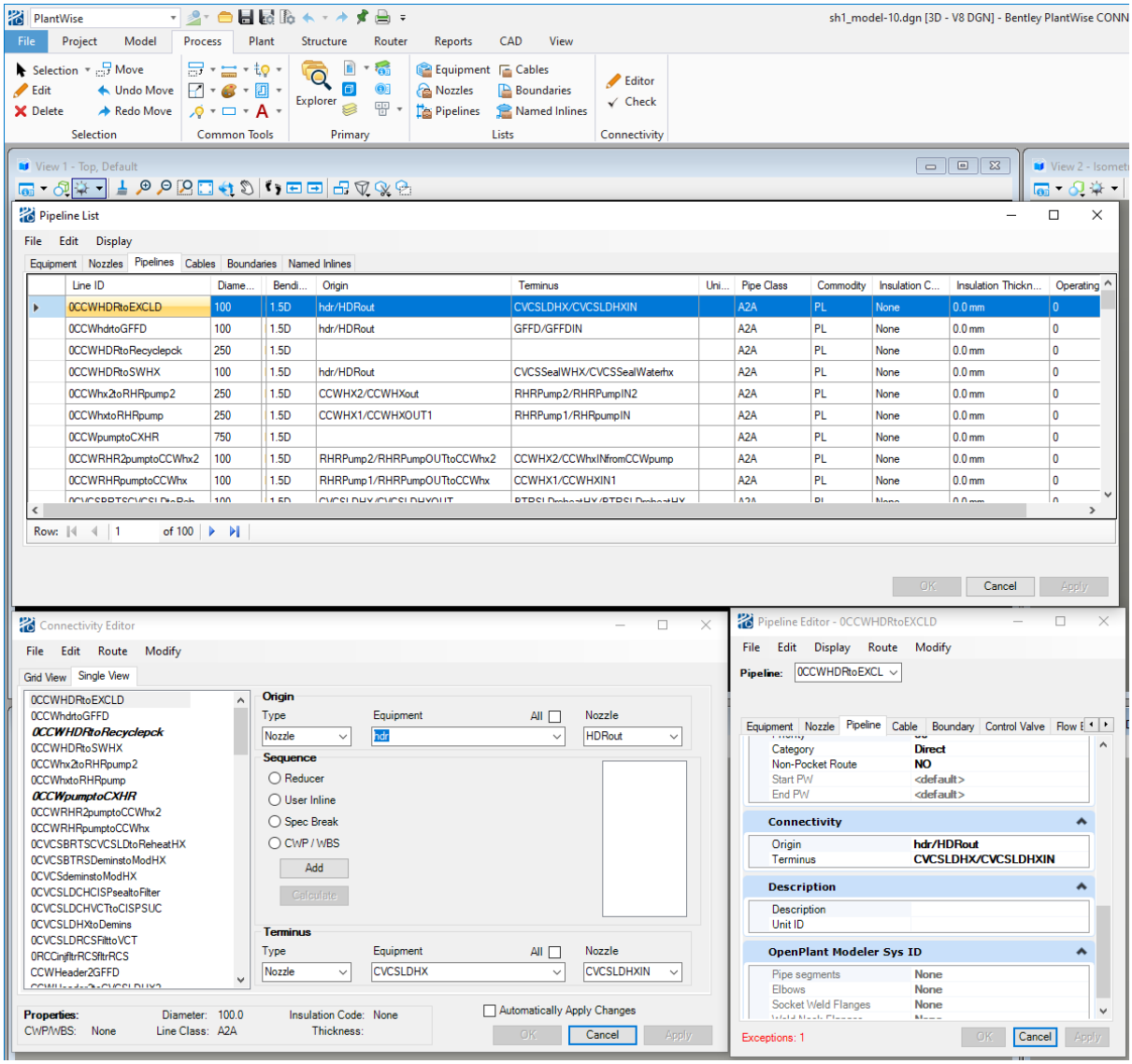


Figure 4-3 – Defining pipelines and pipeline connectivity in Bentley PlantWise (CCW example)

Other features such as structures (pipeways, multilevel structures, pedestals, other obstacles) can be placed.

The AutoRouter pipe routing feature uses a combination of algorithms and rules based on pipers' practices to find good, low-cost routes between endpoints and around obstacles. This is useful for plant designers to assess concept options quickly, enabling them to make small changes to equipment locations and update the model instantly.

4.4 Summary

The literature review in Chapter 2 highlighted layout optimisation has not considered modularisation previously. It was proposed in chapter 3 to develop a novel layout optimisation method to consider modularisation. This is required for the analysis and development of factory-built road transportable

nuclear system modules. Chapter 4 presents the novel layout optimisation methods developed for the optimisation of modular plants. The optimisation is developed with a systems engineering methodology by decomposing the problem into three parts. Section 4.1 outlined the mathematical model for the optimisation of modules layout from a pre-exiting design – Model (A). Following this, Section 4.2 describes *Model (Bi)* for the layout of equipment within a single module and also the extension for the equipment to module allocation, *Model (Bii)*. The integration with the plant design framework is discussed in section 4.3. The results from these optimisation models are discussed in chapter 5, comparing the output against designs from previous research (Lapp, 1989). The potential benefits of integration with the wider plant design framework are also explored.

5 CHAPTER 5
Results and Discussion

In this chapter, the results are discussed for the layout of modules Model (A), the layout of equipment within a single module, *Model (Bi),* and novel extension to consider the allocation of equipment to modules, *Model (Bii)*. The results are compared with the output against designs from previous research (Lapp, 1989). Furthermore, the link to plant design is presented and explored along with general observations from the optimisation and limitations.

5.1 Layout of Modules Results Model (A)

The balance of plant systems objective function for the reworked assembly on-site (Lapp, 1989) Shearon Harris Power Plant (Figure 2-18) was determined to be 14914. This would be higher in the plant design as the program evaluates rectilinear distances. The pipe layout must nevertheless redirect circumferentially around the outside of the nuclear island containment.

The leading safety systems that are fixed and connected to the RCS; SIS, RHR, and CS, make up a count of 11786 in the objective function. However, they are not incorporated into the calculations as they are in optimal positions, adjacent to the RCS. Furthermore, the RHR is split across two floors, meaning more consideration would be needed for modularisation. This indicates a sizable percentage of the piping is attributed with these highly linked and critical safety systems.

5.1.1 High level MathWorks genetic algorithm description

The genetic algorithm utilised is the default MATLAB function (ga). The high level MathWorks genetic algorithm works as follows (Mathworks, 2020a):

1. The algorithm initialises a random population.
2. A succession of new populations are then established. The entities in the existing generation are used to produce the following population in the subsequent steps.
    a. The existing population fitness value are evaluated.
    b. The fitness scores are scaled to transform them into a more practical format called expectation values.
    c. Chooses parent members from their expectation values.
    d. Elite population are selected with the lowest fitness values. These elite individuals are dispatched to the subsequent population.
    e. From the parents, generates children. Children are created either by crossover (merging the vector values of a pair of parents) or by mutation (producing random changes to a single parent).
    f. Changes the current population with the children to create the subsequent generation.
3. The algorithm ends when one of the termination criteria is met.

More detail about the MathWorks Genetic Algorithm can be found at (Mathworks, 2020a).

5.1.2 Results

Both three and four level arrangements were evaluated where modules are situated on two sides of the nuclear island. The minimum number of levels required was three as a two-level arrangement does not have sufficient space for all the modules to be assigned. The outcome for the three-level arrangement balance of plant objective function was 9855, while the outcome for the four-level arrangement (Figure 5-1) was 9279.

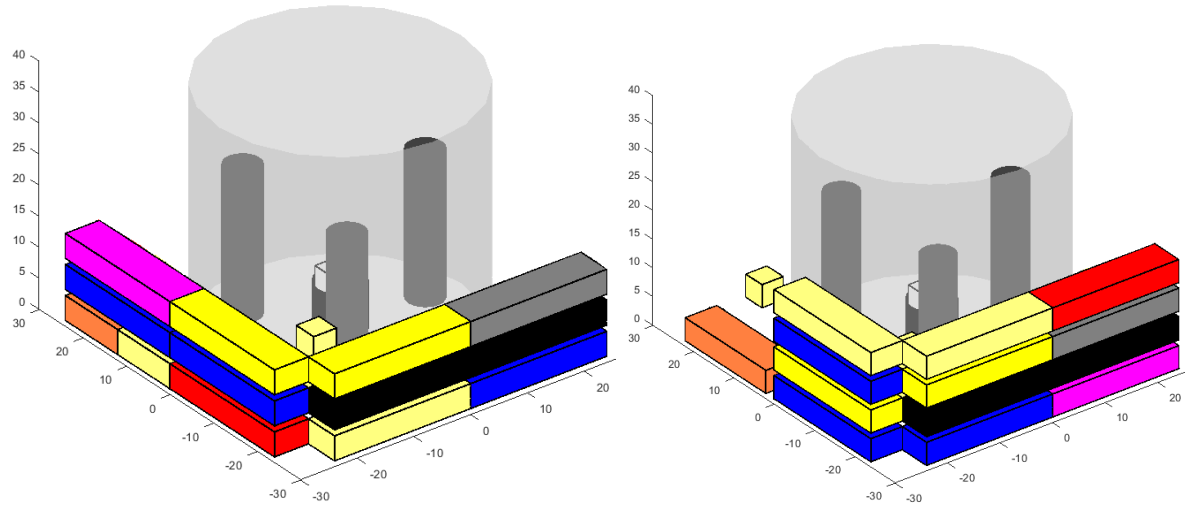


Figure 5-1 – Three-floor and Four-floor layout for modules located on two sides of the nuclear island

In the three-level standardised grid consideration (Figure 5-2), the BOP objective function was 8132, meanwhile the four-level arrangement was 8036. This signifies a substantial reduction on the previous plant, a decrease of 46.1%.

Establishing the modules on two sides of the nuclear island arrangement is a comparable layout to the original three sided plans for the plant (Figure 2-18). For the three and four level arrangements in this layout, the BOP pipework score function was decreased by 33.9% and 37.8% correspondingly.

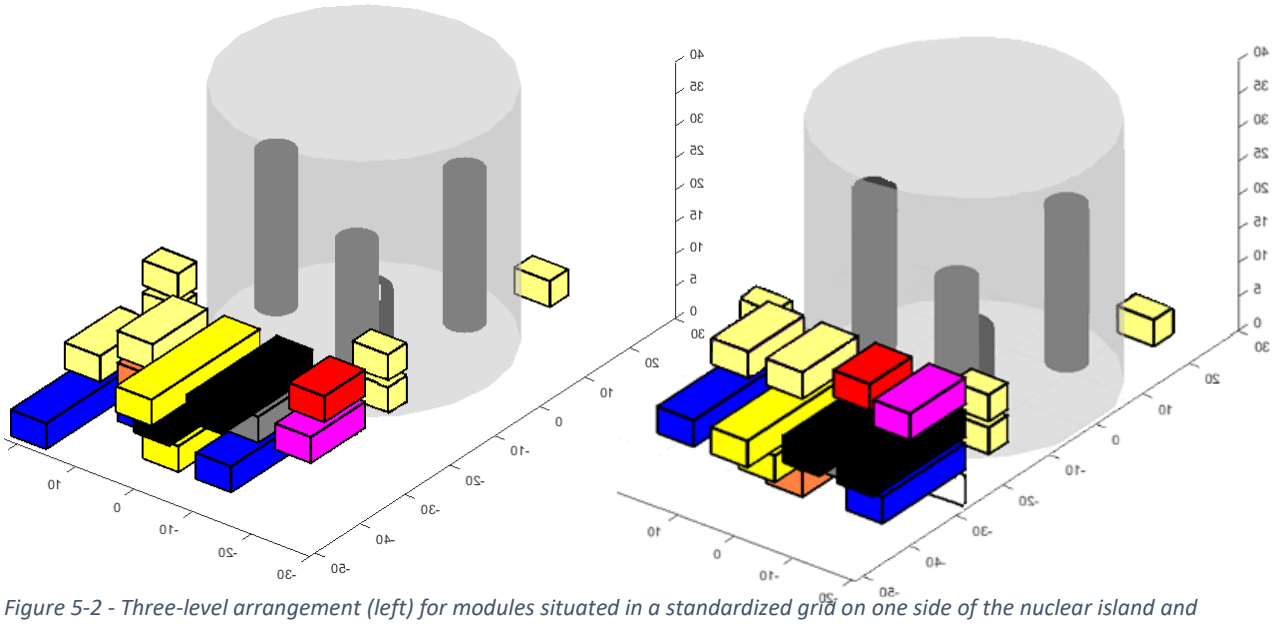


Figure 5-2 - Three-level arrangement (left) for modules situated in a standardized grid on one side of the nuclear island and four-level arrangement (right)

Three and four-level arrangements in the standardized grid were decreased by 45.4% and 46.1% respectively. Moreover, this layout could offer easier integration with the standardised grid, as modules may be readily managed into the grid formation and could assist with construction scheduling (Lloyd & Roulstone, 2018a) and construction technique (Giovanni Maronati et al., 2018).

The grid layout and incorporating the structural, mechanical, instrumentation and electrical into a standardised composite module aids with transferring work offsite to factory build (Haney, 2012). Lloyd & Roulstone, (2018a) recommend SMRs should aim for a minimum of 60% of the site area for modularisation to realise cost competitiveness with other methods of energy production. Plants should be designed to maximise this Degree of Modularisation figure.

Piping may consist of up to 20% of a process plant capital cost. A decrease in pipework by 46.1% might present considerable reductions. However, transferring this work to an offsite factory is not considered, which could offer further cost reductions. The findings of the different arrangements examined are presented in Table 5-1.

Number of sides	Number of floors	Objective function score	GA generations	GA function counts
Two	Three	9855	53	5021
Two	Four	9279	55	5144
One	Three	8132	67	6946
One	Four	8036	58	5538

Table 5-1 - Results for Genetic Algorithm performance and Objective Function for various arrangements

For each scenario, the algorithm was executed 100 times. The box plot of findings is presented in Figure 5-3.

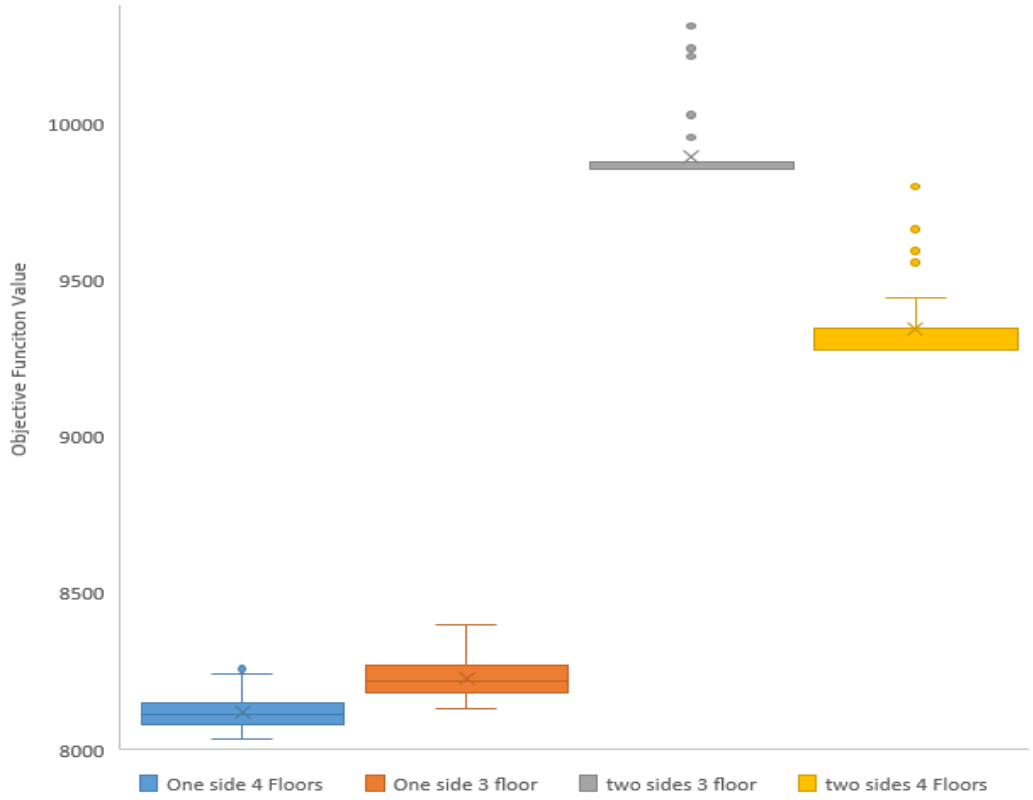


Figure 5-3 – Box plot of the variation in the objective function scores

The results show a narrow interquartile range highlighting accurate and precise results. However, the two sided arrangement shows a number of outliers, where the genetic algorithm has rested in local minima. Further investigations would be needed to investigate this phenonima. Although changing population size, probability of crossover/mutation, stall gen limits seeemed to have little effect.

5.2 Layout of Equipment within a Single Module (model Bi)

The second case study analyses the CVCS system from (Lapp, 1989). The *Model (Bi)* utilises MATLAB's intlinprog, mixed- integer linear programming solver outlined below:

5.2.1.1 High level MathWorks Mixed-Integer Linear Programming Algorithm description

A generic Branch and Bound pseudocode is shown in Figure 5-4 (Morrison, Jacobson, Sauppe, & Sewell, 2016).

Algorithm 1: Branch-and-Bound(X, f)

```
1 Set L = {X} and initialize x̂
2 while L ≠ ∅:
3     Select a subproblem S from L to explore
4     if a solution x̂' ∈ {x ∈ S | f(x) < f(x̂)} can be found: Set x̂ = x̂'
5     if S cannot be pruned:
6         Partition S into S_1, S_2, ..., S_r
7         Insert S_1, S_2, ..., S_r into L
8     Remove S from L
9 Return x̂
```

Figure 5-4 - Pseudocode for a generic Branch and Bound technique is presented in Algorithm 1 (Morrison et al., 2016)

The high level MathWorks Mixed-Integer Linear Programming Algorithm "Intlinprog" (Mathworks, 2020c) uses the following fundamental approach to solve mixed-integer linear programs:

1. Use Linear Program preprocessing to decrease the problem size
    a. The intention of preprocessing measures is to enhance the scaling of the model and sparsity of the constraint matrix, remove unnecessary variables and constraints, identify the primal and dual infeasibility of the model and bolster the limits on variables.
2. Initially solve a relaxed (noninteger) problem using Linear Programming.
3. Tighten the LP relaxation of the mixed-integer problem through Mixed-Integer Program Preprocessing.
4. Additionally tighten up the LP relaxation of the mixed-integer problem with Cut Generation
5. Use heuristics to attempt to unearth integer-feasible results.
6. Examine systematically the best solution using a Branch and Bound algorithm. Constricted limits of plausible values of the integer variables are used to solve the LP relaxations in this algorithm. A series of revised bounds on the optimal objective function value are generated.

Any of the steps can be used to solve the problem with Intlinprog. Intlinprog does not execute the subsequent steps if the problem is solved in a previous step. More detail about the MathWorks Intlinprog can be found at (Mathworks, 2020c).

5.2.2 CVCS Results

The original CVCS module layout for the heuristically assigned equipment for on-site assembly method (Lapp, 1989) is shown below (Figure 5-5). The locations of equipment are given in the appendix (Table 0-5).

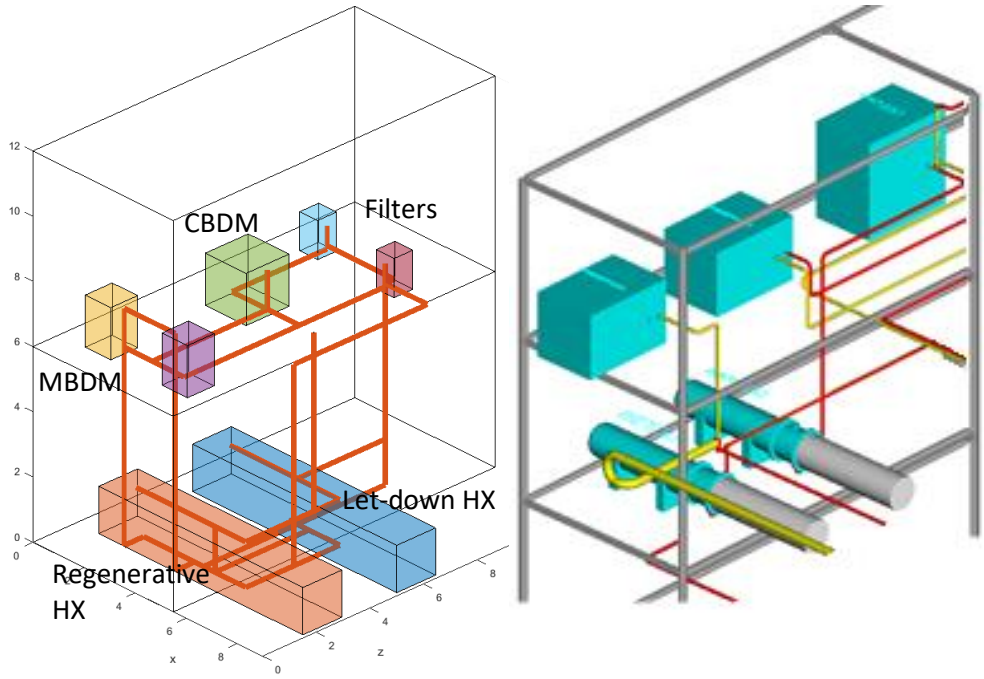


Figure 5-5 - The original CVCS plant layout for the matrix reordering and clustering technique for on-site assembly method (Lapp, 1989) modelled in MATLAB 2019b (left) and Bentley PlantWise CAD (right) (Lapp, 1989)

The objective function for the module piping was calculated at 154.8m. Using Equation (46), the Pipe cost is $144000.

Welding costs for the 3 demineralisers are between $ 98880 - 173040 (in 2019 USD) in an on field assembly area (Stone & Webster Engineering Corporation, 1977). Welding costs for the 2 Reactor Cooling System (RCS) Filters are $101187 (in 2019 USD) in an on field assembly area (Stone & Webster Engineering Corporation, 1977).

Welding on-site could be $5000 per weld in 2019 USD (Stone & Webster Engineering Corporation, 1977). There are 4 cross modules on-site connections so this would be $20,000 in total.

The total welding and piping costs for the on-site assembly CVCS system are between $364675 - $438,835. Each example was modelled using MATLAB problem-based modelling system v2019b. Each run was solved to global optimality.

The optimisation results for the factory-built CVCS module are shown in Figure 5-6, and the equipment locations are found in Table 5-2.

Equipment	x (m)	y (m)	z (m)	R
Regenerative HX	4.3	0.8	0.75	1
Let-down HX	5.2	2.3	0.75	1
Filters 1	2.7	0.65	2.1	0
Filters 2	2.7	1.35	2.1	0
Mixed Bed Demineralisers (MBDM) 1	4.4	0.5	2.5	2
Mixed Bed Demineralisers (MBDM) 2	4.4	1.5	2.5	3
Cation Bed Demineraliser (CBDM)	4.7	1	2.3	1

Table 5-2 - Equipment locations for optimised CVCS module

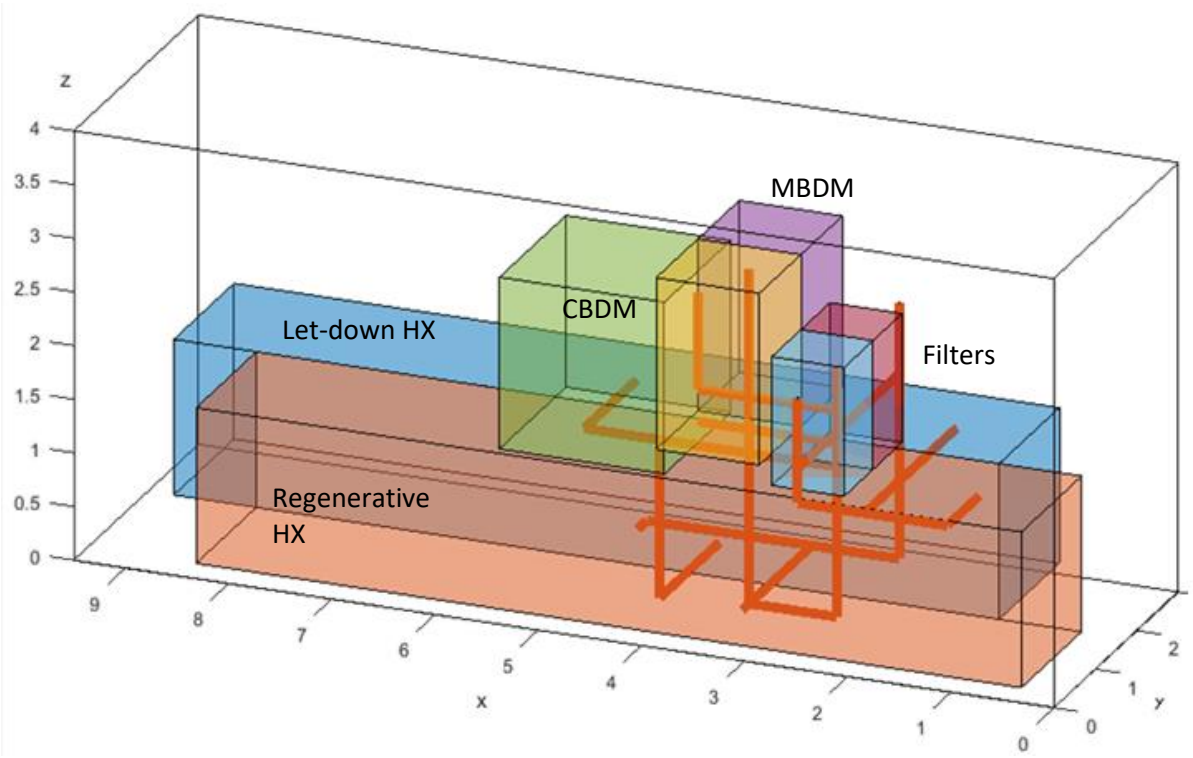


Figure 5-6 - Optimised module layout for factory-built, road transportable module with heat exchanger extraction space

The model was implemented in MATLAB 2019b by formulating a MILP model and solved through the MILP solver, intlinprog (Mathworks, 2018c). The model was solved in around 8 minutes to a gap tolerance of 0.

The lowest objective function for the optimised module piping was calculated at 50.2m. The pipe cost (installation and materials), was calculated at $46167 utilising Equation (46). This equates to a decrease of around 68% compared to the onsite assembly CVCS system in Figure 5-5.

According to the Generation IV International Forum Cost Estimating Guidelines (Generation IV International Forum, 2007), Structural steel is small in comparison at $2/kg compared to $933.86 per linear meter piping installation costs and the transport and installation of a further module.

A Stone & Webster Engineering Corporation, (1977) report on modularising the CVCS system suggested welding cost savings of between $216552- $302400 in 2019 USD for moving to on-site assembly compared to a stick built system.

Welding costs for the 2 RCS Filters are $101187 (in 2019 USD) in an on field assembly area (Stone & Webster Engineering Corporation, 1977). Moving this work to a factory could result in welding costs being reduced to $33729, a saving of $67458, representing a 66% saving.

Welding costs for the 3 demineralisers are between $98880 - $173040 (in 2019 USD) in an on field assembly area (Stone & Webster Engineering Corporation, 1977). Moving this work to a factory could result in welding costs being reduced to $32960 - $57680 a saving between $65920 -$ 115360.

The total pipe and welding costs for the factory-built CVCS equate to between $112856 and $137576.

Therefore, the total pipe and welding cost savings for the factory-built CVCS could equate to between $251819 and $301259.

In this example, the system equipment does not fit into the 3x18x4.5m module, due to volumetric spatial constraints of the equipment and module size. This requires either one 5x24x4.5m module or two 3x18x4.5m modules.

5.2.3 BTRS System Optimisation Results

The BTRS system from the work in (Lapp, 1989) can be seen in a representative 3D MATLAB model in Figure 5-7.

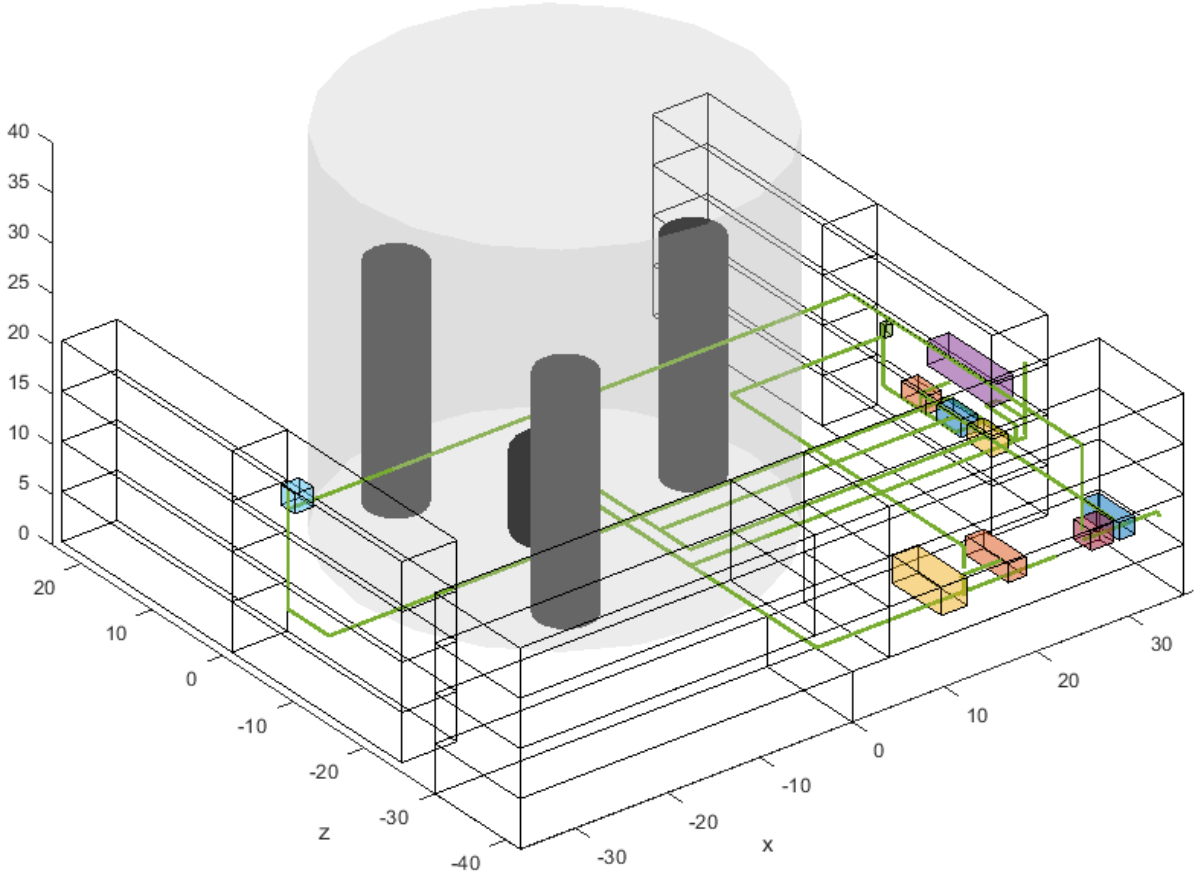


Figure 5-7 - BTRS system from the work in (Lapp, 1989)

The locations of (Lapp, 1989) BTRS equipment from Figure 5-7 are located in Table 0-8.

The objective function calculated from the centre of equipment was 575.3.

5.2.4 BTRS - One Larger Module Result

The BRTS system would not fit into one smaller 3m road transportable module as the optimisation provided an error in this scenario. Two configurations were considered, one larger 5m wide module and two smaller modules. The layout optimisation results for the larger 5x24x4.5m module configuration is shown in Figure 5-8 and the positional outputs are in Table 5-3. The highly connected equipment is clustered close to the module input and output locations, while the Recycle holdup tank and Boron Recycle Evaporator are considered less important due to the lower connectivity.

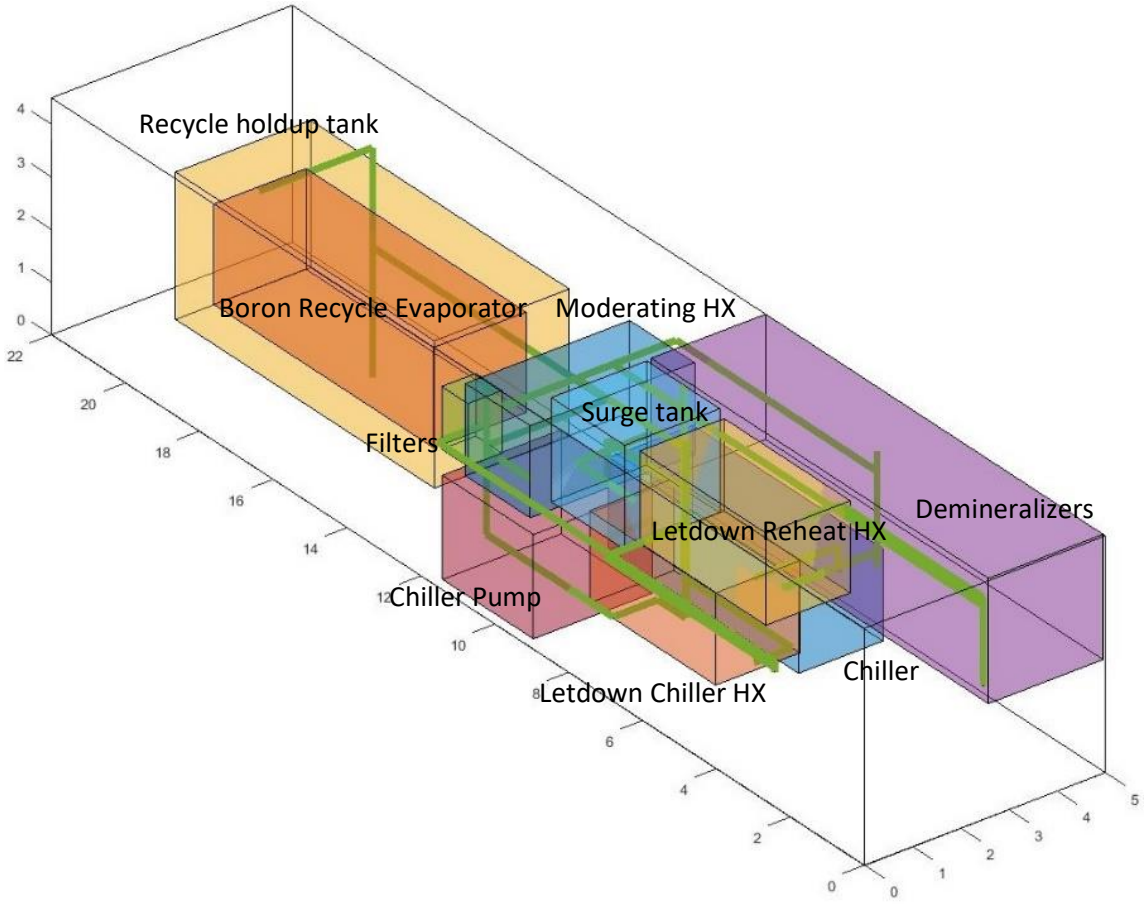


Figure 5-8 – Larger 5x24x4.5m module layout optimisation results

The objective function for the optimisation is 96.09. The model was solved to a Relative gap (%) 4.63 in a time of 204.41s with 300000 nodes explored. Ensuring all the equipment is contained into one larger module results in less assembly work required to join the systems together at the construction-site but the transportation will be more restricted.

Equipment	**x (m)**	**y (m)**	**z (m)**	**θ**
Moderating HX	0.11	9.19	2.35	90
Letdown Chiller HX	0.87	5.16	0.75	0
Letdown Reheat HX	0.87	3.8	2.51	180
Demineralizers	2.62	0.06	2.12	0
Filters	0.16	10.94	2.51	270
Surge tank	0.55	7.21	2.5	270
Chiller Pump	0.06	9.035	0.14	270
Chiller	2.62	5.2	0.34	180
Boron Recycle Evaporator	0	11.65	2.59	0
Recycle holdup tank	1.91	14.125	0.02	0
Module in	2.5	0.05	2.5	270
Module out	0.05	2.5	2.5	270

Table 5-3 - BTRS system equipment location optimisation results for one 5x24x4.5m module

5.2.5 BTRS - Two Smaller Module Results

The layout optimisation results for the two smaller 3x18x4.5m module configuration are shown in Figure 5-9. In this optimisation, a module separator non-overlapping constraint was added between the two modules. The locations of BTRS equipment for the two 3x18x4.5m modules from Figure 5-9 are located in Table 5-4. The objective function was calculated as 85.57. Again, in this configuration, the highly connected equipment such as the heat exchangers, chillers, and filters are close together.

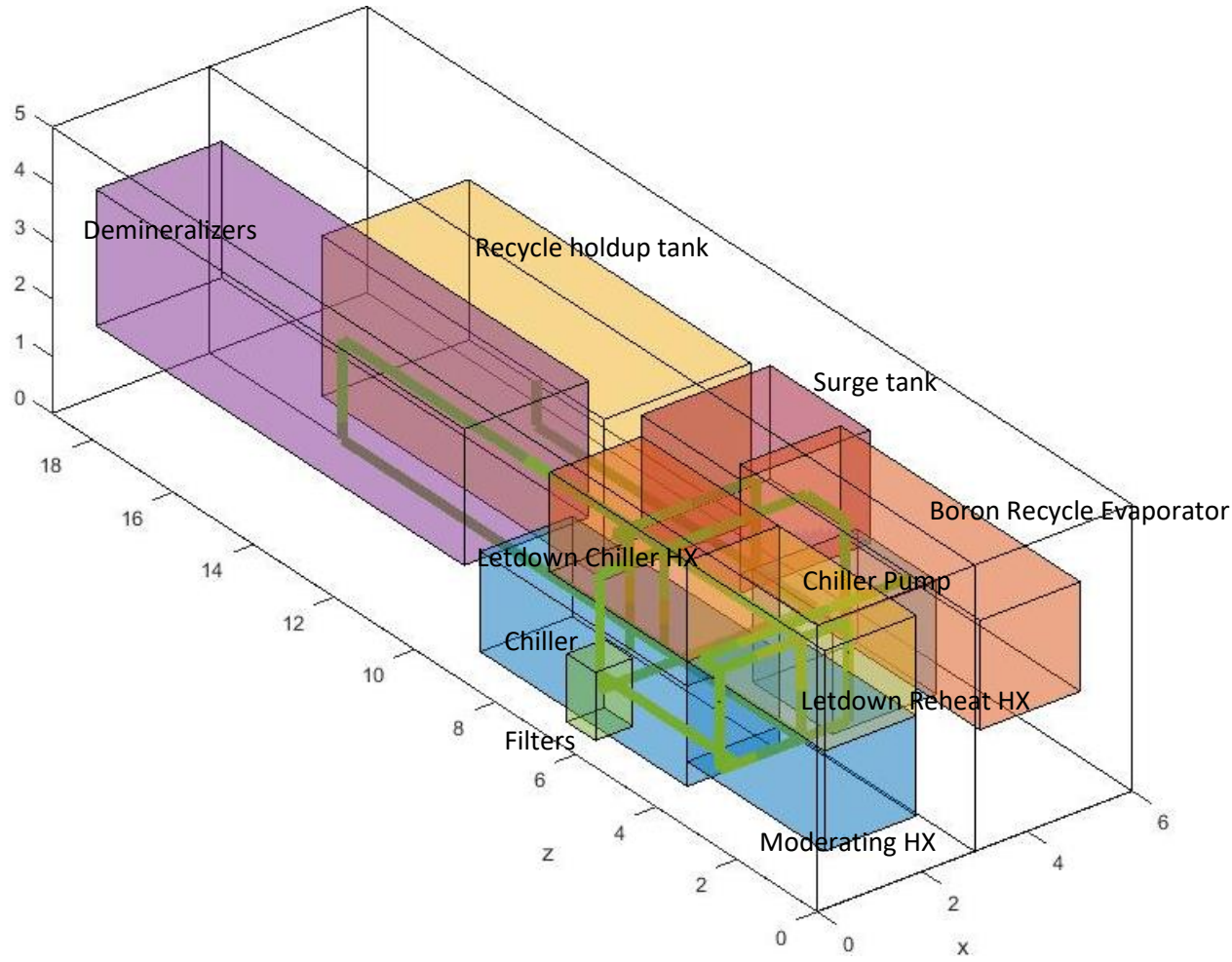


Figure 5-9 - Smaller 3x18x4.5m module layout optimisation results

Equipment	x (m)	y (m)	z (m)	θ
Moderating HX	0.75	0.8	0.43	0
Letdown Chiller HX	0.75	4.21	2.18	0
Letdown Reheat HX	0.75	0.8	2.18	0
Demineralizers	0.435	9.34	1.62	0
Filters	0.04	5.56	0.43	0
Surge tank	3.34	3.97	0.11	0
Chiller Pump	3.1	5.95	1.75	0
Chiller	0.75	4.21	0	0
Boron Recycle Evaporator	3.1	0	2.09	0
Recycle holdup tank	3.1	9.34	0.43	0
Module in	2.5	2.5	2.5	0
Module out	0.05	2.5	2.5	0

Table 5-4 - BTRS system equipment location optimisation results for the two 3x18x4.5m modules

The model was solved to a Relative gap (%) 4.63 in a time of 204.41s with 300000 nodes explored.

A reduction in the objective function from 5775.3 to 85.57 is a significant reduction. It is also slightly less than the 96.09 objective function for the larger 5m module. However, more connections would be required at site due to the system being split across two modules.

5.2.6 Large Module Full Systems and Equipment Results (Model Bi)

Using the same layout optimisation *Model (Bi)* as provided in section 4.2, but not considering nozzle locations, initial analysis shows the layout for a maximum road transport module of 6m wide, 4.5m high and 50m long (Figure 5-10). This could be split into two 25m long modules.

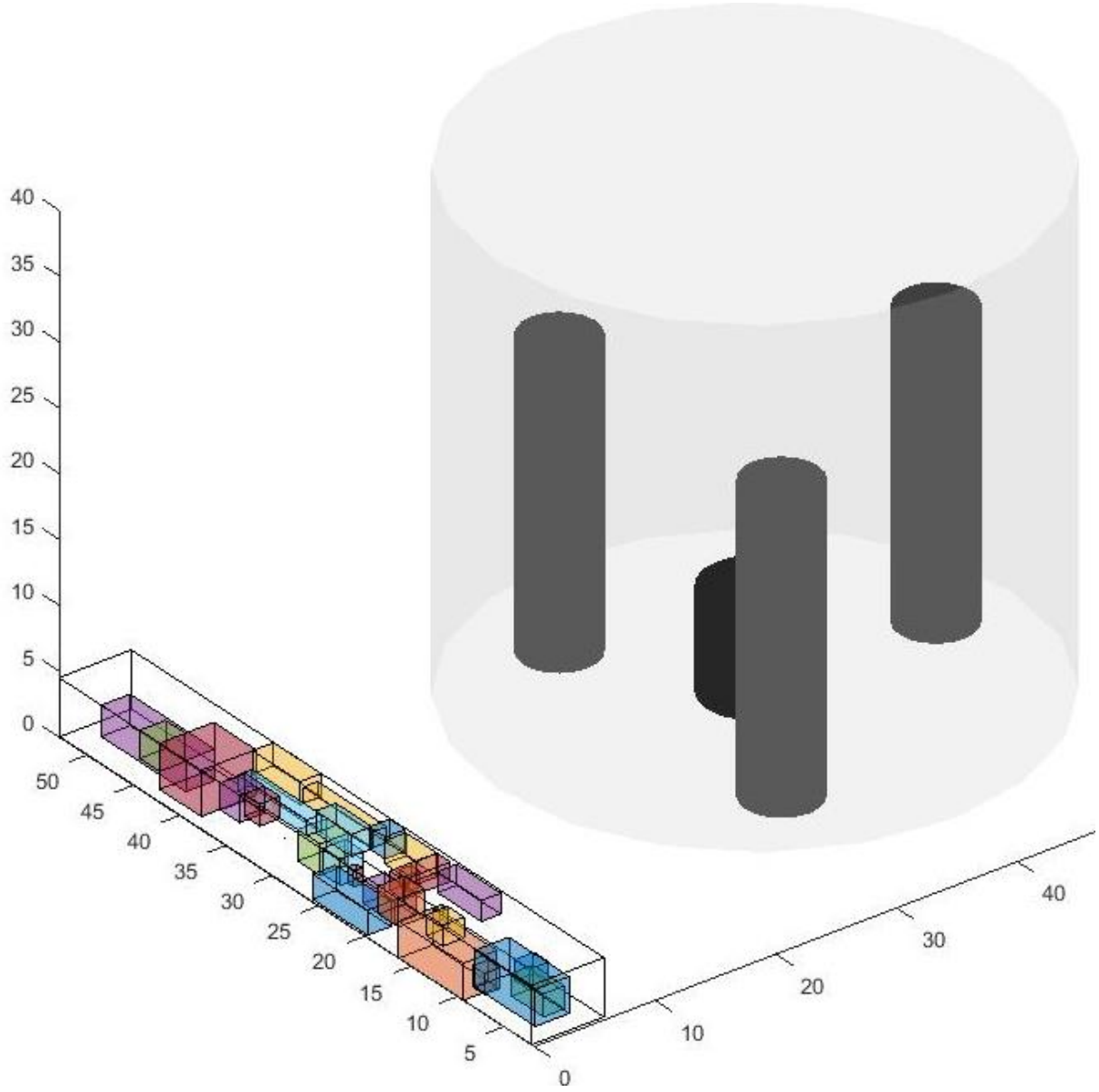


Figure 5-10 - 6m wide, 4.5m high and 50m long module with an option of splitting the module into two 25m long modules.

The objective function for the original modular assembly area Shearon Harris plant was calculated at 26121. If the 1-3-8 from shipbuilding is used, the objective function would be 3x this at 78363 (Barry,

2009) (Giovanni Maronati et al., 2018). The objective function using the optimisation model was calculated at 2958. The reactor pressure vessel is assumed to be within the module however, to ensure non-overlapping constraints are not broken. The locations of the equipment are detailed in Table 5-5. Adding further module separator constraints ensured this caused erroneous results from the optimisation.

#	Equipment locations for plant layouts								
	Figure 3-4			Figure 5-10			Figure 5-11		
	x (m)	y(m)	z (m)	x (m)	y(m)	z (m)	x (m)	y(m)	z (m)
1	-33	22.7	5	4.28	23.38	2.80	0.235	17	2.83
2	-33.5	20	5	0.00	16.35	2.36	0	0.17	0.61
3	-30	20	5	4.52	25.05	2.80	0.475	23.54	3.26
4	-32.3	-5	5	0.00	33.51	2.44	0	31.1	0.06
5	-33.5	-20	5	0.00	42.14	2.36	0	47.45	2.36
6	-30	-8	5	2.06	28.94	2.80	0.475	9.54	3.26
7	-33	-21.5	5	0.39	31.84	2.80	0.235	17	0
8	20	-31.1	5	0.23	19.97	0.00	2.14	9.31	1.75
9	12	-37.2	5	0.00	9.35	0.00	0	2.31	0.03
10	34.5	-20	5	4.25	19.97	2.44	2.14	25.17	2.12
11	34.5	-15.7	5	2.49	19.97	0.06	4.05	34.91	2.75
12	34.5	-10.7	5	2.80	4.35	0.06	2.14	15.26	2.12
13	34.5	18	5	2.80	25.05	2.75	0.235	19.65	2.5
14	34.5	21.4	5	2.06	18.49	2.75	0	54.35	1.35
15	20	-38	10	0.00	1.58	1.59	3.09	18.67	1.7
16	15	-30	10	0.77	8.08	0.77	3.855	28.02	0.08
17	32	-32	10	0.31	11.98	2.80	0.28	33.16	1.67
18	32	-15	10	2.18	42.14	0.06	2.03	38.32	2.12
19	32	-5	10	4.56	17.78	0.06	4.26	29.29	0.16
20	33	5	10	2.39	25.76	0.37	2.4	25.21	0.14
21	33	12	10	2.98	25.05	0.37	3.89	28.58	2.51
22	33	18	10	4.25	7.76	0.00	4.41	15.41	2.83
23	33	23	10	4.55	21.20	1.25	2.14	27.07	0.16
24	32	-30	5	4.24	32.51	2.75	2.14	31.1	0
25	5	-35	0	4.32	13.02	2.80	0.275	49.59	2.91
26	30	-1	6	2.14	27.62	0.37	2.14	55.83	2.12
27	0	0	0	1.00	30.00	2.50	1	30	2.5
28	0	-32.2	5	0.00	37.64	1.00	0	58.21	0.06

Table 5-5 – Comparing equipment locations from the (Lapp, 1989) *plant to Figure 8-9 and Figure 5-11*

The optimisation was run again, with a module split at 30m, resulting in the equipment locations in Table 5-5 and the layout in Figure 5-11.

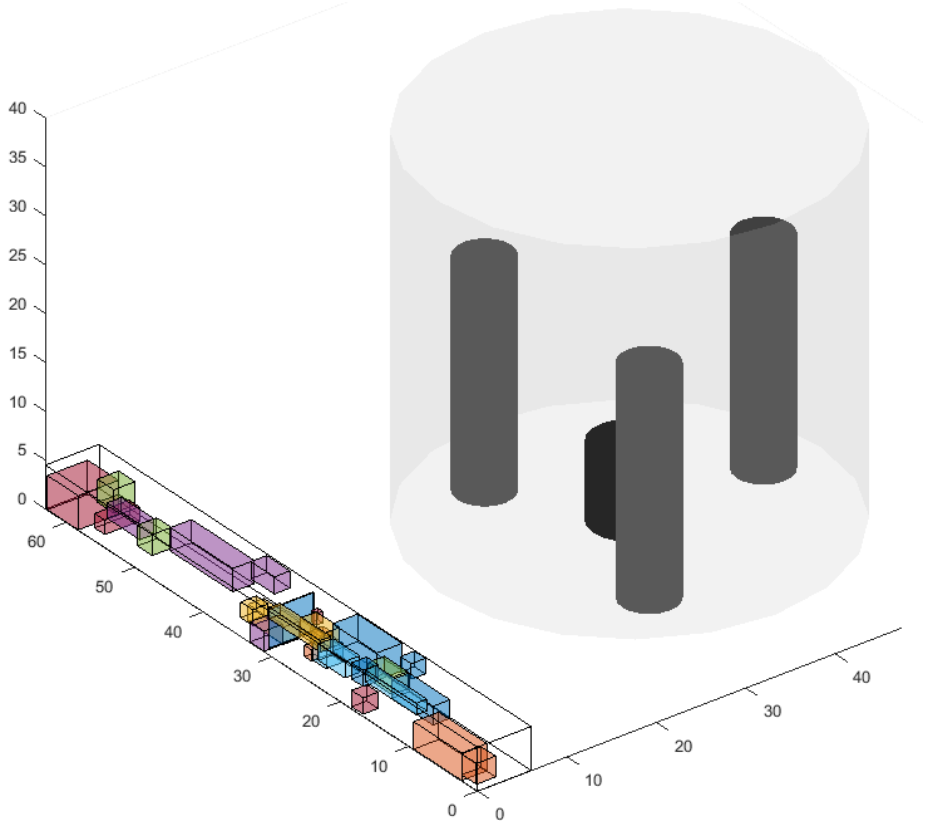


Figure 5-11 - Two 6m wide, 4.5m high and 32m long modules with module separator at 30m

Adding more than one module separator constraint to the previous model caused a MATLAB error with any module boundary below 12m for unknown reasons (Figure 5-12). An investigation would need to be conducted with an optimisation expert to find the cause of this phenomenon.

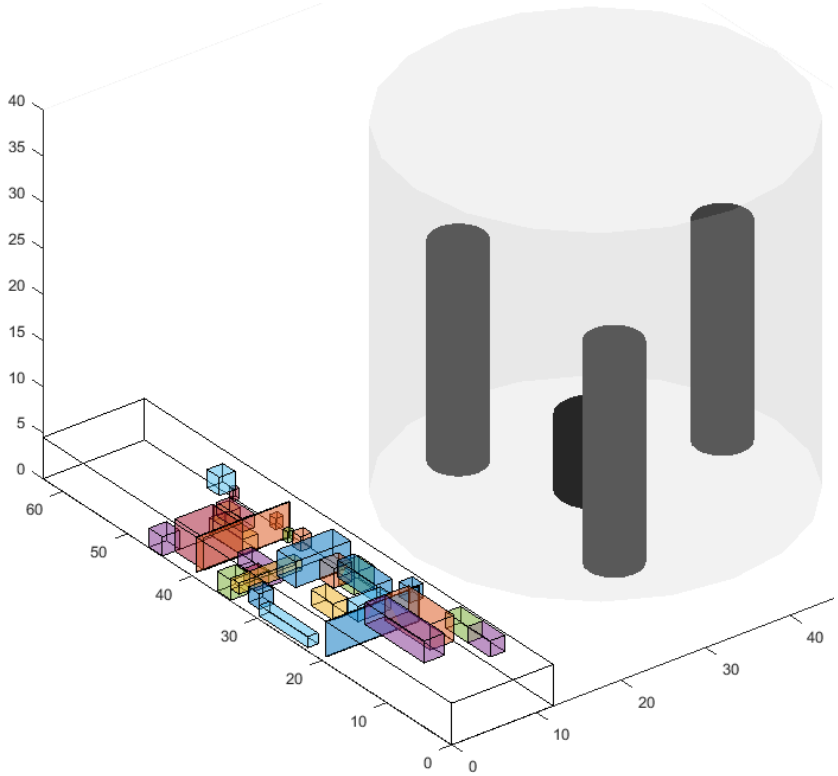


Figure 5-12 – 12m wide, 4.5m high and 20m long modules with module separators at 20m and 40m

5.2.7 Module Separator Constraints GA Function Soft Constraints Alternative

An alternative to solve this problem was trialled with soft constraints in the MATLAB GA function.

5.2.8 No Module Boundary Constraints Comparison

An optimisation model without module overlapping constraints was initially run to set a baseline target (Figure 5-13). Using no module constraints, the objective function was 9863, a decrease of 62.24%, this would represent the closest the equipment could be clustered, not practical in reality, but serves as an initial estimate to aim for.

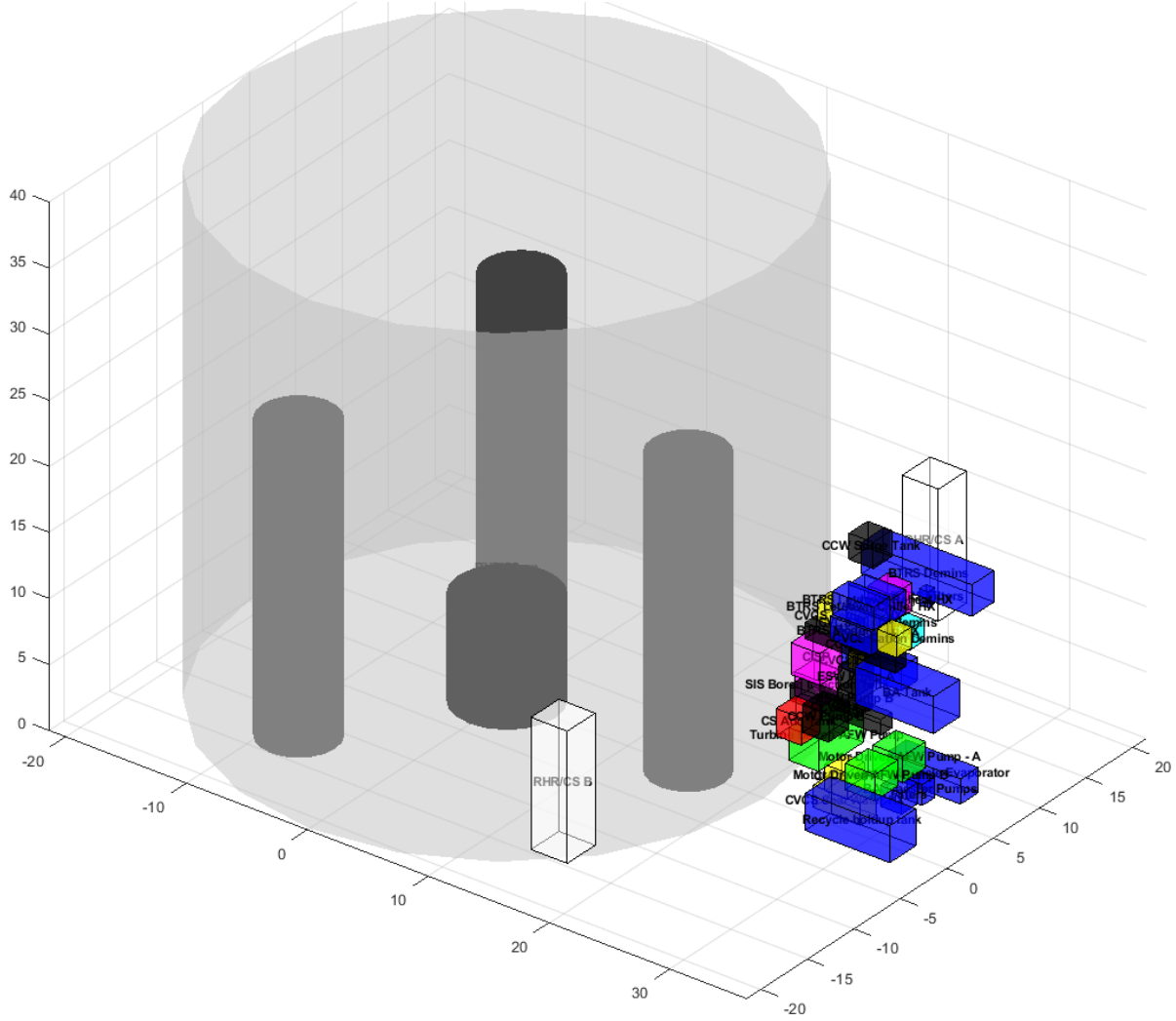


Figure 5-13 - No module boundary constraints comparison

The GA algorithm outputs for the optimisation with no module constraints are seen in Table 5-6.

Output Description	Result Value
Best	9863
Generations	1320
Function count	1849400
Population size	1400, 87

Table 5-6 - GA algorithm outputs for the optimisation with no module constraints

5.2.9 Longitudinal Arrangement with Modules 3m Wide

Figure 5-14 shows the modules arranged longitudinally, the objective function was 10947, a decrease of 58.09%.

	Longitudinal 3m wide			
#		x	y	z
1	ESW Booster Pump A	33.4	0.96	7.9
2	CCW Pump A	31.2	1.17	16.1
3	CCW HX - A	31.2	1.01	9.3
4	CS Additive Tank	27.5	1.14	11.1
5	CCW Pump B	28.2	1.15	13.4
6	CCW HX - B	28.2	-0.65	13.4
7	ESW Booster Pump B	30.1	0.94	13.4
8	Boron Recycle Evaporator	30.5	1.04	3.5
9	Recycle holdup tank	30.4	-1.46	3.5
10	BTRS Letdown Reheat HX	38.9	1.09	9.0
11	BTRS Moderating HX	38.8	-0.92	9.0
12	BTRS Letdown Chiller HX	38.9	1.01	7.3
13	CVCS Seal Water HX	28.4	-0.88	10.9
14	CVCS Letdown HX	32.4	-0.79	10.8
15	Boric Acid Tank	31.9	1.45	21.4
16	Boric Acid Transfer Pumps	30.9	1.42	19.1
17	Boric Acid Filters	30.4	-0.92	20.8
18	BTRS Demineralisers	38.9	1.27	11.2
19	BTRS Filters	40.9	-0.59	9.2
20	CVCS Volume Control Tank	34.9	-0.98	3.9
21	CVCS Filters	32.9	-0.79	5.6
22	CVCS Cation Bed Demins	34.4	-0.89	17.6
23	CVCS Mixed Bed Demins	41.8	-0.80	9.1
24	Chillers	32.0	-0.93	15.9
25	sampling	31.1	0.95	11.0
26	CISP	25.6	1.27	3.7
27	Gross Failed Fuel Detector	36.2	-1.09	16.1
28	SIS Boron Injection Tank	25.4	0.02	11.1
29	CCW Surge Tank	27.6	1.18	21.0

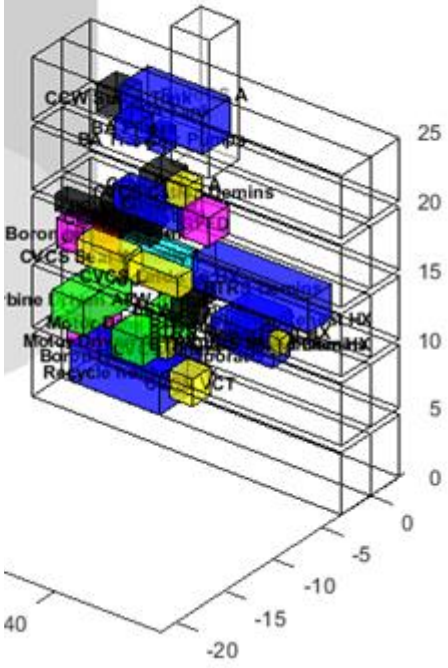


Figure 5-14 - Longitudinal arrangement with modules 3m wide layout and equipment locations

The GA algorithm optimisation outputs for the longitudinal arrangement with modules 3m wide are seen in Table 5-7.

Output Description	**Result Value**
Best	10947
Generations	497
Funccount	4980000

Table 5-7 - GA algorithm outputs for the longitudinal arrangement with modules 3m wide optimisation

5.2.10 Longitudinal Arrangement with Modules 5m Wide

Figure 5-15 shows a longitudinal arrangement with modules 5m wide layout and equipment locations. The objective function was calculated as 11170.

	Longitudinal 3m wide			
#		x	y	z
1	ESW Booster Pump A	31.5	0.02	10.8
2	CCW Pump A	34.5	0.02	21.1
3	CCW HX - A	31.5	0.01	9.3
4	CS Additive Tank	27.5	0	11
5	CCW Pump B	41.1	1.08	12.3
6	CCW HX - B	33.2	0.75	12.3
7	ESW Booster Pump B	33.2	0.75	10.8
8	Boron Recycle Evaporator	39.4	0.65	23
9	Recycle holdup tank	39.4	0.65	3.5
10	BTRS Letdown Reheat HX	37	-0.7	12
11	BTRS Moderating HX	42.4	-0.2	15.9
12	BTRS Letdown Chiller HX	37.6	-0.5	14
13	CVCS Seal Water HX	40.7	0.01	9.07
14	CVCS Letdown HX	32.4	1.35	9.16
15	Boric Acid Tank	37.4	0	18
16	Boric Acid Transfer Pumps	39.4	0.64	11.8
17	Boric Acid Filters	39.4	0.65	5.8
18	BTRS Demineralisers	43.3	-1.2	12
19	BTRS Filters	43.1	1.07	15.9
20	CVCS Volume Control Tank	33.3	0.02	16
21	CVCS Filters	34.6	0.02	15.6
22	CVCS Cation Bed Demins	39.8	0.93	15.8
23	CVCS Mixed Bed Demins	33.1	0.67	7.83
24	Chillers	36.2	0.67	7.55
25	sampling	30	0.32	15.8
26	CISP	25.6	0	3.71
27	Gross Failed Fuel Detector	32.4	0.75	21
28	SIS Boron Injection Tank	25.4	0	11
29	CCW Surge Tank	40.2	0.86	21

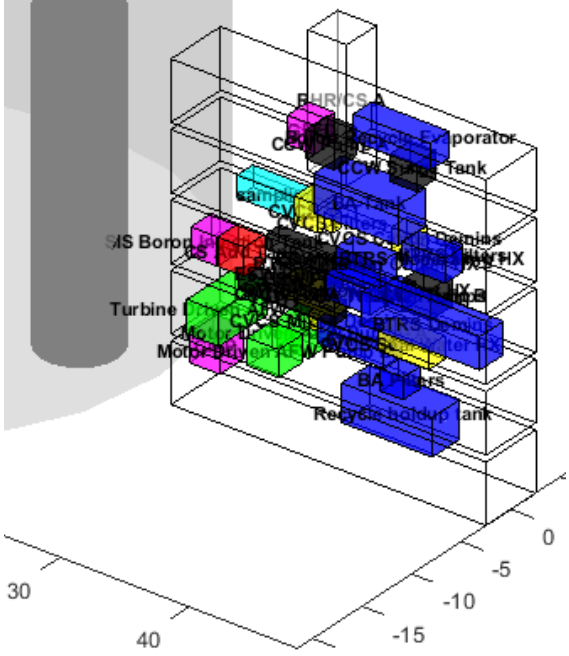


Figure 5-15 - Longitudinal arrangement with modules 5m wide layout and equipment locations

The GA algorithm outputs for the longitudinal arrangement with modules 5m wide optimisation are seen in Table 5-8.

Output Description	**Result Value**
Best	11170
Generations	1059
Funccount	10600000

Table 5-8 - GA algorithm outputs for the longitudinal arrangement with modules 5m wide optimisation

5.2.11 Latitudinal Arrangement with Modules 3m Wide

Figure 5-16 shows a latitudinal arrangement with modules 3m wide layout and equipment locations. The objective function was calculated as 11994.

	Latitudinal 3m wide			
#		x	**y**	**z**
1	ESW Booster Pump A	28.30	-0.17	15.9
2	CCW Pump A	28.52	0.00	21.1
3	CCW HX - A	28.30	0.00	17.3
4	CS Additive Tank	28.48	2.52	3.9
5	CCW Pump B	26.00	0.10	3.8
6	CCW HX - B	26.00	0.00	9.3
7	ESW Booster Pump B	26.41	-3.57	7.9
8	Boron Recycle Evaporator	28.40	5.48	21.0
9	Recycle holdup tank	25.95	5.47	3.5
10	BTRS Letdown Reheat HX	28.32	1.16	9.0
11	BTRS Moderating HX	28.38	-2.90	11.1
12	BTRS Letdown Chiller HX	26.48	-3.57	11.0
13	CVCS Seal Water HX	26.23	-2.92	4.1
14	CVCS Letdown HX	28.20	2.61	15.7
15	Boric Acid Tank	28.86	6.12	8.5
16	Boric Acid Transfer Pumps	28.63	5.67	6.3
17	Boric Acid Filters	26.48	5.47	6.3
18	BTRS Demineralisers	28.65	5.75	11.2
19	BTRS Filters	28.62	-2.28	4.3
20	CVCS Volume Control Tank	26.42	-0.94	11.0
21	CVCS Filters	28.21	-0.94	4.3
22	CVCS Cation Bed Demins	28.32	-1.84	15.8
23	CVCS Mixed Bed Demins	28.32	-3.11	15.7
24	Chillers	26.45	-2.98	15.9
25	sampling	26.19	1.97	16.0
26	CISP	28.64	0.00	11.2
27	Gross Failed Fuel Detector	26.32	-5.44	8.9
28	SIS Boron Injection Tank	28.48	0.45	3.9
29	CCW Surge Tank	26.39	0.02	21.0

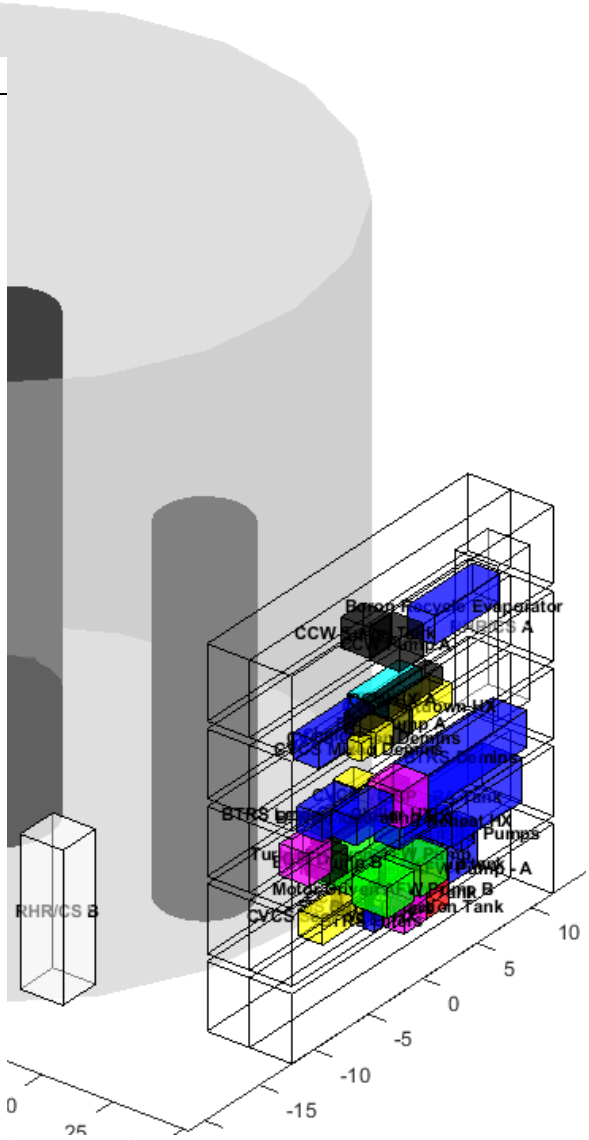


Figure 5-16 - Latitudinal arrangement with modules 3m wide layout and equipment locations

The GA algorithm outputs for the latitudinal arrangement with modules 3m wide optimisation are shown in Table 5-9.

Output Description	**Result Value**
Best	11994
Generations	769
Funccount	7700000

Table 5-9 - GA algorithm outputs for the latitudinal arrangement with modules 3m wide optimisation

5.2.12 Latitudinal Arrangement with Modules 5m Wide

Figure 5-17 shows a latitudinal arrangement with modules 5m wide layout and equipment locations. The objective function was calculated as 10920.

	Latitudinal 5m wide			
#		x	y	z
1	ESW Booster Pump A	26.40	1.32	9.1
2	CCW Pump A	25.71	1.32	21.1
3	CCW HX - A	25.71	1.32	10.6
4	CS Additive Tank	27.51	0.00	11.0
5	CCW Pump B	25.47	-2.10	12.3
6	CCW HX - B	25.29	0.00	4.3
7	ESW Booster Pump B	27.06	3.58	6.0
8	Boron Recycle Evaporator	25.82	1.00	18.5
9	Recycle holdup tank	25.82	7.48	18.5
10	BTRS Letdown Reheat HX	28.26	3.09	4.0
11	BTRS Moderating HX	26.14	3.09	12.1
12	BTRS Letdown Chiller HX	28.25	3.09	8.9
13	CVCS Seal Water HX	25.51	0.00	2.6
14	CVCS Letdown HX	26.62	0.03	4.2
15	Boric Acid Tank	25.80	-5.99	8.5
16	Boric Acid Transfer Pumps	25.81	6.24	13.5
17	Boric Acid Filters	25.82	6.25	20.8
18	BTRS Demineralisers	28.21	3.09	13.3
19	BTRS Filters	27.74	3.09	15.6
20	CVCS Volume Control Tank	26.81	-3.56	3.9
21	CVCS Filters	26.62	-2.27	4.2
22	CVCS Cation Bed Demins	26.59	4.53	4.1
23	CVCS Mixed Bed Demins	26.55	2.56	4.3
24	Chillers	26.63	3.55	23.0
25	sampling	25.43	5.12	5.8
26	CISP	25.60	3.93	8.7
27	Gross Failed Fuel Detector	25.71	3.43	21.0
28	SIS Boron Injection Tank	25.44	0.00	12.2
29	CCW Surge Tank	25.50	-1.34	21.0

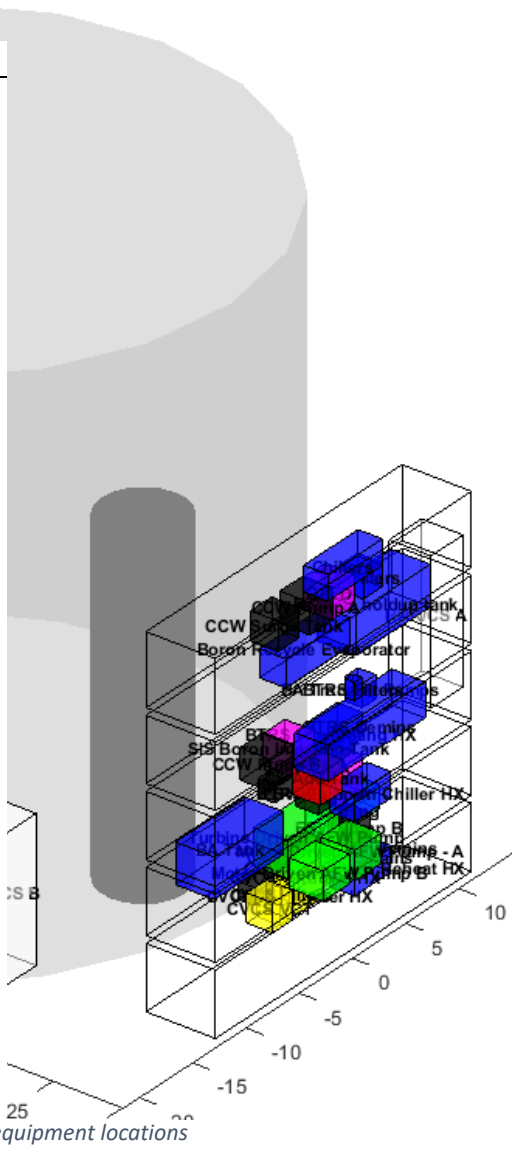


Figure 5-17 - Latitudinal arrangement with modules 5m wide layout and equipment locations

The GA algorithm outputs for the latitudinal arrangement with modules 5m wide optimisation are seen in Table 5-10.

Output Description	**Result Value**
Best	10920
Generations	1037
Funccount	10380000

Table 5-10 - GA algorithm outputs for the latitudinal arrangement with modules 5m wide optimisation

5.2.13 Genetic Algorithm Soft Constraints Conclusions

The results of the four optimisations in Figures 8-11-14, show a small variation in objective function, i.e. the pipe lengths optimise to similar results in all situations, this shows further factors could be considered within the objective function such as reducing the number of modules.

5.3 Equipment to Module Allocation Results (Model Bii)

The novel extended *Model (Bii)* considers allocation of equipment to modules utilising MATLAB's intlinprog, mixed- integer linear programming solver. Instead of considering non-overlapping as soft constrains in the genetic algorithm function, in *Model (Bii)*, the constraints are coded as hard constraints within the linear programming constraints format of A, b, Aeq and beq matrices (Mathworks, 2020b) and constraints. Latitudinal and longitudinal arrangements with 3m and 5m modules were considered, similar to the genetic algorithm arrangements. The pipework for the original (Lapp, 1989) plant amounted to 15099.

5.3.1 Latitudinal 3m Arrangement Model Bii

The 3m wide latitudinal arrangement in Figure 5-18 occupied 7 modules and the pipework objective score was 2949. The model was solved to a gap tolerance of 42.4% in 481s and 42.2% in 1800s.

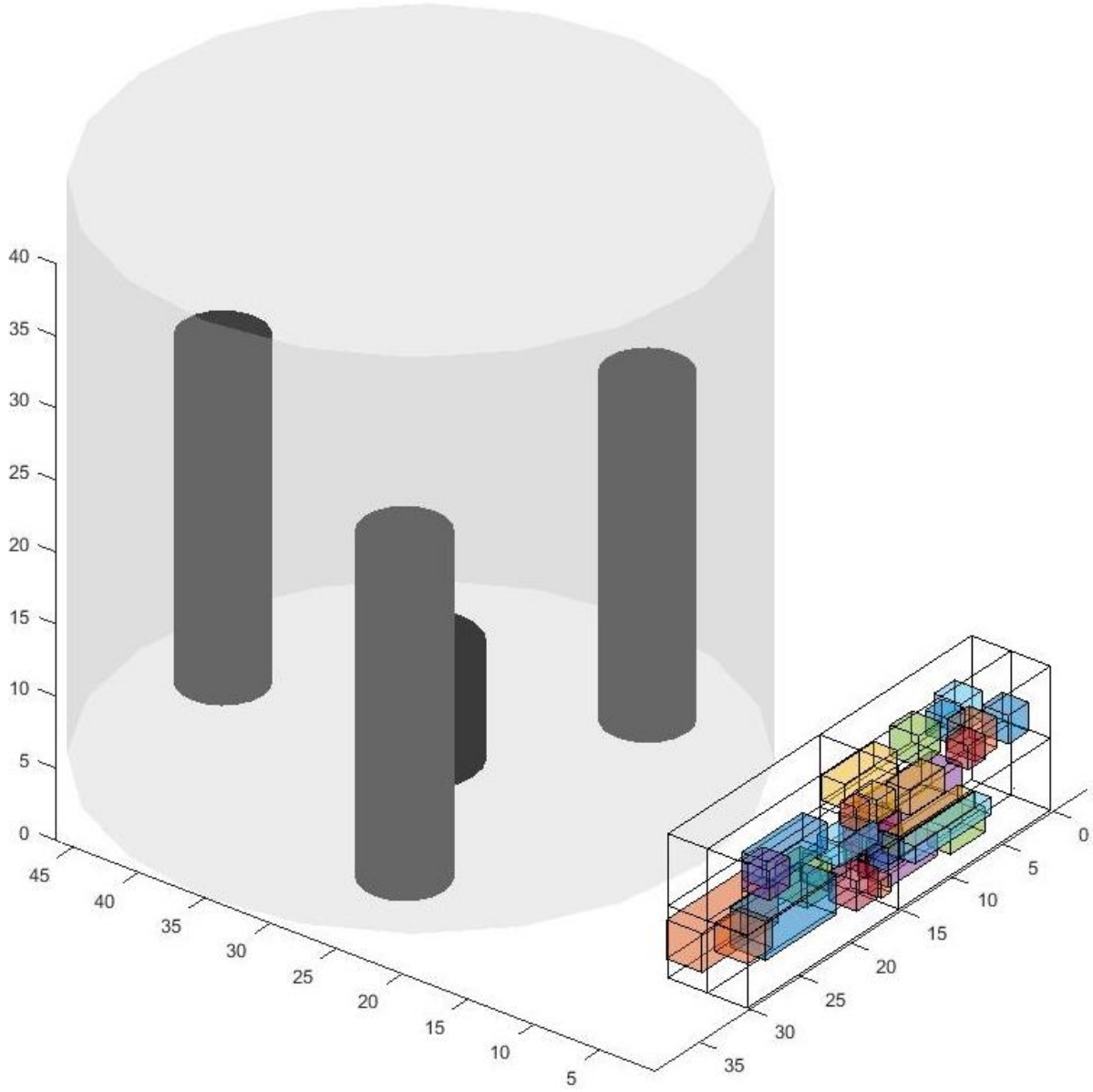


Figure 5-18 – 3m wide latitudinal arrangement for the 29 equipment item model Bii arrangement

The equipment locations and module locations for 3m wide latitudinal arrangement *Model (Bii)* can be seen in Table 5-11.

#	Latitudinal 3m arrangement				Latitudinal 5m arrangement			
	X (m)	Y (m)	Z (m)	R (m)	X (m)	Y (m)	Z (m)	R (m)
1	3.84	4.84	6.67	E	6.98	4.91	3.67	N
2	1.73	4.33	6.07	W	6.74	1.07	3.31	N
3	2.20	6.03	2.50	W	8.51	5.94	3.73	W
4	1.03	25.74	6.45	N	3.97	33.87	1.23	W
5	4.07	6.90	6.07	S	6.74	4.73	1.66	N
6	0.91	6.03	2.50	W	8.51	6.03	2.44	W
7	0.83	6.67	6.67	W	6.98	6.74	2.78	W
8	1.85	20.97	6.55	W	5.95	23.81	3.55	W
9	4.35	22.59	1.35	W	8.63	23.71	3.12	W
10	1.93	9.31	5.13	W	6.94	14.61	3.36	W
11	3.87	10.94	1.05	E	8.78	15.30	2.05	E
12	1.56	5.74	0.93	W	8.78	6.41	0.87	E
13	1.83	15.95	4.83	W	8.11	21.90	0.83	W
14	3.74	11.18	2.76	E	8.65	14.30	3.76	E
15	1.35	20.73	2.15	W	3.65	24.08	2.44	W
16	1.80	16.85	6.56	N	6.36	19.45	2.96	E
17	1.40	14.87	6.56	N	4.13	19.61	3.28	N
18	4.19	4.57	1.85	E	6.62	12.24	1.19	E
19	5.44	13.10	1.15	N	5.36	18.36	0.60	W
20	4.80	15.29	0.99	S	9.07	18.93	0.99	S
21	3.36	14.36	1.30	S	7.27	18.36	1.30	W
22	2.01	13.21	2.17	N	7.02	17.21	3.28	N
23	2.02	14.49	0.60	W	9.52	20.80	0.60	W
24	3.87	11.44	6.63	W	6.94	10.23	3.36	W
25	2.00	9.93	1.01	W	8.70	10.60	0.95	W
26	4.19	17.55	1.19	S	3.81	19.29	1.19	W
27	4.03	2.83	6.47	E	8.97	1.08	3.47	E
28	1.77	16.10	1.03	W	6.15	20.10	1.03	W
29	1.00	2.17	6.49	N	5.99	2.17	1.15	N
30	1.57	26.77	2.51	S	6.23	32.87	1.29	W
31	35.0	14.10	0.10	N	35.0	18.10	0.10	E
32	2.10	2.10	2.10	N	9.10	2.10	2.10	W
33	5.10	27.10	2.10	W	4.10	35.10	2.10	E

Table 5-11 – Equipment locations for Model (Bii) Latitudinal arrangements

5.3.2 Latitudinal 5m Arrangement Model Bii

The 5m wide latitudinal arrangement in Figure 5-19 occupied 3 modules and the pipework objective score was 3837. The model was solved to a gap tolerance of 0.54% in 1800s.

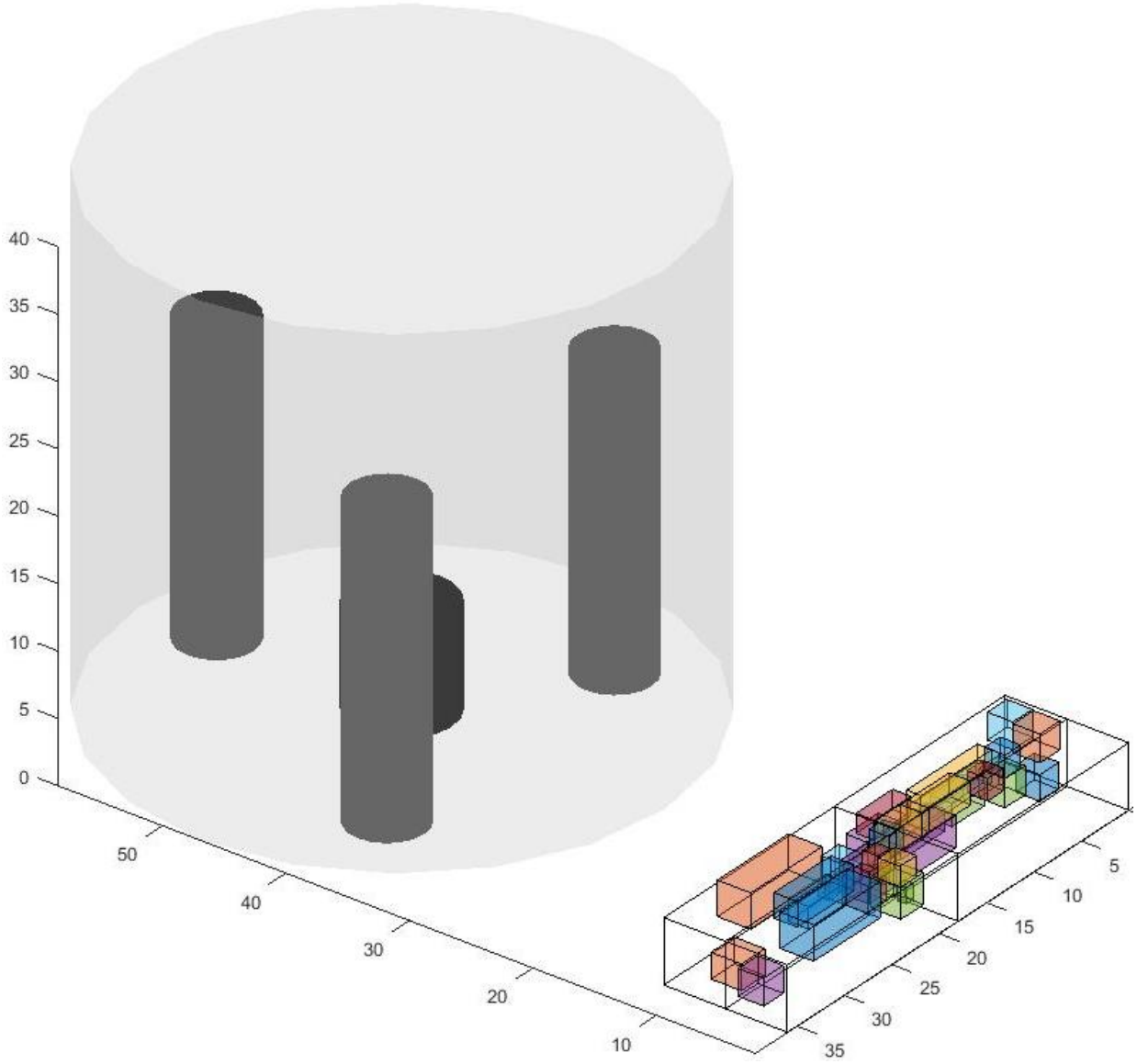


Figure 5-19 – 5m wide latitudinal arrangement for the 29 equipment item Model (Bii) arrangement

The equipment locations and module locations are found in Table 5-11. The highly connected equipment is clustered around the centre of the module, close to where the pipe run to the nuclear island is located and the less connected equipment is dispersed to the further edges of the module.

5.3.3 Longitudinal 3m wide Arrangement Model Bii

The 3m wide longitudinal arrangement in Figure 5-20 occupied 6 modules The pipework objective score was 3317 in 4912s at a gap tolerance of 32.2%. The pipework objective score was reduced to 3205 in 14000s with a gap tolerance of 32.12%.

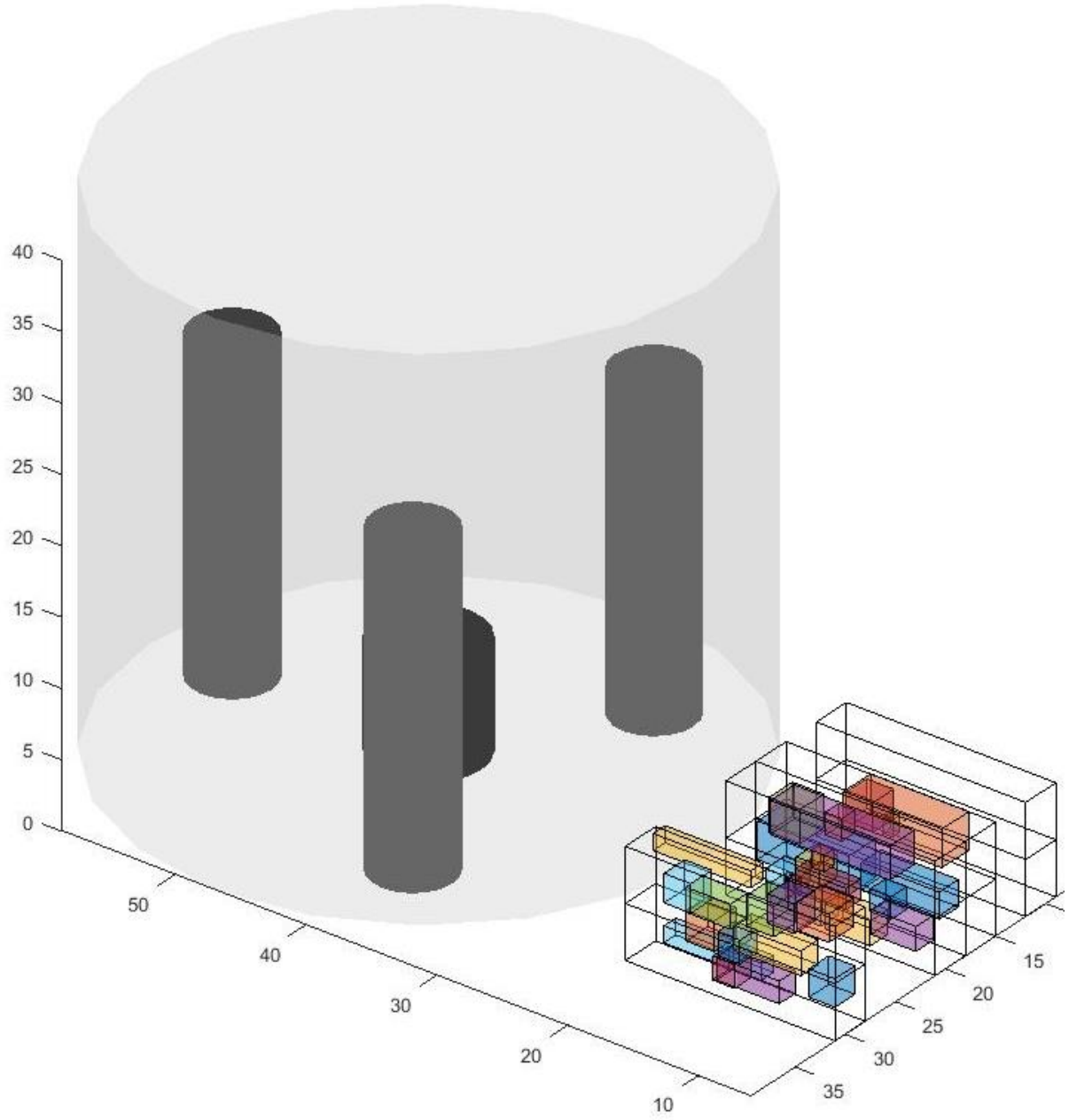


Figure 5-20 – 3m wide latitudinal arrangement for the 29 equipment item Model (Bii) arrangement

The equipment locations and module locations are found in Table 5-12. Equipment is clustered close to the Centrepoint, where the connection to the nuclear island is located. This configuration may be less efficient than a latitudinal arrangement as cross module connections would have to cross the access passage, doubling the amount of connections required.

#	Longitudinal 3m arrangement				Longitudinal 5m arrangement			
	x	y	z	R	x	y	z	R
1	13.49	29.03	2.60	W	12.36	25.12	1.50	W
2	15.83	28.07	2.43	N	16.13	26.29	3.31	W
3	14.13	27.60	6.84	N	13.17	23.60	2.22	N
4	9.05	28.97	6.45	W	16.97	19.01	3.38	E
5	11.25	28.07	5.07	N	16.13	25.37	1.07	S
6	13.30	27.60	0.66	N	13.83	23.60	0.93	N
7	13.82	29.12	0.83	W	14.12	25.12	0.83	W
8	7.27	17.05	2.55	N	9.23	19.25	3.55	N
9	11.38	10.65	2.15	N	11.01	11.65	3.15	N
10	10.32	20.12	0.94	N	7.87	25.72	1.07	N
11	6.81	20.12	1.79	N	10.55	26.06	1.46	W
12	14.13	29.07	4.87	S	13.25	26.93	0.87	S
13	14.08	20.16	0.98	N	13.79	18.56	3.67	W
14	12.25	20.26	2.76	N	14.22	24.95	3.65	W
15	13.85	16.65	2.15	N	8.96	16.85	2.26	N
16	13.98	18.64	6.09	N	11.57	19.87	1.70	W
17	15.17	18.87	2.71	N	9.96	19.17	1.50	N
18	8.57	19.81	6.31	N	4.57	25.88	3.24	N
19	17.64	9.36	0.60	N	0.36	15.86	0.60	E
20	17.07	19.20	0.99	E	13.23	19.23	1.74	N
21	16.48	20.64	1.82	E	15.31	20.14	2.94	S
22	9.41	19.40	2.71	N	12.58	24.26	3.71	S
23	14.14	20.52	4.60	N	16.52	16.03	3.89	S
24	9.66	27.87	2.63	N	6.77	23.87	0.87	N
25	10.51	29.08	0.86	N	9.31	23.79	3.71	N
26	15.91	19.19	6.00	N	15.91	16.69	2.00	N
27	16.97	28.97	5.10	S	12.35	26.19	3.47	W
28	16.97	10.85	2.47	E	13.59	16.91	1.03	N
29	6.00	29.01	2.35	N	10.22	26.15	3.51	W
30	6.68	28.23	6.51	N	15.67	19.27	1.26	S
31	35.0	11.90	3.40	N	35.0	12.90	4.40	N
32	17.10	28.10	2.10	W	17.10	24.10	2.10	S
33	17.10	20.60	2.10	E	17.10	19.60	2.10	N

	3m Module Locations			5m Module Locations		
1	6	9	0	6	9	0
2	6	15	0	6	17	0
3	6	18	0	6	24	0
4	6	27	0			
5	6	9	4			
6	6	15	4			
7	6	18	4			
8	6	27	4			

Table 5-12 - Equipment locations for Model (Bii) Longitudinal arrangements

5.3.4 Longitudinal 5m Wide Arrangement Model Bii

The 5m wide longitudinal arrangement in Figure 5-21 occupied 3 modules and the pipework objective score was 3246. The model was solved to a gap tolerance of 1.07% in 1800s.

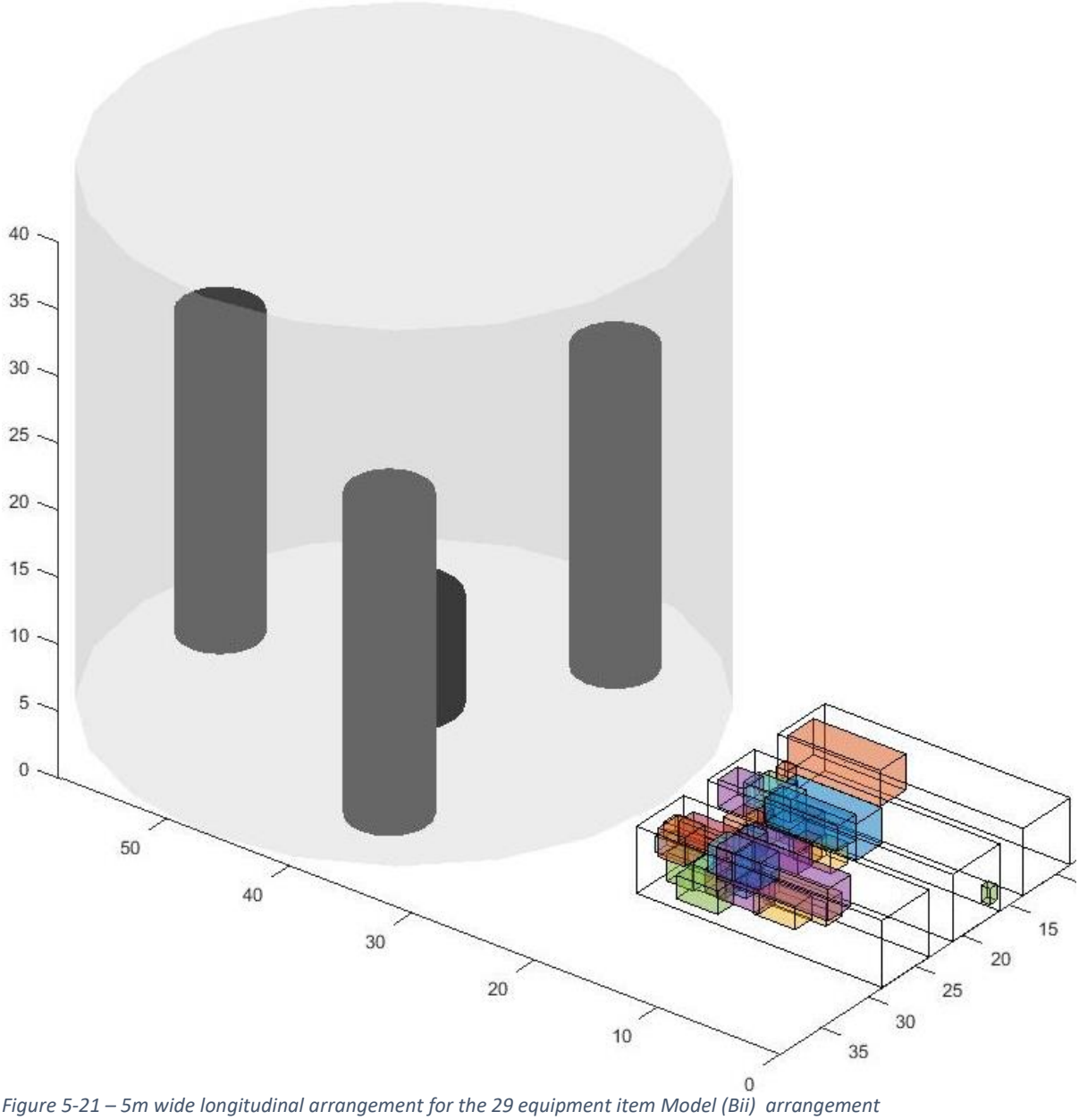


Figure 5-21 – 5m wide longitudinal arrangement for the 29 equipment item Model (Bii) arrangement

The equipment locations and module locations are found in Table 5-12. Equipment is clustered close to the Centrepoint, where the connection to the nuclear island is located. This configuration may be less efficient than a latitudinal arrangement as cross module connections would have to cross the access passage, doubling the amount of connections required.

5.4 Time to Optimality for Large Models

As the model becomes more complex, it is vital to explore how the model behaves as the number of equipment items rises. To determine this, the Watts-Strogatz model for random graph production was utilised (Matlab, 2020). Overall, 32 graphs were randomly produced (4 per value of n = 4, 6, 8, …18). A possibility of rewiring p = 0.7 was utilised, the equipment items and connections were then randomly assigned information within provided limits.

Every individual graph was then provided to *Model (Bi)* and *Model (Bii*) and afforded a time threshold of 600s to achieve a best possible solution utilising Gurobi, averaging the outcomes across every figure of n. The complexity of averaging the concurrent time log data leads to perceptible small differences in the graph where the object or gap seems to deteriorate.

The likelihood of discovering an optimal solution inside a realistic timeframe turns out to be progressively doubtful as the relative gap persists to be elevated for an enlarged number of items. It is evident, however, that the relative gap and objective function cost settle down inside a sufficient period. The results seem to be adequately helpful as an initial beginning point for a plant design specialist. Nevertheless, more costing information and constraints are essential for increasingly detailed design and the time for a reasonable optimal solution needs to be studied further.

5.5 Module Layout Optimisation Results plant design

The Shearon Harris Three Loop Westinghouse PWR was modelled in Bentley PlantWise (Figure 5-22) using the pipeline connections from (LAPP 1989) Appendix 3 and the equipment placements from (LAPP 1989). Once the optimisation provides the location results of the equipment items, they can be updated in the PlantWise model. The Autopipe function can then revise the pipe routing and the engineer can interrogate the solution further.

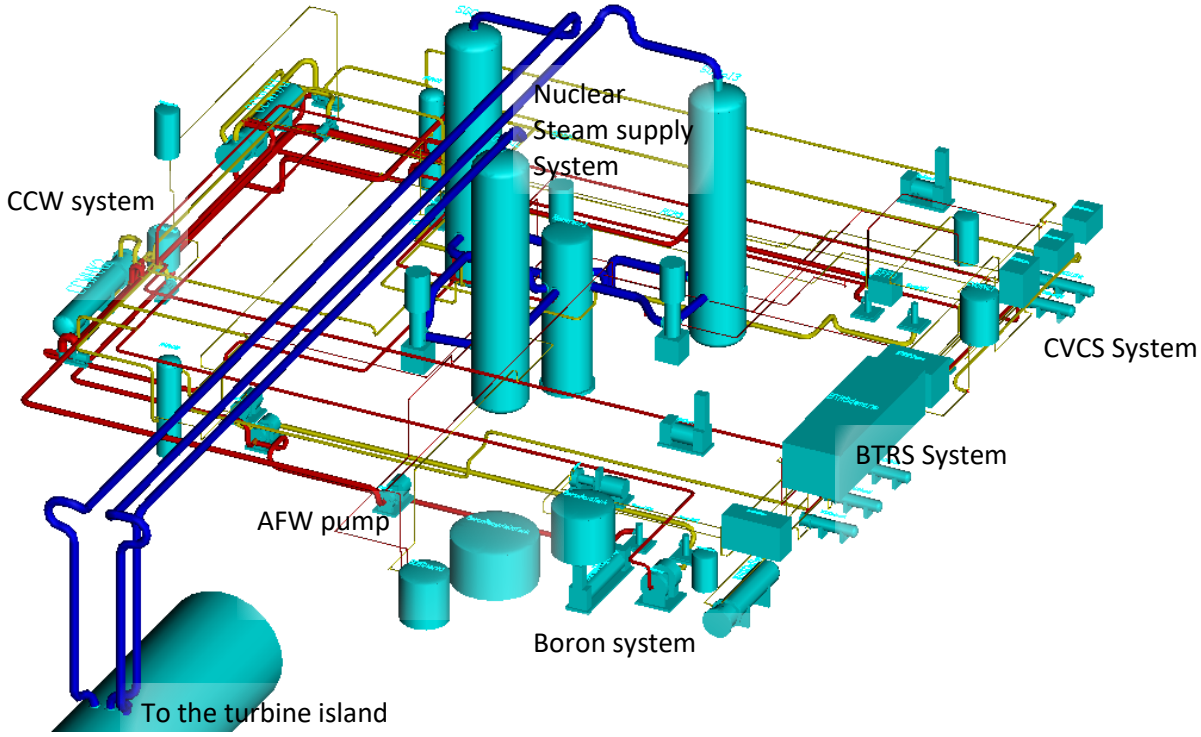


Figure 5-22 – Bentley PlantWise representation of the Shearon Harris on site assembly area plant (top with modules)

The reduction from the original (LAPP 1989) plant piping lengths (Figure 5-22) to the results of the genetic algorithm can be seen in Figure 5-23 and Figure 5-24 showing large reductions in CCW, RHR,SIS and ESW. Figure 5-23 shows the difference in stick-built pipe length between on-site constructed modules and off-site Factory-built modules.

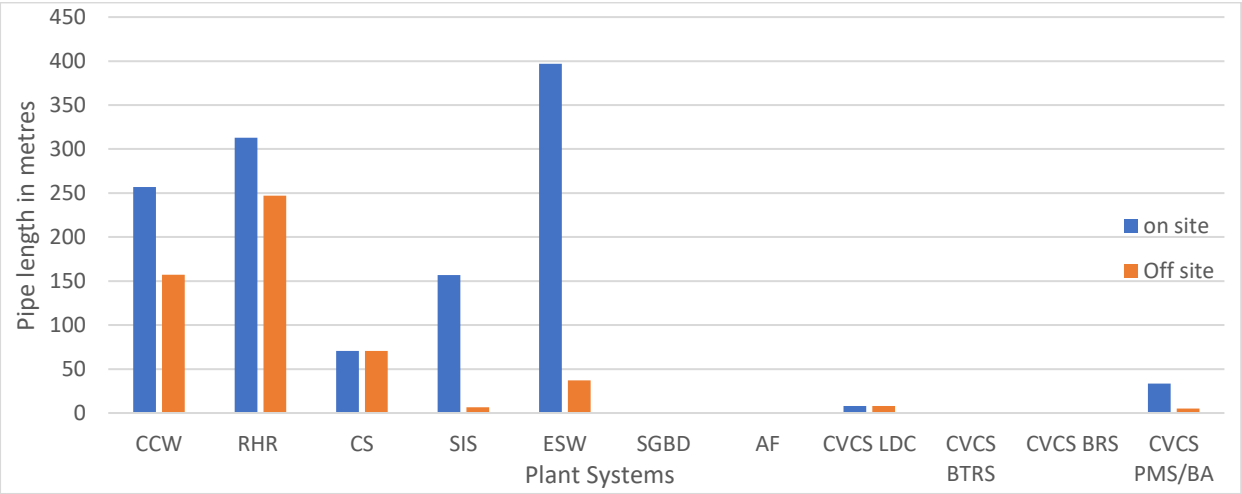


Figure 5-23 - The difference in stick-built pipe length between on-site constructed modules and off site Factory-built modules

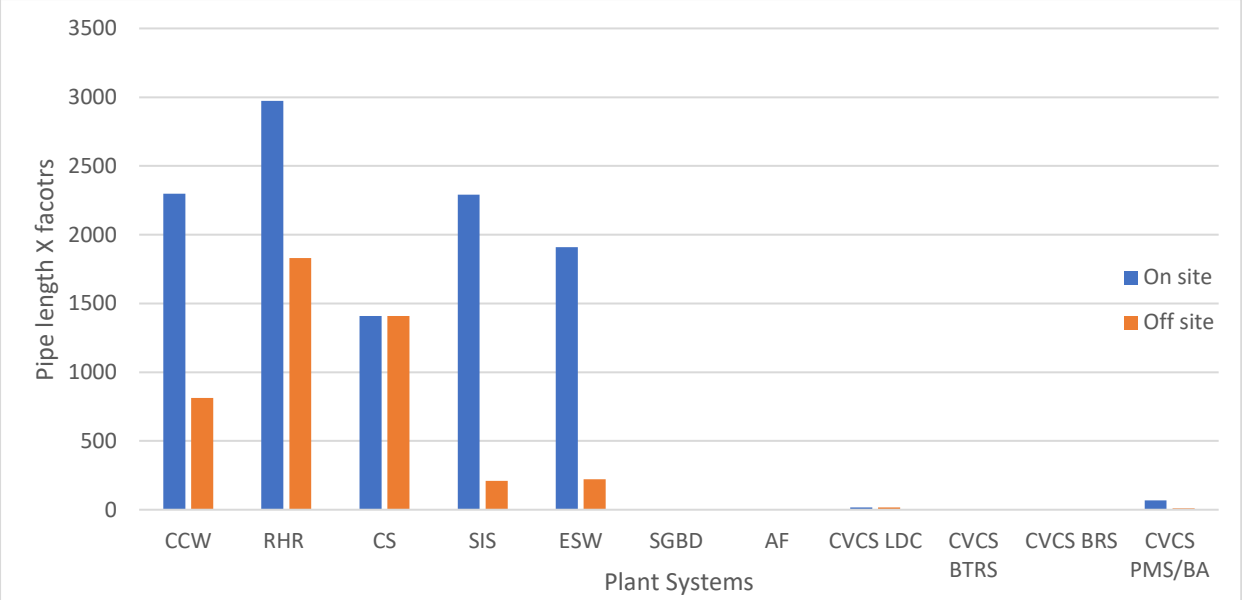


Figure 5-24 - The difference in stick-built pipe "cost" between on-site constructed modules and off-site Factory-built modules

Figure 5-24 shows the difference in stick-built pipe "cost" between on-site constructed modules and off-site Factory-built modules. Figure 5-25 shows the piping being routed circumferentially around the nuclear island containment in the original (LAPP 1989) plant.

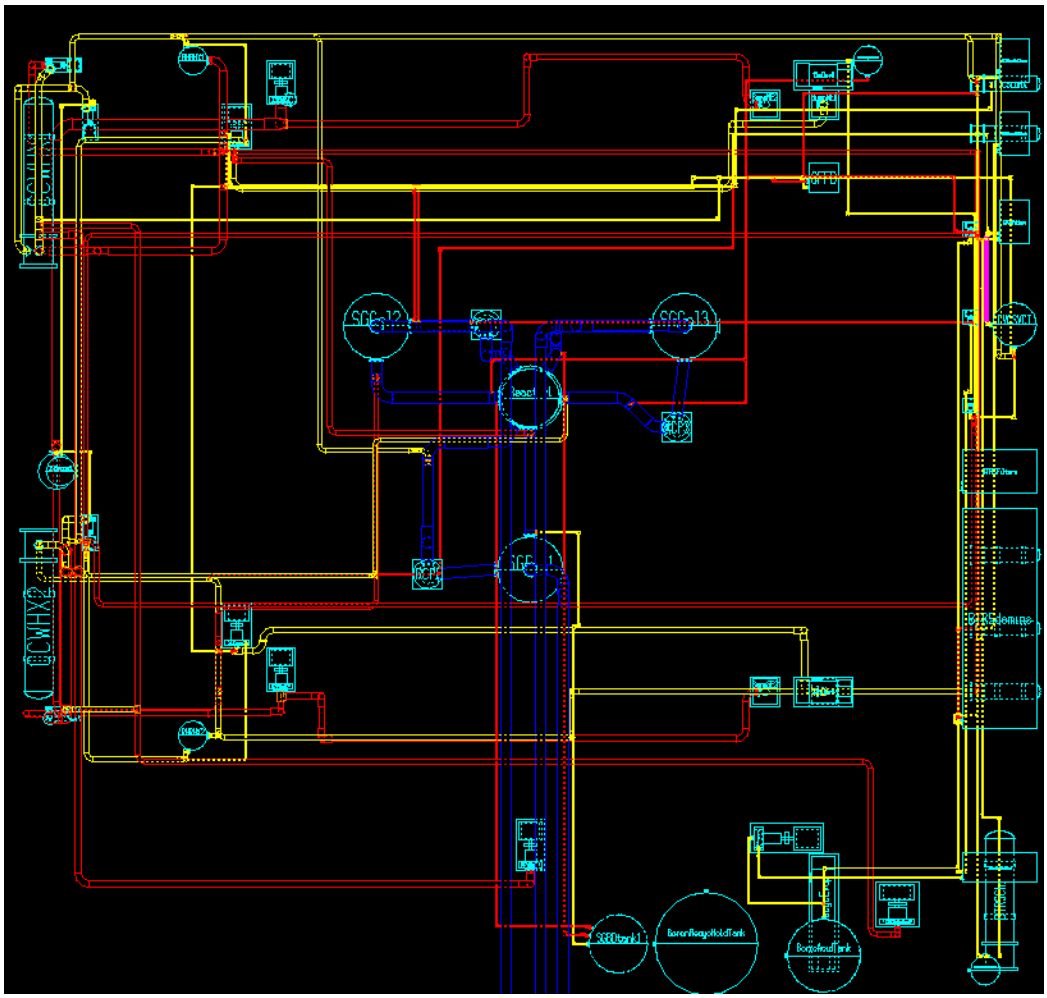


Figure 5-25 – Figure showing AutoRoute pipelines for the Shearon Harris Lapp plant

5.6 General Optimisation Findings

Overall, it was found that a genetic algorithm was much simpler to set up than a MILP model. The MILP formulation must be correct and expert knowledge in this field is required to set up a model and to debug the code. The genetic algorithm can be set up utilising soft constraints within the genetic algorithm function itself. This makes setting up an optimisation easier for beginners and could be accomplished without expert optimisation knowledge. This method could be useful for general engineers to obtain an initial analysis for early plant layout options. As the understanding and detail of a project is progressed, the analysis would have to move to MILP to be more accurate and provide a better solution. However, the genetic algorithm has limitations when utilising soft constraints to separate out equipment into modules as this was considered in the objective function, causing conflicts in some situations with pipe length.

Be developing the model with the systems engineering methodology of decomposing the problem, the model was validated with the smaller models *Model (Bi)* , before expanding to the larger Model (Bii).

5.6.1 Impact on Design Engineering CAD Modelling

It was found that as a design engineer lays out the module, the process is logical, starting from the beginning of the P&ID and working through to the end. By the end of the process, the piping becomes complicated, with multiple returning legs extending back across the module. This layout optimisation tool can be utilised as an initial layout for the design engineer and also for concept engineering studies. As the design becomes more mature and extra requirements are developed, these can be added to the optimisation model. It was established that utilising the existing NX 9 design software, a model could take weeks to design. However, if a small change is required, the model would create numerous errors and must be redesigned from scratch. With the optimisation process and integrated Bentley Plantwise Autopipe routing solution, a design change could be accommodated within minutes rather than days for the current Rolls-Royce Process.

5.7 Limitations of the Study

The study is limited by its data. The only nuclear power plant systems data available publicly is the assembly area on site study (Lapp, 1989). This only provides connections between equipment items and approximate dimensions of equipment items. Nozzle locations have had to be assumed for the optimisation as the data was not available.

5.8 Summary

This section summaries the results of the optimisation models.

5.8.1 Case study 1 – Optimising module locations from previously designed modules

The first case study results from the optimisation of layout of pre-existing module designs reduced the objective function by 46%. This first case study proved that layout optimisation could significantly improve the piping costs of an existing heuristically designed plant. If piping can take up as much as 20% of a process plant capital costs (Moran, 2016a), this would suggest almost 10% could be saved for the whole plant.

5.8.2 Case study 2 – Optimising the layout of equipment within a single module

Section 5.2 outlined the results from the optimisation model considering the layout of equipment within a module, applying non overlapping constraints from Papageorgiou & Rotstein, (1998). The CVCS & BTRS systems were considered. A representation of the (Lapp, 1989) CVCS system was compared to a module designed for on-site assembly.

The total estimated costs for an onsite assembled CVCS system are $364675 to $438835 for piping and welding. However, the total pipe and welding costs for the factory-built CVCS equate to between $112856 and $137576 a saving of 33%. This demonstrated there are significant savings to be attained through the optimal design of equipment layout within a module.

The BTRS system does not fit into one 3m wide module, therefore requiring either a 5m module or two 3m modules. The objective function was reduced from 575m to 85.6m for two 3m wide modules whereas the objective function for one large 5m wide module was 96.1m. It was found that when implementing non-overlapping constraints to divide modules would only work with one divide. Utilising more than one divide would cause erroneous results. A solution would be required through either soft constraints in the genetic algorithm function or introducing a new variable within the MILP.

5.8.3 Soft Constraints Within the Genetic Algorithm Function

Utilising soft constraints within the Genetic Algorithm function enabled more non-overlapping constraints to divide modules. The lowest objective function for the full 29 equipment optimisation was 10920 within 1037 generations for the latitudinal arrangement with modules 5m wide. However, arranging 3m modules longitudinally saw an objective function of 10947 within 497 generations, a decrease of 58.1% from the original plant.

Longitudinal arrangement with modules 5m wide layout saw an objective function of 11170 within 1059 generations, whereas the latitudinal 3m arrangement objective function was 11994 in 769

generations. Generations ranged from 497 to 1059. The results of the four optimisations in Figures 8-11-14, show a small variation in objective function. This shows much more emphasis needs to be placed on equipment to module allocation.

5.8.4 Case study 3 – Assigning Equipment to Modules and Module Cost (Model Bii)

The novel optimisation *Model (Bii)* was developed to introduce multiple module equipment allocation constraints. In this case study, the previous model was extended to consider assigning equipment to modules. The model was extended with the variable $m_{vk,}$ to consider if an item v is in module k. The equipment was optimised into three 5m wide modules, with objective functions of 3837 for the latitudinal arrangement and 3246 for the longitudinal arrangements. For the 3m wide modules, the latitudinal arrangement pipework objective score was 2949 in 7 modules. The longitudinal arrangement model was solved to 3205 in 6 modules. The results show that *Model (Bii)* can effectively reduce the number of modules by packaging equipment more efficiently. This would mean there would be less connections required to be completed on site, reducing costs.

5.8.5 Optimisation output link with Plant Design Software

Linking the optimisation output with Plant Design Software provides an early estimate for concept engineering studies to enable the design team to understand and learn from changing different parameters. As the model is developed, more constraints and knowledge can be included.

The Bentley Plantwise model can be easily revised to include the new equipment positional information and updated with the Bentley AutoRoute function to further enhance engineering studies. In this environment, manufacturing and assembly, operators, maintenance engineers, human factors and safety personnel can interrogate the design to ensure it meets their requirements. The optimisation model can then be updated with additional information in an iterative process.
The new updated process was compared to the current process at Rolls-Royce. Large time savings were realised when updating the model.

6 CHAPTER 6
Conclusions, Major Findings, Recommendations and Future Work

Modularisation is concerned with the breaking down of complex systems. In construction, modularisation is utilised to move work off the critical path to off-site areas to improve efficiency in cost and schedule as productivity is higher in factories or in on-site assembly areas. This is due to factors such as better tools, environment, training or management.

The aim of this Applied Research Programme was to develop an efficient and effective analysis tool for modularisation in industrial plant systems. Specifically focusing on modularisation of Small Modular Nuclear Reactor systems but the process could also be applied to the wider industrial plant industry.

The objectives were to understand the state of the art in modular construction and automating design through a literature review. The literature review in this thesis highlighted that automating earlier parts of the plant design process have been researched (equipment databases, selection tools and modular P&IDs) in modular industrial process plants; however, 3D layout has not been studied. It was also found that layout optimisation for industrial process plants has not considered modularisation.

It was therefore proposed to develop and investigate a novel mathematical layout optimisation model for modularisation of industrial plant systems, by employing the systems engineering technique of decomposing the problem into three parts. The method was developed then demonstrated on publicly available nuclear power plant data creating new knowledge and data in the process.

The second objective was to investigate the factors around modularisation.

6.1 Conclusions and Major Findings

6.1.1 Objective 1 - Understand the State of the Art in Modular Design and Construction

The first objective for the Applied Research Programme was to understand the state of the art in modularisation in nuclear power and plant design by conducting a systematic literature review (Section 2.3). This included analysing what to modularise in a nuclear plant. It was established that only a few research articles have studied modularisation in nuclear power outside of an integrated nuclear steam supply system, but mostly focused on locating singular equipment items in individual modules (Stone & Webster Engineering Corporation, 1977) (Kadak & Berte, 2006) or heuristically assigning highly linked equipment to module areas (Lapp, 1989). The matrix reordering method from (Lapp, 1989) is discussed.

Knowledge based engineering, the technique of automating parts of the design process, was analysed as a tool for aiding modularisation. It was discovered that current KBE technologies could automate equipment design such as heat exchangers, tanks, pressure vessels and pump modules (P. Wrigley et al., 2019). However, 3D plant design would require level 4 “Innovative” Knowledge based engineering involving exploring a larger search space with artificial intelligence.

Some research has been conducted into earlier stages of the modular industrial plant design process in the past ten years but not considering 3D layout design. Other automation construction techniques were highlighted that may be developed for further research in nuclear power plant design.

6.1.2 Objective 2 & 3 - Propose a Method for Modular Plant Sub-Division

The data for the Applied Research Programme and case studies utilised in this thesis is obtained from the previous on-site assembly method study (Lapp, 1989). It is outlined in Appendix C - Equipment data and Assumptions. This data was utilised to analyse the equipment sizes for transport. It was found that some equipment may be too large for the transport envelope and may need redesigning. There are options for different size limits of road transport depending on restrictions on logistics and planning. The larger the size, more planning and logistics are required. More logistical analysis would be required to consider which option might be best for an SMR.

The third objective was to propose a method for analysing modular industrial plants (Thesis Chapter 3). The literature review highlighted industrial plant mathematical layout optimisation has not considered modularisation. The proposal was therefore to develop a novel layout optimisation method for modularisation in off-site factory built industrial plant systems.

6.1.3 Objective 4 - Novel Layout Optimisation Method outline and Effectiveness

A novel method for aiding in the design process of modular process plants and integration with the wider plant design framework was developed using mathematical layout optimisation. A Systems Engineering approach was taken to decompose the problem to build up the capability and verify the models. The method for the layout optimisation model and novel extension Model (Bii) for offsite modular plants is described in Chapter 4. The model is split into 3 formulations:

1. Develop a method to arrange previously designed modules from (Lapp, 1989) (section 4.1) *Model (A).*
2. Develop a method to layout components in modules (section 4.2) Model (Bii).
3. Develop a method to allocate equipment items into modules (section 4.2) Model (Bii) extension.

The case studies built up the required capability for the optimisation.

The first case study outlined is an improvement to a previous modular design (Lapp, 1989) utilising the heuristically designs modules, a layout optimisation method was developed to arrange the plant modules into a standardised grid. Instead of the connected piping systems being installed around the containment, which is manually labour intensive, a more compact plant reduces work on-site, this reduced the objective function by 46%. This first case study proved that layout optimisation could significantly improve the piping costs of an existing heuristically designed plant. If piping can take up as much as 20% of a process plant capital costs (Moran, 2016a), this would suggest almost 10% could be saved for the whole plant, creating new knowledge and data in the process.

The second case study was to introduce non overlapping constraints to analyse the layout of equipment in a module. The CVCS and BTRS systems were utilised and the optimisation provided a saving of 67.6% in piping and installation costs compared to the previous design and a further 66% saving in welding costs. The BTRS System produced 85.1% reduction in pipe and installation costs. The model validated the optimisation model and showed the optimisation could reduce the objective function compared to previous designs, creating new knowledge and data in the process.

The third case study was developed to introduce assigning equipment to multiple modules. The objective was to reduce pipe length and reduce the number of modules used. The results showed a significant reduction in pipework and installation costs compared the original layout (Lapp, 1989) and also that the number of modules could be reduced, creating new knowledge and data in the process. The model also showed how different configurations of modules could be considered.

The optimisation output was integrated with Plant Design Software, automatically updating the equipment locations and pipe routing, providing an early estimate for concept engineering studies to enable the design team to understand and learn from changing different parameters. As the model is developed, more constraints and knowledge can be included (Figure 3-3). The new updated process was compared to the current process at Rolls-Royce where large time savings were realised when updating the model, showing a new design process framework could be highly efficient for modular industrial plant design.

6.2 Contribution to Knowledge

The following contributions to knowledge are presented in this thesis:

A literature review into modularisation in nuclear power, industrial process plants and off-site manufacture was conducted. The knowledge gap highlighted the need for a novel layout optimisation model for modularising industrial plant systems into modules designed for off-site manufacture and transport.

Optimisation *Model (A)* considered the rearrangement of modules from the (Lapp, 1989) producing a new, more efficient layout in a standardised grid reducing pipework by 46%, compared to the old layout, creating new knowledge and new data.

The second *Model (Bi)* validated the model with a smaller number of equipment. It showed reductions in pipe cost and installation compared the previous designs in (Lapp, 1989), creating new data and knowledge in the process.

A novel layout optimisation Model (Bii) was developed and defined to consider allocation of equipment to modules. The novel layout optimisation model was tested on nuclear plant system data. Cost reductions in piping, connections and the number of modules utilised were realised, creating new knowledge and new data and verifying the usefulness of the model.

Furthermore, the link to plant design does not seem to be considered in layout optimisation research literature. Objective 3d was to investigate this an compare the new proposed process with the current design process at Rolls-Royce. It was found that the new process is much more efficient and could produce improved results. Itis a useful feature to quickly explore concepts with the design engineers

6.3 Limitations

The study is limited by its publicly available data (Lapp, 1989) which only providing connections between equipment items and approximate dimensions of equipment items. Nozzle locations have had to be assumed for the optimisation as the data was not available. Furthermore, also noted is a lack of a qualified layout design engineer to advise on suitable and good quality layouts for the results of the optimisation.

Generation IV International Forum, (2007) suggests piping is a magnitude more expensive than structural steel. This implies installing variable platforms heights to reduce pipe bends and distance would be more economic than fixing items to the floor (constrained z axis) or on a platform and creating more complicated pipework.

6.4 Future Work

The author whilst laying important and original contributions in this field recognises the need for further research as follows:-

1. A layout optimisation model can increase in complexity (fidelity) expanding to include new features and requirements as they are developed. As a project is developed, more constraints and knowledge can be included to improve the design optimisation further.
2. More research is required on logistics, transportation, planning and scheduling to understand what module size might be optimum for an SMR.
3. Further investigation into the trade-off between pipework and structural steel, would it be more efficient to fix items to the floor, or build platforms for the equipment to reduce pipework, bends and welding.
4. Further studies can be performed on the time taken to achieve optimality and the detail required for design engineers. Is a further less complex model or simulation required or useful?
5. A more detailed study could be performed on the time efficiency savings with the optimisation model and design engineering interaction compared to a manual design process.
6. This fidelity could include the development of an automated link with plant design software, rather than the manual excel location data import, to iterate with plant design software design analysis output features to improve the optimisation further.
7. The Bentley Plantwise model can be easily revised to include the new equipment positional information and updated with the Bentley AutoRoute function to further enhance engineering studies. In this environment, manufacturing and assembly, operators, maintenance engineers, human factors and safety personnel can interrogate the design to ensure it meets their requirements. The optimisation model can then be updated with additional information in an iterative process

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Appendix A – Literature search papers and method

	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 & Berte, 2006)	X			
(Carelli et al., 2010)	X			
(Lu et al., 2013)	X			
(Lu, 2013).	X			
(Upadhyay & Jain, 2016)	X			
(Black et al., 2019)	X			
(Yotsuya et al., 2004)		X		
(León et al., 2009)		X		
(Y. Il Lee et al., 2010)		X		
(Obata et al., 2010)		X		
(D. Y. 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, Petrovic, & Ferroni, 2018).			X	
(Holcomb, Peretz, & Qualls, 2011). (Lloyd & Roulstone, 2018b)			X	

(Generation IV International Forum, 2007) (Lloyd & Roulstone, 2018a)			X	
(Benito Mignacca et al., 2018).			X	
(Lyons & Roulstone, 2018)			X	
(B Mignacca et al., 2019)			X	
(Lloyd, 2019).			X	
(Lyons, 2020).			X	
(B. Mignacca & Locatelli, 2020).			X	
(Williamson & Townsend, 2003).				X
(Memmott et al., 2012)				X
Research not available found in the INES IAEA database				
(Takada et al., 2005)				
(Fang, 2010)				
(L. Song, Yuan, & Junming, 2011)				
(Fang, 2015)				
(T. Hu & Wang, 2017)				
(Yongfei, 2017)				

The research aim of understanding the state of the art in nuclear power in this Applied Research Programme 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 research question by reading the abstracts. The bibliometric research for modular design in nuclear power was set initially by inputting keywords in Scopus. Four separate searches in Scopus were performed denoted below and summarised in the appendix to allow repeatability of the search:

The bibliometric research was set initially by inputting keywords in Scopus. 4 separate searches in Scopus were performed denoted below:

The search for “TITLE-ABS-KEY (“modul* design” AND nuclear AND power OR reactor OR plant)” provided 214 search results.

The search for “KEY (modular AND construction AND nuclear) provided 266 search results

The search for “TITLE-ABS-KEY (modularization AND nuclear) provided 148 search results

The search for “TITLE-ABS-KEY (modul* "balance of plant" nuclear) provided 53 search results

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 do not focus on modular nuclear power design by reading the abstracts.

- 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.

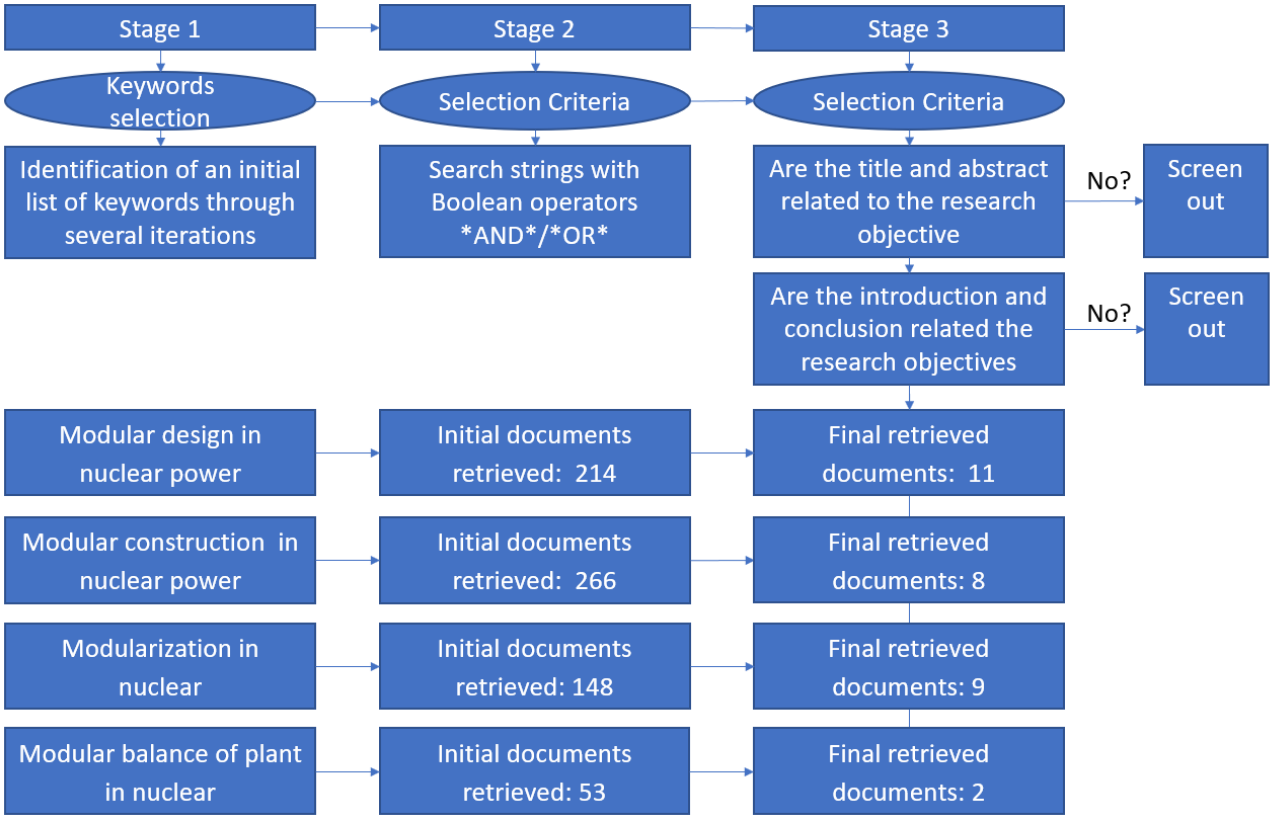


Figure 0-1 - Systematic Literature Review method from Jin et al., (2018) and (B. Mignacca & Locatelli, 2020)

Modular Plant Design

Scopus search was utilised with the search criteria of:

TITLE (modul* AND plant AND design).

129 search results were returned. After careful screening of abstracts and titles, 5 articles were identified as relevant to the research question.

(Hady & Wozny, 2011), (Seifert et al., 2012), (Seifert et al., 2015), (Eilermann, 2016) (Eilermann et al., 2017) (Eilermann et al., 2018). (Eilermann et al., 2019).

Following this, the reference lists, author documents and citing articles were checked in Scopus. This identified another 12 research items:

(Bramsiepe et al., 2012), (Krasberg et al., 2014), (Sievers et al., 2016), (Fleischer-Trebes et al., 2017), (Hohmann et al., 2017), (Baldea et al., 2017), (Uzuner, 2017), (Radatz et al., 2017), (Radatz et al., 2019), (Bielenberg & Palou-Rivera, 2019).

Offsite Modular Construction Literature

A search for MEP modules was conducted to understand if similarities between modular MEP design and industrial plants exist.

Scopus search was utilised with the search criteria of:

TITLE-ABS-KEY (mep AND layout)

24 search results were returned. After careful screening of abstracts and titles, 1 article was identified as relevant to the research question: (J. Wang et al., 2016).

Scopus search was utilised with the search criteria of:

TITLE-ABS-KEY (mep AND modul*) excluding non-related medical/ biology results

120 search results were returned. After careful screening of abstracts and titles, 5 articles were identified as relevant to the research question:

(Tserng et al., 2011), (Li et al., 2017), (Cheng et al., 2020), (Ciribini et al., 2016) (Samarasinghe et al., 2019).

Scopus search was utilised with the search criteria of:

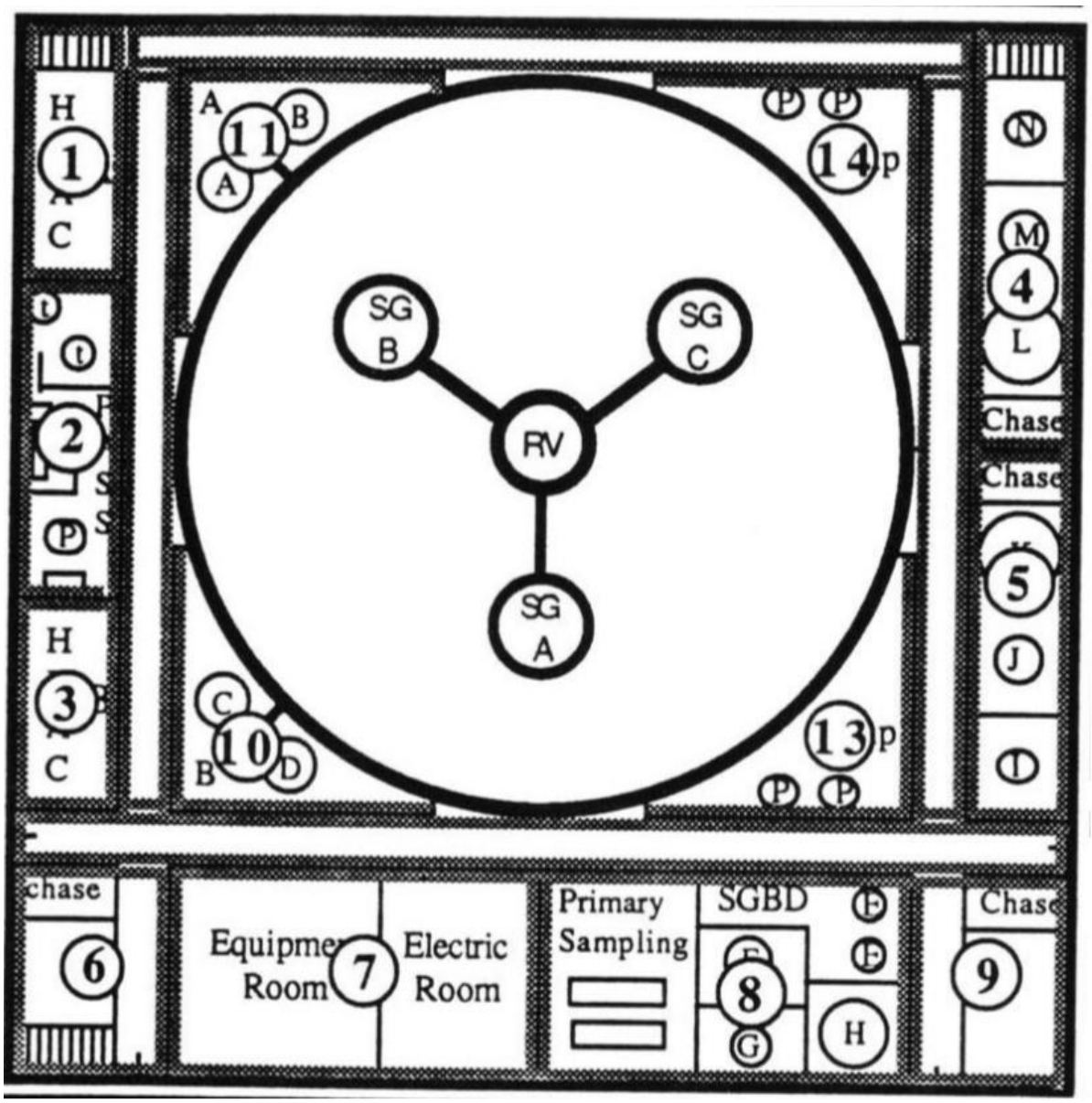
TITLE-ABS-KEY (off-site AND construction OR modular AND literature)

95 search results were returned. After careful screening of abstracts and titles, 5 articles were identified as relevant to the research question and further searches of the references produced the following research articles:

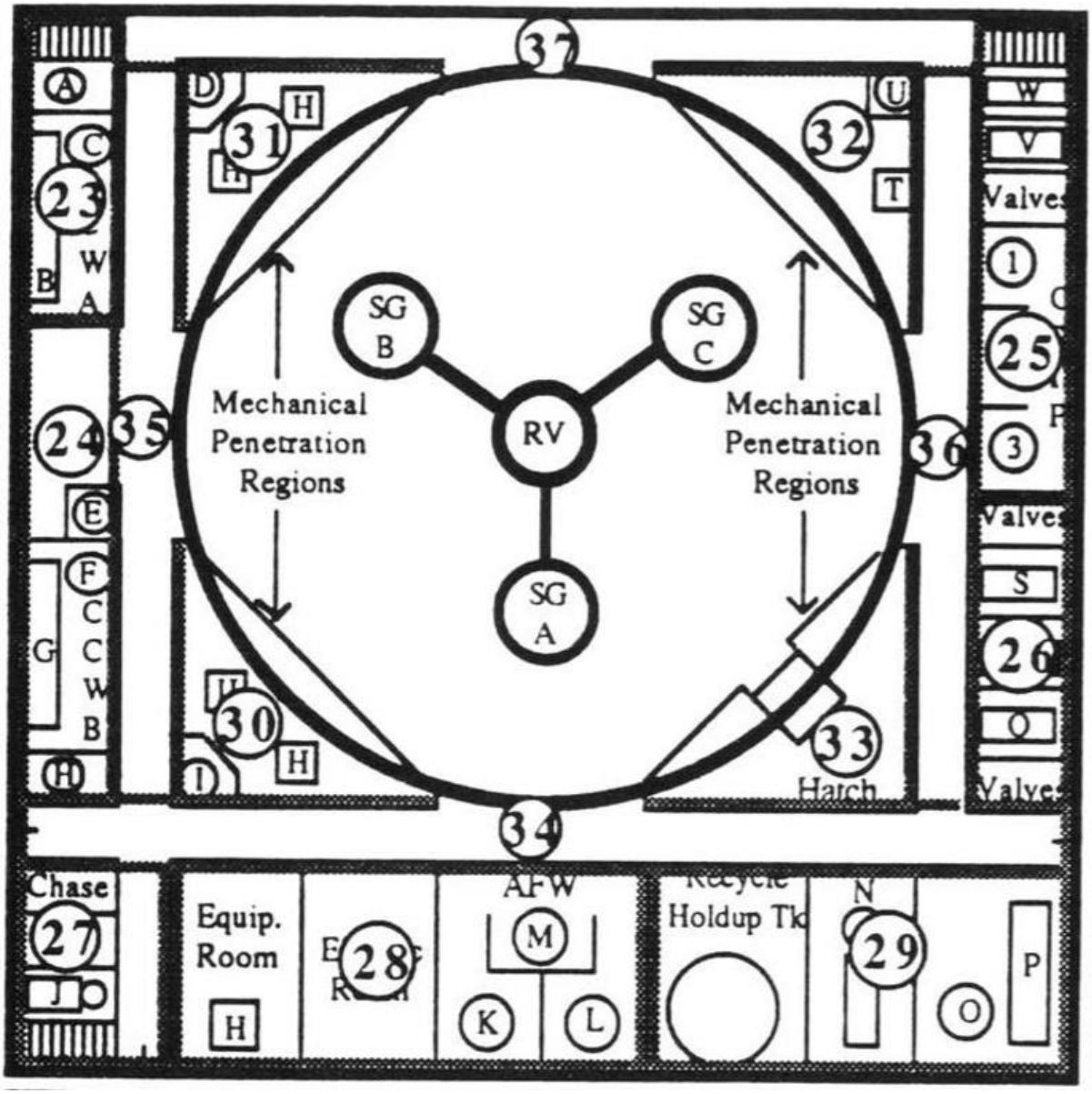
Hosseini et al., (2018) and (Jin et al., 2018) (Yin et al., 2019), (Martinez et al., 2019), (X. Hu et al., 2019), (Choi et al., 2019), (Salama et al., 2017), (De La Torre et al., 1994), (Medjdoub & Chenini, 2015) (Medjdoub & Bi, 2018), (Medjdoub, 2009), (J. Xu & Li, 2012), (H. Song & Choi, 2014), (G. Lee & Kim, 2014), (Bock, 2015), (Anvari et al., 2016), (Taghaddos et al., 2018), (Hsu et al., 2018), (Hsu et al., 2019),(Y. Yang et al., 2019), (Rausch et al., 2019).

Appendix B – Lapp 1989 2D layout data and equipment connections

Level 1

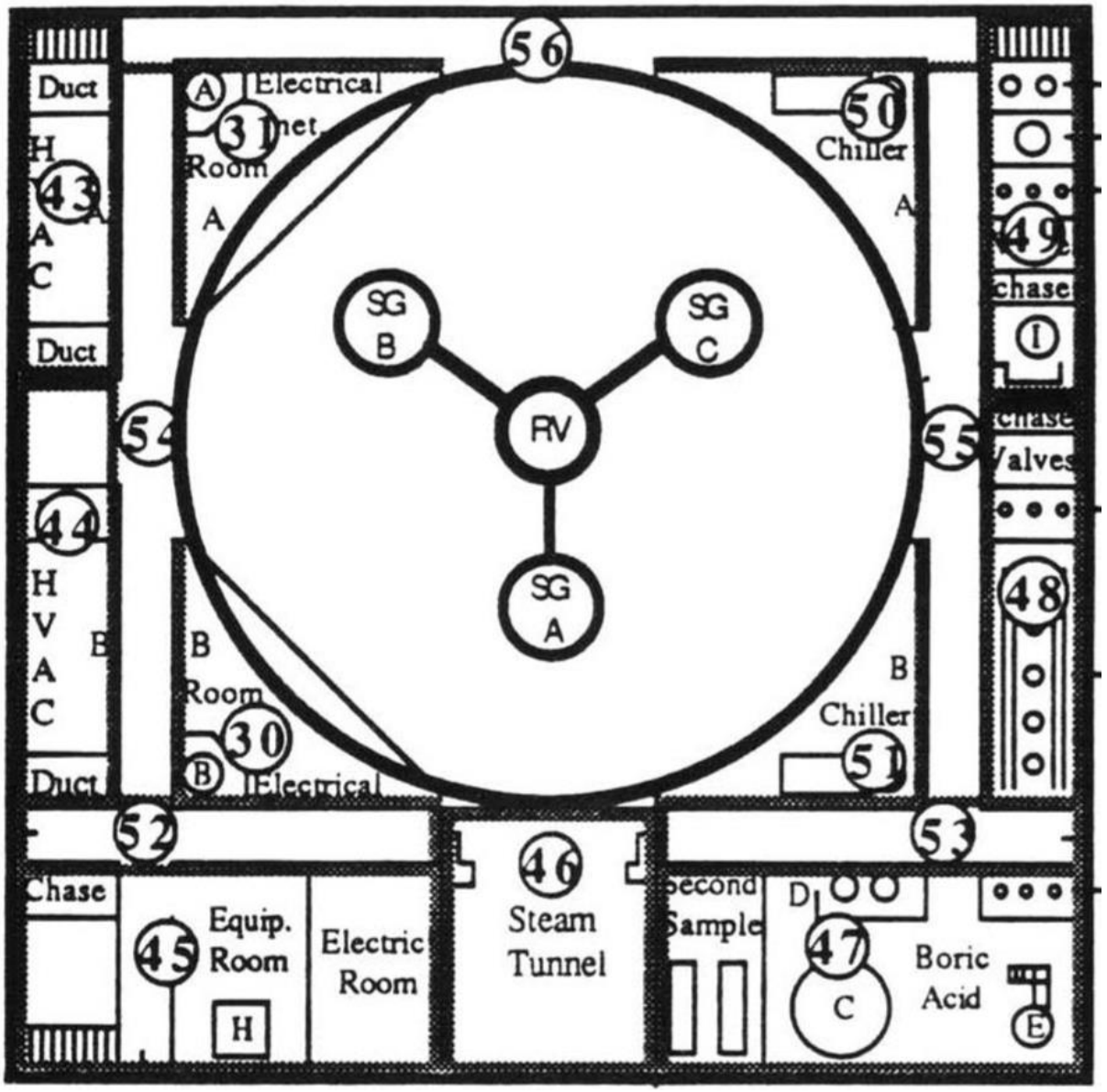


Level 2

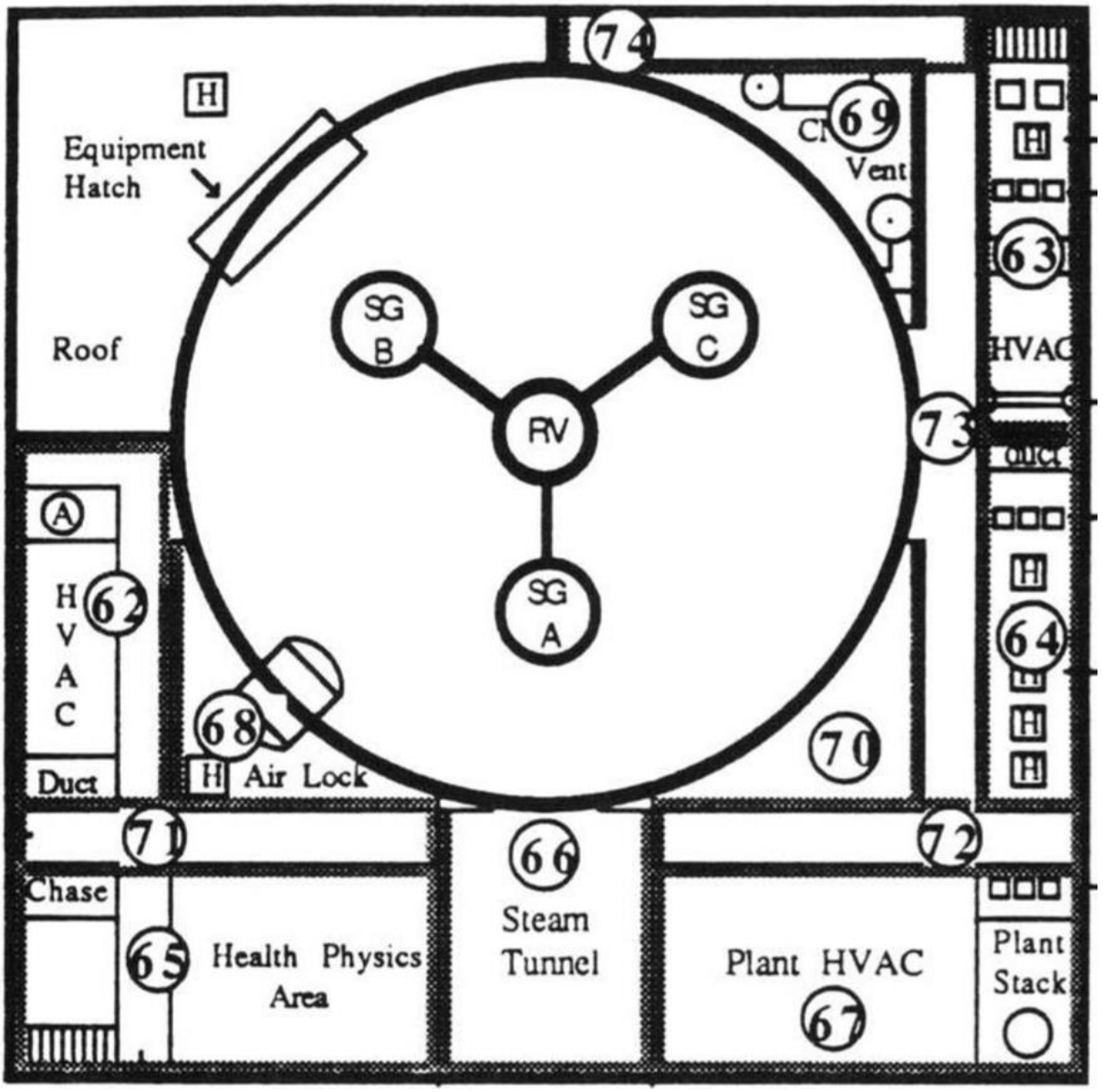


37
SG B
SG C
RV
SG A
Mechanical Penetration Regions
Mechanical Penetration Regions
Valves
Valves
Valves
Hatch
Chase
Equip. Room
AFW
Holdup Tk

Level 3


56
Duct
A
Electrical
31
Room
A
50
Chiller
A
43
HVAC
Duct
SG
B
SG
C
RV
SG
A
54
55
49
Chase
1
Valves
44
HVAC
B
48
B
Room
30
B
Electrical
B
Chiller
51
Duct
52
53
Chase
45
Equip.
Room
H
Electric
Room
46
Steam
Tunnel
Second
Sample
D
47
C
Boric
Acid
E

Level 4



74
H
Equipment
Hatch
69
Vent
63
HVAC
Roof
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SG
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RV
73
duct
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C
62
SG
A
64
68
70
Duct
H
Air Lock
71
66
72
Chase
Steam
Tunnel
65
Health Physics
Area
Plant HVAC
67
Plant
Stack

Equipment connections data from Lapp (1989)

CCW										
	From			To			Class		Size	
	Srg Tk	HVAC	4	pump	CCW	2	-3	2	(S)	1
	pump	CCW	2	hx	CCW	2	-2	4	(L)	5
	Hx	CCW	2	Cross Header	CCW	2	-2	4	(L)	5
	Hx	CCW	2	RHR hx	RHRCS	2	-2	4	(M)	3
	Hx	CCW	2	RHR pmp	RHRCS	1	-2	4	(S)	1
	RHR hx	RHRCS	2	CCW hx	CCW	2	-2	4	(M)	3
	RHR pmp	RHRCS	1	CCW hx	CCW	2	-2	4	(S)	1
	CCW pmp	CCW	2	Cross Header	CCW	2	-2	4	(L)	5
	CCW hdr	CCW	2	RAB			-2	4	(L)	5
	Header	CCW	2	GFFD	SIS	2	-3	2	(S)	1
	Header	CCW	2	RCPs	RCP	1	3	2	(M)	3
	Header	CCW	2	ExLD/RCDT	CVCS	2	3	2	(S)	1
	Header	CCW	2	Seal Water hx	CVCS	2	3	2	(S)	1
	Header	CCW	2	LD hx	CVCS	2	3	2	(S)	1
	Header	CCW	2	Recycle Package			3	2	(M)	3
	Header	CCW	2	Sample Package	Sample	1	3	2	(S)	1
CVCS	Letdown & Charging									
	From			To						
	RCS	RCP	1	L/D hx	CVCS	2	-2	4	(S)	1
	L/D hx	CVCS	2	Demins	BTRS	3	-3	2	(S)	1
	L/D vlv	CVCS	2	RCS fltr	RCP	1	-2	4	(S)	1
	L/D vlv	CVCS	2	BCMS					(S)	1
	Gross FFUELD	SIS	2	L/D out	CVCS	2	-3	2	(S)	1
	RCS fltr	RCP	1	VCT	CVCS	3	-2	4	(S)	1
	RCS	RCP	1	Seal Water hx	CVCS	2	-2	4	(S)	1
	seal wtr hx	CVCS	2	Volume Control Tank	CVCS	3	-2	4	(S)	1
	VCT	CVCS	3	CSIP suct	CVCS	2	-2	4	(S)	1
	CSIP chrg	CVCS	2	RCS	RCP	1	-2	4	(S)	1
	CSIP Seal inj	CVCS	2	RCS fltr	RCP	1	-2	4	(S)	1
	RCS inj fltrRCS	RCP	1	fltrRCS	RCP	1	2	4	(S)	1
CVCS	BTRS									
	From			To						

	CVCS demins	CVCS	3	Mod hx	BRTS2	2	-3	2	(S)	1
	Moderating hx	BRTS2	2	Chlr hx	BRTS1	2	-3	2	(S)	1
	Chiller hx	BRTS1	2	Reheat hx	BRTS2	2	-3	2	(S)	1
	Reheat hx	BRTS2	2	Demins	BTRS	3	-3	2	(S)	1
	CVCS L/D	CVCS	2	Reheat hx	BRTS2	2	-3	2	(S)	1
	Demins	BTRS	3	Moderating hx	BRTS2	2	-3	2	(S)	1
	Moderating hx	BRTS2	2	CVCS fltr	CVCS	3	-3	2	(S)	1
CVCS	BRS									
	Filter Fd			Fd F+Demin	BTRS	3	3	2	(S)	1
	Feed Demins	BTRS	3	Dup Filtr	BRS	2	3	2	(S)	1
	Dup filter	BRS	2	BRS tank	BRS	2	3	2	(S)	1
	BRS tank	BRS	2	EVAP Pmps	BRS	2	N	1	(S)	1
	Evap pumps	BRS	2	EVAP pkg	BRS	2	N	1	(S)	1
	Feed Pkg	BRS	2				3	2	(S)	1
CVCS	PMS/BA									
	Reactor Makeup Water System T			RWMU pumps			3	2	(S)	1
	Reactor Makeup Water System pumps			Blend T	Boric Acid	3	3	2	(S)	1
	BA tank	BA	3	BA pumps	Boric Acid	3	3	2	(S)	1
	BA pumps	BA	3	BA fliter	Boric Acid	3	3	2	(S)	1
	BA filter	BA	3	CSIP Header	CVCS	2	3	2	(S)	1
	BA tank	BA	3	CSIP tdr	CVCS	2	2	4	(S)	1
									(S)	
RHR										
	RWST hdr	RWST		RHR pump	RHRCS	1	2	4	L	5
	RCS sump	RCS	1	RHR pump	RHRCS	1	2	4	L	5
	RHR pump	RHRCS	1	RHR hx	RHRCS	2	2	4	M/L	4
	RCS hot leg	RCS	1	RHR pump	RHRCS	1	2	4	L	5
	RHR hx	RHRCS	2	RHR h.l.	RHRCS	1	2	4	M/L	4
	RHR hx	RHRCS	2	RCS c.l.	RCS	1	2	4	M/L	4
	RHR x-over			CVCS L/D	CVCS	2	(2/3)	3	S/M	2
	RHR hx out	RHRCS	2	CSIP suct	CS		(2/3)	3	M	3
Cont. Spray	RWST			CS pump	RHRCS	1	(2) 4	4	L	5
	CS tank			CS pump	RHRCS	1	2/3	3	S	1
	Cont. sump			CS pump	RHRCS	1	(2) 4	4	L	5

	CS pump	RHRCS	1	Spray hdr	RHRCS		(2) 4	4	M	3
	CS pump	RHRCS	1	RWST	RCP	1	(N) 1	1	M	3
Safety Injection	High Pressure									
	RWST			CSIPs	RHRCS	1	(2) 4	4	M/L 4	4
	CSIPs	CVCS	2	BIT			(2) 4	4	S	1
	BIT			RCS (CL)	RCP	1	(2) 4	4	S	1
	CSIP	CVCS	2	RCS (CL)	RCP	1	(2) 4	4	S	1
	CSIP	CVCS	2	RCS (HL)	RCP	1	(2) 4	4	S	1
	CSIP	CVCS	2	RCS (HL)	RCP	1	(2) 4	4	S	1
	Low Pressure									
	RHR hx out	RHRCS	2	CSIP	CVCS	2	(2) 4	4	L) 5	5
	RHR hx out	RHRCS	2	RCS (HL)	RCP	1	(2) 4	4	L	5
	RHR hx out	RHRCS	2	RCS (CL)	RCP	1	(2) 4	4	L	5
Auxiliary Feedwater										
	CST			AFW pmps	AFW	2	3	2	M	3
	AFW pumps	AFW	2	FW pipes	RCP	1	(3/2)	3	M	3
Emergency Service Water										
	ESW hdr	CCW	2	CCW hx	CCW	2		2	XL	7
	CCW hx	CCW	2	ESW hdr	CCW	2		2	XL	7
	ESW hdr	CCW	2	AFW pmps	AFW	2		2	M	3
	ESW hdr	CCW	2	CSIP clr	CVCS	2		2	S	1
	ESW hdr	CCW	2	ESWB pmp				2	L	5
	ESW bstr pmp	CCW	2	ESW Rtn				2	L	5
	ESW hdr	CCW	2	Chillers	BRTS1	2		2	M	3
	CVCS chiller	BRTS1	2	ESW Rtn				2	M	3
	ESW hdr	ESW		WC-2				2	L	5
	WC-2			ESW hdr				2	L	5
	ESW hdr	ESW		FPB pump				2	M	3
	ESW hdr	ESW		AH-3				2	L/M	4
	ESW hdr	ESW		AH-2				2	L/M	4
	AH-3			ESW Rtn				2	L	5
	AH-2			ESW Rtn				2	L	5
Steam Generator Blowdown										
	SG - A	RCP	1	Flash tk 6	SGBD	1	(3) 2	2	S	1
	SG - B	RCP	1	Flash tk 5	SGBD	1	(3) 2	2	S	1
	SG - C	RCP	1	Flash tk 5	SGBD	1	(3) 2	2	S	1

Appendix C - Equipment data and Assumptions

There are a few assumptions made about the equipment items within the data.

	floor 1 3m		floor 2 8m		floor 3 13 m		floor 4 18m	
Configuration	x	y	x	y	x	y	x	y
two sides	-12	-27	-12	-27	-12	-27	-12	-27
	12	-27	12	-27	12	-27	12	-27
	-27	-12	-27	-12	-27	-12	-27	-12
	-27	12	-27	12	-27	12	-27	12
one side 3 floors	-27	0	-27	0	-27	0		
	-18	0	-18	0	-18	0		
	-9	0	-9	0	-9	0		
	0	0	0	0	0	0		
	9	0	9	0	9	0		
	18	0	18	0	18	0		
	27	0	27	0	27	0		
one side 4 floors	-18	0	-18	0	-18	0	-18	0
	-9	0	-9	0	-9	0	-9	0
	0	0	0	0	0	0	0	0
	9	0	9	0	9	0	9	0
	18	0	18	0	18	0	18	0

Table 0-1 – Point coordinates used in the optimisation for Model (A)

Ion Exchange Assumption

Typical ion exchange equipment (Figure 0-1) ranges "from 3 to 6 ft (0.91-1.83m) in depth" (Lin, 1973). Input and output locations are assumed.

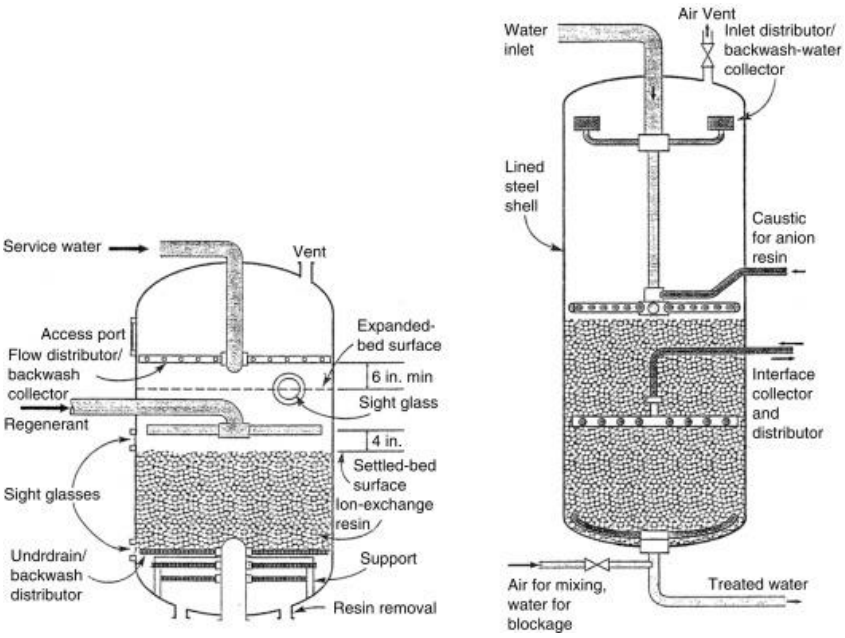

Figure 0-1 - An Example of ion exchange equipment (R. Singh, 2015)

Heat Exchangers

The heat exchangers (Figure 0-2) are assumed to be standard heat exchangers (Stephen, Daniel, Neil, & Esther, 1994), (Si, Tong, Yang, & Huang, 2016). Input and output locations are assumed.

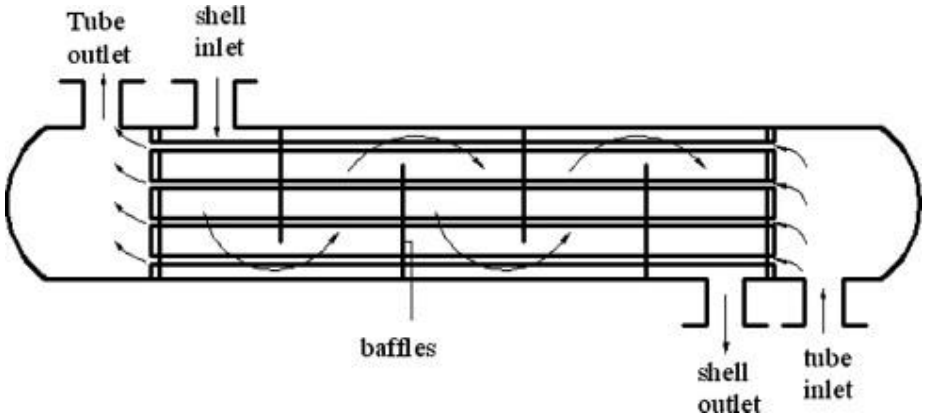

Figure 0-2 – Generic Heat Exchanger design (Guo, Cheng, & Xu, 2009)

Filters

Typical Filtration Systems can be obtained through the supply chain (Thermon, 2019). Input and output locations are assumed.

DSM matrix for Model A – Module layout

The DSM for the P&ID in Model (A) - module to module is shown in Table 0-2.

i	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	0	22	22	6	0	0	0	0	0	0	0	0	0	0	8	0	0	4	0
2	23	0	0	0	0	4	4	16	16	0	0	0	0	0	0	0	0	0	0
3	23	0	0	0	0	4	4	16	16	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	6	4	4	0	2	0	0	12	12	10	0	6	0	2	8	0	0	0	0
7	6	4	4	0	2	0	0	12	12	10	0	6	0	2	8	0	0	0	0
8	56	16	16	0	0	12	12	0	0	0	0	0	0	0	35	0	0	0	0
9	56	16	16	0	0	12	12	0	0	0	0	0	0	0	35	0	0	0	0
10	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	2	2	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0
15	24	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	2	4	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	2	0	2	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	4	0	4	0	0	0	0
19	0	0	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0

Table 0-2 - DSM for the P&ID in module to module Model A

P&ID for Model Bi – Equipment within a Single Module Layout

The second case study is considering a single system equipment layout within one or two modules. It considers two different systems, the CVCS system and the BTRS system, to understand how they might fit into modules.

Example 1 - Chemical Volume and Control System

Example 1 is a Chemical Volume and Control system (CVCS) consisting of 7 equipment items, two heat exchangers, 3 demineralisers and two filters (Lapp, 1989). Shown in Figure 0-3 is the process flow diagram of the plant. The P&ID is from a representative CVCS system (Grove, Travis, & Aggarwal, 1995).

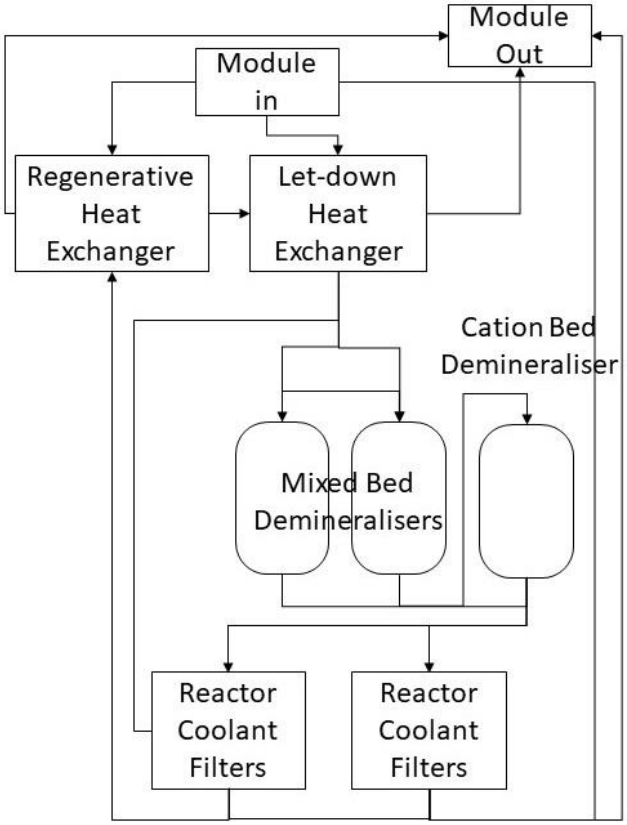

Figure 0-3. CVCS P&ID adapted from the OSTI - U.S. Department of Energy database from (Grove et al., 1995)

The P&ID shown in Figure 0-3 is converted into a DSM matrix shown in Table 0-3.

	1	2	3	4	5	6	7	8	9
HX1	0	1	0	0	0	0	1	1	1
HX2	1	0	1	1	0	0	1	1	1
MBDM1	0	1	0	1	1	0	1	0	0
MBDM2	0	1	1	0	1	0	1	0	0
CIDM	0	0	1	1	0	1	1	0	0
F1	0	0	0	0	1	0	1	0	0
F2	1	1	1	1	1	1	0	1	1
Module IN	1	1	0	0	0	0	1	0	0
Module OUT	1	1	0	0	0	0	1	0	0

Table 0-3 - CVCS P&ID DSM matrix from Figure 0-3

The equipment dimensions and nozzle locations are represented in Table 0-4. The heat exchangers have an extended non-overlapping distance (from 4m to 8m) to ensure the maintenance constraint that allows the heat exchanger tubes to be removed, inspected and replaced.

Equipment	**Dimensions (m) / Locations (m)**		
Heat Exchanger	**d**	**l**	**h**
HX dimensions	4 (8)	1.45	1.45
HX Nozzle	**x**	**y**	**z**
HX Module In	3.3	0	0.7
HX Module Out	0.2	0	-0.7
HX In	0.2	0	0.7
HX Out	1	0	-0.7
Mixed Bed Demineraliser	**d**	**l**	**h**
Dimensions	1	1	1.6
Nozzle Locations	**x**	**y**	**z**
MBD In	0	0.5	0.6
MBD Out	0	0.5	-0.6
Cation Bed Demineraliser	**d**	**l**	**h**
Dimensions	1.6	1.6	1.6
Nozzle Locations	**x**	**y**	**z**
Cation In	0	0.8	0.6
Cation Out	0	0.8	-0.6
Filters	**d**	**l**	**h**
Dimensions	0.7	0.7	1.2
Nozzle Locations	**x**	**y**	**z**
Filter In	0	-0.3	0.3
Filter Out	0	-0.35	-0.3

Table 0-4 – CVCS Equipment dimensions and with nozzle locations from the geometrical centre.

The positions for the CVCS system in Lapp, (1989) are given in Table 0-5.

Equipment	x	y	z
Regenerative HX	5	3.5	0.77
Let-down HX	1.5	3.5	0.77
Mixed Bed Demins 1	1	2	6
Mixed Bed Demins 2	1	5	6
Cation Bed Demins	5	3	6
Filters 1	9	2	6
Filters 2	9	5	6

Table 0-5 -CVCS (Lapp, 1989) Equipment dimensions and nozzle locations

6.4.1 Example 2 – BTRS System

Example 2 is a Boron Thermal Regeneration System developed from Hairston, Kingsley, & Williams, (1978) and Peterka, (1980) consisting of 10 equipment items, three heat exchangers, demineralisers,

evaporator equipment, two tanks, pumps, a chiller and filters (Lapp, 1989). The process flow diagram of the plant is shown in Figure 0-4.

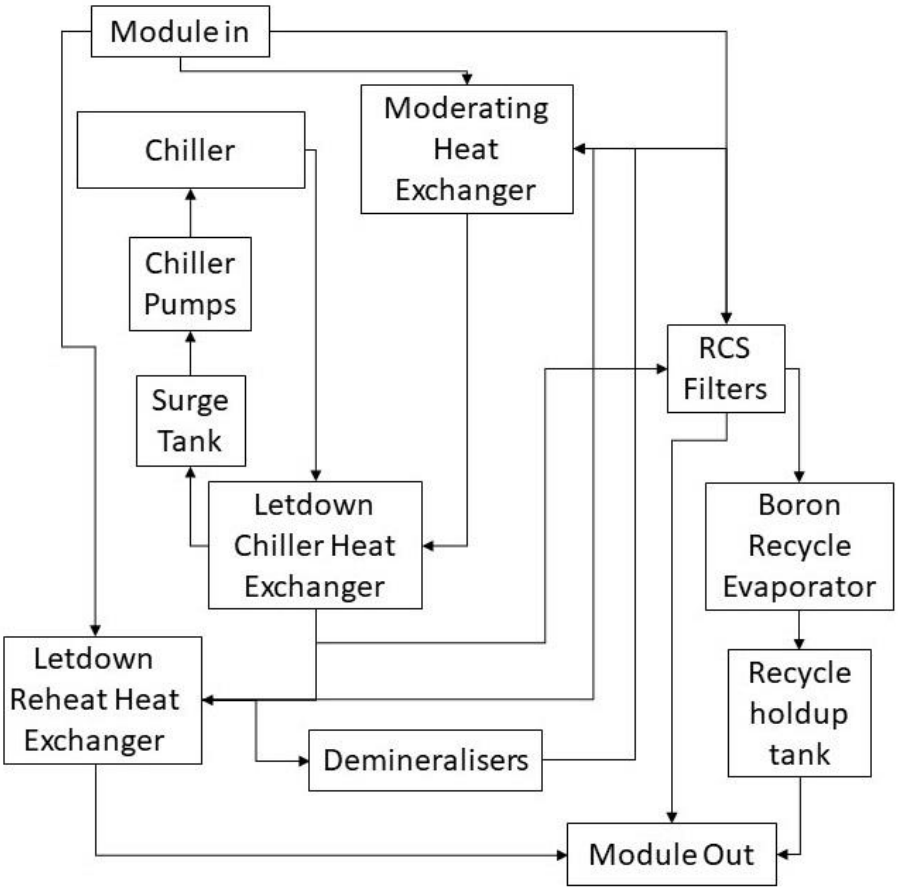

Figure 0-4 - Boron Thermal Regeneration System from (Hairston et al., 1978) *(Peterka, 1980)*

The P&ID DSM matrix for the BTRS system is shown in Table 0-6.

Equipment		1	2	3	4	5	6	7	8	9	10	11	12
Moderating HX	1	0	1	1	1	1	0	0	0	0	0	1	1
Letdown Chiller HX	2	0	0	1	0	1	1	0	1	0	0	0	0
Letdown Reheat HX	3	0	0	0	1	0	0	0	0	0	0	1	1
Demineralizers	4	0	0	0	0	0	0	0	0	0	0	0	0
Filters	5	0	0	0	0	0	0	0	0	0	1	0	0
Surge tank	6	0	0	0	0	0	0	1	0	0	0	0	0
Chiller Pump	7	0	0	0	0	0	0	0	1	0	0	0	0
Chiller	8	0	0	0	0	0	0	0	0	0	0	0	0
Boron Recycle Evaporator	9	0	0	0	0	0	0	0	0	0	0	0	1
Recycle holdup tank	10	0	0	0	0	0	0	0	0	1	0	0	0
In	11	0	0	0	0	0	0	0	0	0	0	0	0
Out	12	0	0	0	0	0	0	0	0	0	0	0	0

Table 0-6 - Boron Thermal Regeneration System DSM matrix

The equipment dimensions and nozzle locations for the BTRS system are in Table 0-7.

Equipment	Dimensions (m) / Locations (m)		
Heat Exchanger	**d**	**l**	**h**
HX dimensions	3.41	1.75	1.75
HX Nozzle	**x**	**y**	**z**
HX Module In	3.3	0	0.7
HX Module Out	0.2	0	-0.7
HX In	0.2	0	0.7
HX Out	1	0	-0.7
Demineralisers	**d**	**l**	**h**
Dimensions	9.13	2.38	2.38
Nozzle Locations	**x**	**y**	**z**
MBD In	0	0.5	0.6
MBD Out	0	0.5	-0.6
Filters	**d**	**l**	**h**
Dimensions	0.7	0.7	1.2
Nozzle Locations	**x**	**y**	**z**
Filter In	0	-0.3	0.3
Filter Out	0	-0.35	-0.3
Surge tank	**d**	**l**	**h**
Dimensions	1.98	1.98	1.98
Nozzle Locations	**x**	**y**	**z**
Surge tank In			
Surge tank Out			
Chiller Pump	**d**	**l**	**h**
Dimensions	2.46	2.46	1.98
Nozzle Locations	**x**	**y**	**z**
Chiller Pump In			
Chiller Pump Out			
Chiller	**d**	**l**	**h**
Dimensions	5.13	1.75	1.75
Nozzle Locations	**x**	**y**	**z**
Chiller In			
Chiller Out			
Boron Recycle Evaporator	**d**	**l**	**h**
Dimensions	5.95	1.91	1.91
Nozzle Locations	**x**	**y**	**z**
Evaporator In			
Evaporator Out			
Recycle holdup tank	**d**	**l**	**h**
Dimensions	7.00	2.80	2.80
Nozzle Locations	**x**	**y**	**z**
Evaporator In			
Evaporator Out			

Table 0-7 – BTRS Equipment dimensions and with nozzle locations from the geometrical centre.

The locations of equipment in the Lapp, (1989) BTRS system are given in Table 0-8.

Equipment	**Locations (m)**		
	w	d	h
Moderating HX	32	-15.7	5
Letdown Chiller HX	32	-10.7	5
Letdown Reheat HX	32	-20	5
Demineralizers	32	-20	10
Filters	32	-5	10
Surge tank	-32	-5	15
Chiller Pump	29	-38	5
Chiller	32	-38	5
Boron Recycle Evaporator	20	-38	5
Recycle holdup tank	12	-39	5
In	0	0	0
Out	0	0	0

Table 0-8 - BTRS (Lapp, 1989) Equipment dimensions and nozzle locations

P&ID for Model Bii– Equipment to Module Allocation Extension

The connections for *Model (Bii)* are shown below in Table 0-9, whilst the equipment dimensions are located in Table 3-1:

		Out coordinates			In coordinates			
Out	**In**	**xsi**	**ysi**	**zsi**	**xsj**	**ysj**	**zsj**	**cost**
0	2	1.6	0.835	1.6	0.2	0.595	1.1	14
0	23	1.6	0.835	1.6	5	0.875	1.6	6
0	25	1.6	0.835	1.6	1.19	3.45	1.19	2
0	30	1.6	0.835	1.6	0	0	0	10
1	2	2.1	1.07	2	3.8	0.595	1.1	20
2	0	0.2	0.595	0.1	0.835	1.6	0	14
2	12	1.2	0.595	0.1	0.2	0.875	1.4	2
2	13	1.2	0.595	0.1	1.945	0.74	0.7	2
2	24	1.2	0.595	0.1	4.6	0.795	1.6	2
2	26	1.2	0.595	0.1	2	1.03	0.1	2
2	30	1.2	0.595	0.1	0	0	0	6
2	31	1.2	0.595	0.1	0	0	0	16
3	31	1	1.03	0.1	0	0	0	3
3	32	1	1.03	0.1	0	0	0	3
3	29	1	1.03	0.1	0	0	0	6
4	5	2.1	1.07	2	0.2	0.595	1.1	20
5	6	0.2	0.595	0.1	0.835	1.6	0	14
5	12	1.2	0.595	0.1	0.2	0.875	1.4	2
5	13	1.2	0.595	0.1	1.945	0.74	0.7	2
5	24	1.2	0.595	0.1	4.6	0.795	1.6	2
5	26	1.2	0.595	0.1	2	1.03	0.1	2
5	30	1.2	0.595	0.1	0	0	0	6
5	31	1.2	0.595	0.1	0	0	0	16
6	5	1.6	0.835	1.6	3.8	0.595	1.1	14
6	23	1.6	0.835	1.6	5	0.875	1.6	6
6	25	1.6	0.835	1.6	1.19	3.45	1.19	2
6	30	1.6	0.835	1.6	0	0	0	10
7	14	2.975	1.6	0.4	3.25	2.8	2.8	3
8	7	3.5	2	0.1	2.975	1.9	1.9	1
9	17	0.1	0.875	1.6	4.565	1.19	1.19	2
10	11	0.1	0.875	0.1	3.4	0.875	1.4	2
10	20	2.7	0.875	0.1	0.355	0	0.3	2
11	0	0.1	0.875	1.7	0.835	1.6	0	6
11	6	0.1	0.875	1.7	0.835	1.6	0	6
11	9	0.1	0.875	1.6	3.4	0.875	1.4	2
12	19	0.1	0.835	0.1	1.8	0.93	1.8	4
12	22	3	0.835	0.1	1.9	0.475	1.1	2
13	9	0.1	0.74	0.1	0.2	0.875	1.4	2
13	20	3	0.74	0.1	0.355	0	0.9	4

		Out coordinates			In coordinates			
Out	**In**	**xsi**	**ysi**	**zsi**	**xsj**	**ysj**	**zsj**	**cost**
14	15	3.25	2	1.2	1.2	0.635	1.2	2
14	25	3.25	2	0.1	1.19	3.45	1.19	4
15	16	1.2	0.635	1.2	1.6	0.875	1.4	2
16	25	1.6	0.875	0.1	1.19	3.45	1.19	2
17	10	4.565	1.19	1.2	0.2	0.875	1.4	2
19	25	1.8	0.93	0.1	1.19	3.45	1.19	4
20	8	0.355	0	0.2	3.5	2	2.6	2
20	19	0.355	0	0.2	1.8	0.93	1.8	4
21	10	0.795	1.6	0.2	3.4	0.875	1.4	2
25	20	1.19	3.45	1	0.355	0	0.3	4
25	27	1.19	3.45	1	2	1.03	2	4
25	30	1.19	3.45	1	0	0	0	4
25	30	1.19	3.45	1	0	0	0	12
26	13	2	1.03	0.1	1.945	0.74	1.4	2
27	30	2	1.03	0.1	0	0	0	4
28	1	2	1	0.1	1.07	2.1	0.6	2
28	4	2	1	0.1	1.07	2.1	0.6	2
29	30	1.2	0	1.6	0	0	0	0
30	12	0	0	0	3.8	0.875	1.4	4
30	13	0	0	0	3.8	0.74	1.4	4
31	2	0	0	0	3.8	0.595	1.1	16
31	5	0	0	0	3.8	0.595	1.1	16
31	25	0	0	0	1.19	3.45	1.19	31
32	25	0	0	0	1.19	3.45	1.19	31

Table 0-9 -Connection costs and nozzle locations for the full plant Model (Bii)

Appendix D – MATLAB Genetic algorithm options

Options for ga, Integer ga, and gamultiobj

Option	Description	Values
ConstraintTolerance	Determines the feasibility with respect to nonlinear constraints. Also, max(sqrt(eps),ConstraintTolerance) determines feasibility with respect to linear constraints. For an options structure, use TolCon.	Positive scalar | {1e-3}
CreationFcn	I* Function that creates the initial population. Specify as a name of a built-in creation function or a function handle. See Population Options.	{'gacreationuniform'} | {'gacreationlinearfeasible'}* | Custom creation function
CrossoverFcn	I* Function that the algorithm uses to create crossover children. Specify as a name of a built-in crossover function or a function handle. See Crossover Options.	{'crossoverscattered'} for ga, {'crossoverintermediate'}* for gamultiobj | 'crossoverheuristic' | 'crossoversinglepoint' | 'crossovertwopoint' | 'crossoverarithmetic' | Custom crossover function
CrossoverFraction	The fraction of the population at the next generation, not including elite children, that the crossover function creates.	Positive scalar | {0.8}
Display	Level of display.	'off' | 'iter' | 'diagnose' | {'final'}
DistanceMeasureFcn	Function that computes distance measure of individuals. Specify as a name of a built-in distance measure function or a function handle. The value applies to decision variable or design space (genotype) or to function space (phenotype). The default 'distancecrowding' is in function space (phenotype). For gamultiobj only. See Multiobjective Options. For an options structure, use a function handle, not a name.	{'distancecrowding'} means the same as {@distancecrowding,'phenotype'} | {@distancecrowding,'genotype'} | Custom distance function
EliteCount	NM Positive integer specifying how many individuals in the current generation are guaranteed to survive to the next generation. Not used in gamultiobj.	Positive integer | {ceil(0.05*PopulationSize)} | {0.05*(default PopulationSize)} for mixed-integer problems
FitnessLimit	NM If the fitness function attains the value of FitnessLimit, the algorithm halts.	Scalar | {-Inf}
FitnessScalingFcn	Function that scales the values of the fitness function. Specify as a name of a built-in	{'fitscalingrank'} | 'fitscalingshiftlinear' | 'fitscalingprop' |

Option	Description	Values
	scaling function or a function handle. Option unavailable for `gamultiobj`.	`'fitscalingtop'` | Custom fitness scaling function
`FunctionTolerance`	The algorithm stops if the average relative change in the best fitness function value over `MaxStallGenerations` generations is less than or equal to `FunctionTolerance`. If `StallTest` is `'geometricWeighted'`, then the algorithm stops if the *weighted* average relative change is less than or equal to `FunctionTolerance`. For `gamultiobj`, the algorithm stops when the geometric average of the relative change in value of the spread over `options.MaxStallGenerations` generations is less than `options.FunctionTolerance`, and the final spread is less than the mean spread over the past `options.MaxStallGenerations` generations. See gamultiobj Algorithm. For an options structure, use `TolFun`.	Positive scalar | `{1e-6}` for ga, `{1e-4}` for `gamultiobj`
`HybridFcn`	I* Function that continues the optimization after ga terminates. Specify as a name or a function handle. Alternatively, a cell array specifying the hybrid function and its options. See ga Hybrid Function. For `gamultiobj`, the only hybrid function is `@fgoalattain`. See gamultiobj Hybrid Function. See When to Use a Hybrid Function.	Function name or handle | `'fminsearch'` | `'patternsearch'` | `'fminunc'` | `'fmincon'` | `{[]}` or 1-by-2 cell array | `{@solver, hybridoptions}`, where `solver` = `fminsearch`, `patternsearch`, `fminunc`, or `fmincon` `{[]}`
InitialPenalty	NM I* Initial value of penalty parameter	Positive scalar | `{10}`
`InitialPopulationMatrix`	Initial population used to seed the genetic algorithm. Has up to `PopulationSize` rows and `N` columns, where `N` is the number of variables. You can pass a partial population, meaning one with fewer than `PopulationSize` rows. In that case, the genetic algorithm uses `CreationFcn` to generate the remaining population members. See Population Options For an options structure, use `InitialPopulation`.	Matrix | `{[]}`
`InitialPopulationRange`	Matrix or vector specifying the range of the individuals in the initial population. Applies to `gacreationuniform` creation	Matrix or vector | `{[-10;10]}` for unbounded components, `{[-1e4+1;1e4+1]}` for unbounded components of integer-constrained

Option	Description	Values
	function. ga shifts and scales the default initial range to match any finite bounds. For an options structure, use PopInitRange.	problems, {[lb;ub]} for bounded components, with the default range modified to match one-sided bounds.
InitialScoresMatrix	I* Initial scores used to determine fitness. Has up to PopulationSize rows and has Nf columns, where Nf is the number of fitness functions (1 for ga, greater than 1 for gamultiobj). You can pass a partial scores matrix, meaning one with fewer than PopulationSize rows. In that case, the solver fills in the scores when it evaluates the fitness functions. For an options structure, use InitialScores.	Column vector for single objective | matrix for multiobjective | {[]}
MaxGenerations	Maximum number of iterations before the algorithm halts. For an options structure, use Generations.	Positive integer |{100*numberOfVariables} for ga, {200*numberOfVariables} for gamultiobj
MaxStallGenerations	The algorithm stops if the average relative change in the best fitness function value over MaxStallGenerations generations is less than or equal to FunctionTolerance. If StallTest is 'geometricWeighted', then the algorithm stops if the weighted average relative change is less than or equal to FunctionTolerance. For gamultiobj, the algorithm stops when the geometric average of the relative change in value of the spread over options.MaxStallGenerations generations is less than options.FunctionTolerance, and the final spread is less than the mean spread over the past options.MaxStallGenerations generations. See gamultiobj Algorithm. For an options structure, use StallGenLimit.	Positive integer | {50} for ga, {100} for gamultiobj
MaxStallTime	NM The algorithm stops if there is no improvement in the objective function for MaxStallTime seconds, as measured by tic and toc. For an options structure, use StallTimeLimit.	Positive scalar | {Inf}
MaxTime	The algorithm stops after running after MaxTime seconds, as measured by tic and toc. This limit is enforced after	Positive scalar | {Inf}

Option	Description	Values
	each iteration, so ga can exceed the limit when an iteration takes substantial time. For an options structure, use `TimeLimit`.	
MigrationDirection	Direction of migration. See Migration Options	`'both'` | `{'forward'}`
MigrationFraction	Scalar from 0 through 1 specifying the fraction of individuals in each subpopulation that migrates to a different subpopulation. See Migration Options	Scalar | `{0.2}`
MigrationInterval	Positive integer specifying the number of generations that take place between migrations of individuals between subpopulations. See Migration Options.	Positive integer | `{20}`
`MutationFcn`	I* Function that produces mutation children. Specify as a name of a built-in mutation function or a function handle. See Mutation Options.	`{'mutationgaussian'}` for ga, `{'mutationadaptfeasible'}*` for `gamultiobj` | `'mutationuniform'` | Custom mutation function
`NonlinearConstraintAlgorithm`	Nonlinear constraint algorithm. See Nonlinear Constraint Solver Algorithms. Option unchangeable for `gamultiobj`. For an options structure, use `NonlinConAlgorithm`.	`{'auglag'}` for ga, `{'penalty'}` for `gamultiobj`
`OutputFcn`	Functions that ga calls at each iteration. Specify as a function handle or a cell array of function handles. See Output Function Options. For an options structure, use `OutputFcns`.	Function handle or cell array of function handles | `{[]}`
`ParetoFraction`	Scalar from 0 through 1 specifying the fraction of individuals to keep on the first Pareto front while the solver selects individuals from higher fronts, for `gamultiobj` only. See Multiobjective Options.	Scalar | `{0.35}`
PenaltyFactor	NM I* Penalty update parameter.	Positive scalar | `{100}`
`PlotFcn`	Function that plots data computed by the algorithm. Specify as a name of a built-in plot function, a function handle, or a cell array of built-in names or function handles. See Plot Options. For an options structure, use `PlotFcns`.	ga or `gamultiobj`: `{[]}` | `'gaplotdistance'` | `'gaplotgenealogy'` | `'gaplotselection'` | `'gaplotscorediversity'` |`'gaplotscores'` | `'gaplotstopping'` | `'gaplotmaxconstr'` | Custom plot function ga only: `'gaplotbestf'` | `'gaplotbestindiv'` | `'gaplotexpectation'` | `'gaplotrange'`

Option	Description	Values
		gamultiobj only: 'gaplotpareto' | 'gaplotparetodistance' | 'gaplotrankhist' | 'gaplotspread'
PlotInterval	Positive integer specifying the number of generations between consecutive calls to the plot functions.	Positive integer | {1}
PopulationSize	Size of the population.	Positive integer | {50} when numberOfVariables <= 5, {200} otherwise | {min(max(10*nvars,40),100)} for mixed-integer problems
PopulationType	Data type of the population. Must be 'doubleVector' for mixed integer problems.	'bitstring' | 'custom' | {'doubleVector'} ga ignores all constraints when PopulationType is set to 'bitString' or 'custom'. See Population Options.
SelectionFcn	I* Function that selects parents of crossover and mutation children. Specify as a name of a built-in selection function or a function handle. gamultiobj uses only 'selectiontournament'.	{'selectionstochunif'} for ga, {'selectiontournament'} for gamultiobj | 'selectionremainder' | 'selectionuniform' | 'selectionroulette' | Custom selection function
StallTest	NM Stopping test type.	'geometricWeighted' | {'averageChange'}
UseParallel	Compute fitness and nonlinear constraint functions in parallel. See Vectorize and Parallel Options (User Function Evaluation) and How to Use Parallel Processing in Global Optimization Toolbox.	true | {false}
UseVectorized	Specifies whether functions are vectorized. See Vectorize and Parallel Options (User Function Evaluation) and Vectorize the Fitness Function. For an options structure, use Vectorized with the values 'on' or 'off'.	