Balance of Plant Modules Layout Optimization in Light Water Modular Nuclear Reactor Power Plants

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Abstract

The Small Modular Reactor (SMR) concept has been proposed to solve some of the construction problems of large reactors. SMRs are designed to be "shop fabricated and then transported as modules to the sites for installation". As a consequence they theoretically have shorter build schedules and require less capital investment (Locatelli et al., 2014). A literature review has highlighted a lot of work has been undertaken in the research and development of different types of reactors and reactor modules but the design of balance of plant modules has not been extensively researched (Wrigley et al., 2018). The focus of this paper will be on a case study for balance of plant modules in a light water reactor.

Wrigley et al., (2018) highlighted two methods of modularization for balance of plant modules in nuclear reactors to support modularization for SMRs. If the modules are to be designed for factory build and transport in a standardized grid approach, a design method needs to be developed to help achieve this approach. To enable this, we propose a three step method: how to group components into modules, how to layout the modules and how to arrange components inside the modules.

The Shearon Harris Nuclear Power Plant was chosen for its publically available data. A previous study on this plant used matrix reordering techniques to group components and heuristically assign them to large modules, highlighting a potential capital cost savings of 15%. A method of assigning components to modules could be developed in future studies, but this was not the focus of this paper. We therefore use the same allocation of components and modules as the previous study but tackle how balance of plant modules should be arranged. The literature review has highlighted that although the facility and plant layout problem has been extensively researched, no layout optimization has been applied to nuclear power plants.

The work in this paper develops an optimization model using a genetic algorithm for module layout and allocation within a nuclear power plant. This paper analysed two configurations of modules, where balance of plant modules are located on either one or two sides of the nuclear island.

The optimization in this paper reduced the objective function for balance of plant modules from 14914 for the original plant to 9993 and 9279 for three and four floor layouts on two sides respectively. For modules located on one side, the three and four floor objective functions were 8174 and 8036 respectively, a significant reduction of 46.1%. This will reduce materials used, reduce build time and hence reduce the cost of a Nuclear Power Plant. Factory built modules can increase safety, due to higher quality tools and inspection. This method will also save design time when developing the layout of modules around the plant

Keywords

Layout Optimization,
Small Modular Nuclear Reactor,
Genetic Algorithm,
Balance of Plant

Abbreviations

Abbreviations	Description
AFW	Auxiliary Feed Water System
BEA	Bond Energy Algorithm
BOP	Balance Of Plant
Boric Acid	Boric Acid
BRS	Boron Recycle System
BRTS	Boron Thermal Regeneration System
BTRS	Boron Thermal Regeneration
CCW	Component Cooling Water
CP_{ij}	Connections Penalty Matrix
CSS	Chemistry Sampling System
CVCS	Chemical and Volume Control System
DSM	Design Structure Matrix
EE	Electrical and Equipment

HVAC	CCW Surge Tank
HVAC	Heating and Ventilation
MINLP	Mixed Integer Non Linear Programming
MILP	Mixed Integer Linear Programming
MWe	Megawatt Electric
NLP	Nonlinear Programming
P&ID	Process and Instrumentation Diagram
RHRCS	Residual Heat Removal and Containment Spray
RPV	Reactor Pressure Vessel
SGBD	Steam Generator Blowdown
SIS	Safety Injection System
SMR	Small Modular Reactor
Notations used in the optimization	
Indices	**Description**
i	Module i
j	Module j
k	Location k
Parameters	
CP*ij*	Connection Penalty between module i and module j
XLocations	Defines the X coordinate locations for modules
YLocations	Defines the Y coordinate locations for modules
ZLocations	Defines the Z coordinate locations for modules
SCP	Safety Class Penalty
PSP	Pipe Size Penalty
N	Number of Modules
K	Number of Locations
Optimization variable	
Yik	Matrix of number of modules i and number of locations k
Variables	
Vij	Vertical distance between module i and module j if module i is above module j
Hij	Horizontal distance between module i and module j in the x direction
Fij	Horizontal distance between module i and module j in the y direction

Table 1 - shows the indices, parameters, system variables, decision variables and their corresponding definitions that were used in the model formulation.

1 Introduction

Modular building techniques has been employed in construction of nuclear power plants since at least the 1970s (Stone & Webster Engineering Corporation, 1977) to reduce construction costs. The Small Modular Reactor (SMR) concept has been proposed to solve some of the construction problems of large reactors by being "shop fabricated and then transported as modules to the sites for installation" (IAEA, 2018). This factory produced method enables shorter build schedules though productivity increases and parallel working and standardization enables direct costs reductions. Smaller plants require less capital costs meaning less financial investment and risk for utilities (Locatelli et al., 2014).

There are more than 50 SMR designs under development. These may include gen 4 nuclear technology such as: High Temperature Gas Cooled (10 designs), Fast Neutron Spectrum (9 designs), Molten Salt (10 designs) or standard light water (25 designs) (IAEA, 2018). As these designs are all in commercial development and are highly specialised design areas, the focus of this paper will be on the balance of plant modules. A literature review has highlighted the design of balance of plant modules has not been extensively researched (Wrigley et al., 2018).

If factory built SMRs are to be built in factories, the optimum size of these modules needs to be considered. Salama et al., (2017) introduced the Modular Suitability Indicator (MSI) to select the optmimum size of residential modules for the constrctiuon industry based on connections, transportation limits, shipping distance, crane cost and concrete volume. This could be a useful tool to select modules sizes if adapted for industrial rather than residential modules.

Modularization is the method of breaking a system down to reduce its complexity. To understand how to modularize we first need to understand why Modularization is relevant in constructing nuclear power and what to modularize.

1.1 Why modularize?

Generation III+ large nuclear power stations are designed around economies of scale (Roulstone, 2015). The delays and cost overruns experienced by reactors currently under construction demonstrate the challenges with this approach (Gilbert et al., 2017). Modularization can especially aid where onsite labor cost is high and where construction sites are remote and have adverse weather (Bondi et al., 2016). Modularization has been estimated to reduce the construction schedule by 20- 50% and provide cost savings of 7-20% (Mignacca et al., 2018).

Maronati et al., (2018) proposed that the use of the 1-3-8 (Figure 1) rule of modularization can reduce the total capital investment cost of a Westinghouse SMR by 42% compared to if the plant was stick built. The 1-3-8 rule is based on observed data from shipbuilding (Barry, 2009) where 1 represents the time taken to perform the same task in a factory is ⅛th the time it takes to stick build. 3 represents if the work is performed in an on-site assembly area, taking ⅓rd of the time compared to stick built and 8 is for if the work is stick built. The 1-3-8 rule underlines the idea of productivity increases in factory built, road transportable SMRs.

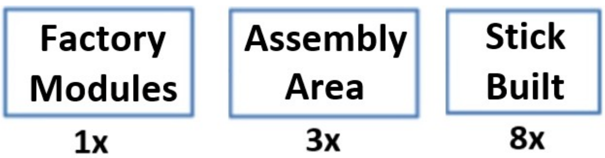


Figure 1 – 1-3-8 rule from shipbuilding (Maronati et al., 2018)

1.2 What to modularize - Plant level modularisation

The 1-3-8 rule can be related to how modularization of a nuclear plant, at a top level, can be broken down into 3 strategies (Upadhyay and Jain, 2016):

- Scope modularization: A single large reactor is divided into a number of modules (super modules)
- Combined Scale modularization: A large nuclear power plant is formed of multiple reactors
- Standardized Scale modularization: A large plant site is formed of multiple nuclear power plants

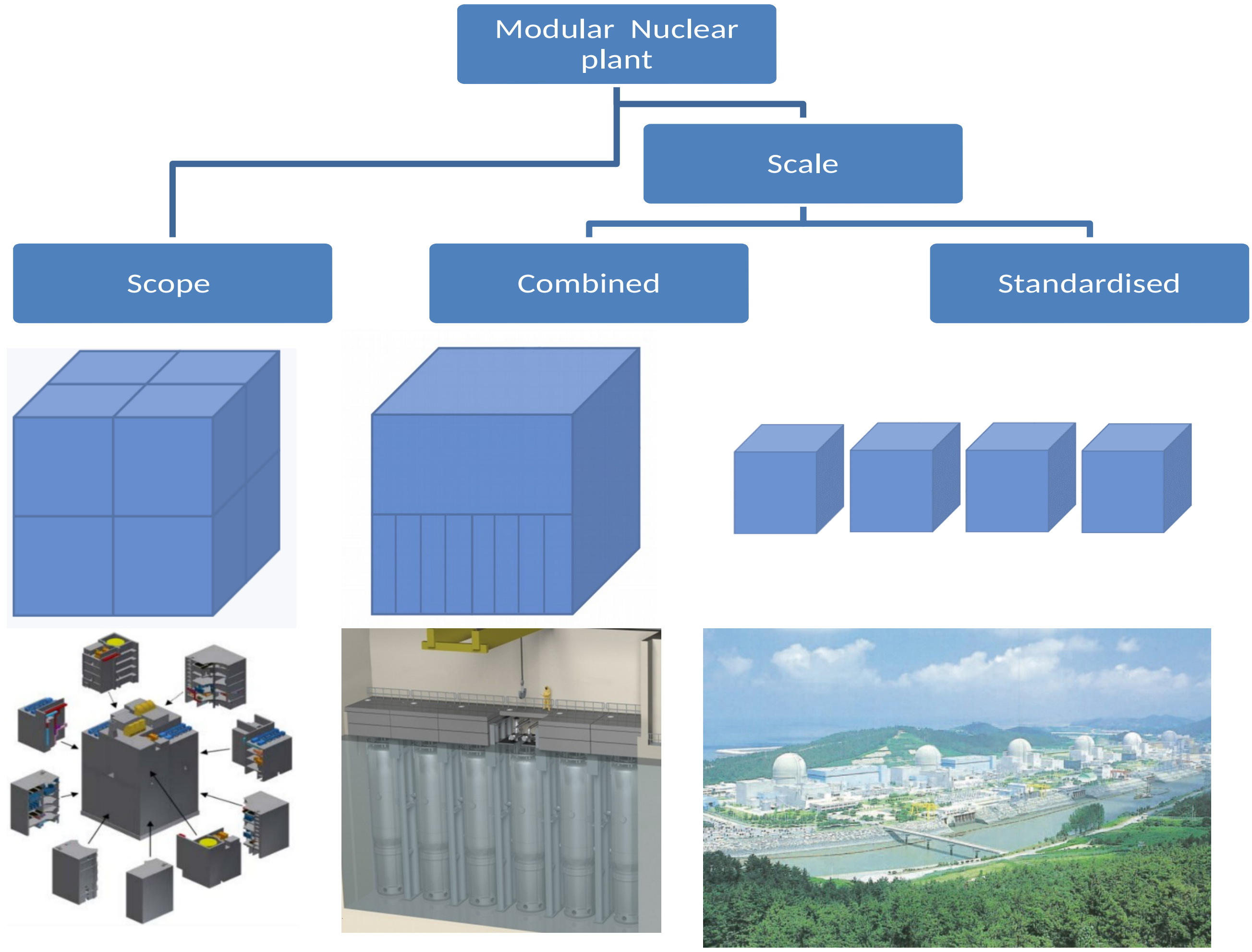


Figure 2 – Different methods of modularising nuclear power plants. Adapted from (Mignacca et al., 2018, ICONE 26 presention). (left) AP1000 plant. (Middle) Nuscale plant (Ingersoll et al., 2014), Korean standardized plants.

Scope modularization has been applied in large nuclear power plants in constructing super (1000 tonne +) modules in an on-site assembly area. The a study for the US Department of Energy by the Technology Transfer Modularization Task team, (1985) evaluated shipbuilding, petrochemical, aircraft and auto industry applications to nuclear modularization. They recommended a 600MW plant using shipbuilding technology (on-site assembly area) which could achieve a 12 percent cost saving. A subsequent study on modularization looked into how this on-site assembly area could be implemented in practice (Lapp, 1989). It also studied a matrix reordering technique to group highly connected components and heuristically assign them to modules.

A more recent scope modularization concept breaks down the MIT pebble bed reactor (Figure 4) to be constructed utilising a 'virtual factory' concept and module space frames (Kadak and Berte, 2006).

The combined Scale concept is formed of multiple integral reactors. Integral reactors were being considered in the 1980s (Matzie et al., 1992) as these designs eliminated loss-of-coolant accidents (LOCA) through removal of large bore pipework and have enhanced passive safety features compared to large nuclear power plants. They also are more easily transported than large nuclear power plant components. This concept realizes economies of volume production of integral reactors, instead of the economies of scale of power output of large nuclear plants.

Standardized plant designs have been employed across the world, with the best examples in Korea (Gilbert et al., 2017) and France. Standardized plant designs aim to benefit from next of a kind learner benefits, where multiple builds of the same design can bring down costs, as supply chains are developed and production processes improved.

1.3 What to modularize - Balance of plant modularization

Looking at modules within the plant, (Upadhyay and Jain, 2016) categorized modules into 9 groups. It is proposed that the mechanical, electrical, instrumentation and system groups all be combined into one composite balance of plant module to maximise off-site assembly and productivity (Figure 3). A previous literature review concluded that there has not been much research conducted into how Balance Of Plant (BOP) modules will be designed and deployed (Wrigley et al., 2018). One study identifies a number of plant components for modularization consideration (Stone & Webster Engineering Corporation, 1977): reinforcing steel, structural steel, polar crane supports, pipe modules, pipe racks, liners (containment and fuel related), skid-mounted modules, condenser, tanks, cable installations, cable trays and precast concrete.

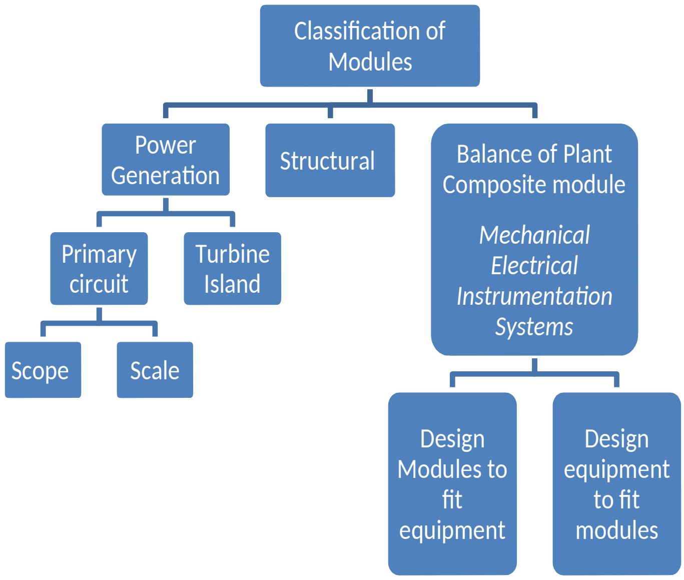


Figure 3 – Classification of modules

Two different methods for modularization (Figure 3) were highlighted for Balance of Plant modules in SMRs (Wrigley et al., 2018). One method is to design the modules to fit the system and the other is to Design equipment/ systems to fit modules.

1.3.1 Design modules to fit the system/ equipment

Designing the modules to fit the system has been employed in the nuclear island super module (1000 tonne +) and onsite assembly area concept (Lapp and Golay, 1997) but the method has experienced problems leading to delays and cost overruns (Hals and Flitter, 2017).

Kadak and Berte, (2006) break down the MIT Pebble bed reactor (Figure 4) into individual components housed in space frames and is constructed using a 'virtual factory' method. This method has the benefits of removing the capital needed for a central, balance of plant, factory, hence 'virtual factory'. However, it has the disadvantage of increasing work on site, requiring more connections, contradictory to the SMR goal of 'factory built'. Therefore this method may be more suited to 'one off' construction projects. If the method of a virtual factory is chosen, a standard plant layout optimization algorithm could be used.

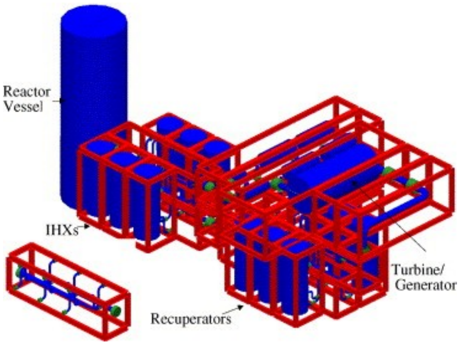


Figure 4 –Modules designed to fit the components, MIT pebble bed reactor (Kadak and Berte, 2006)

1.3.2 Design equipment to fit modules

The other method is to design the system around the modules as proposed in the standardized modules concept shown in Figure 5. An advantage of this method is that the modules are standardized and should benefit from the economies of volume production. Standardization allows for more efficient supply, construction, operation and enables the benefit of learner effects (Mignacca et al., 2018). Packing more components in modules allows more work to be taken offsite, but there is a size limit for road transport.

A disadvantage is more investment in upfront engineering design and facilities is required, compared to stick built, or the virtual factory method. This type of modularization would benefit multiple standardized construction projects. This paper will develop a method to analyse the allocation of modules to a standardized grid.

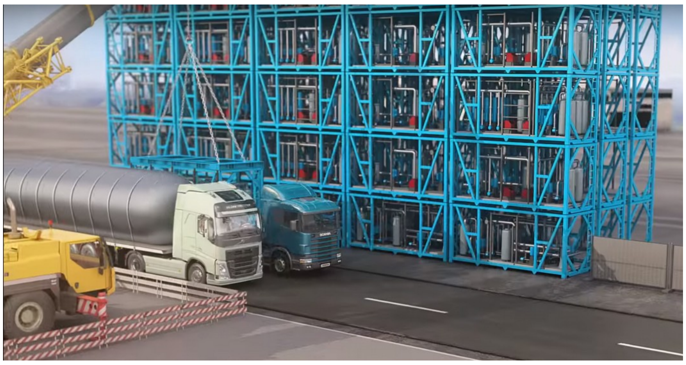


Figure 5 – Systems designed to fit the standardized modules concept (Rolls-Royce, 2017)

2 Modularisation method for balance of plant systems in Standardised modules

In the typical plant design process (Figure 6), the plant design engineer takes a Process and Instrumentation Diagram (P&ID) and a database of components and lays out the components and pipework within 2D or 3D design software.

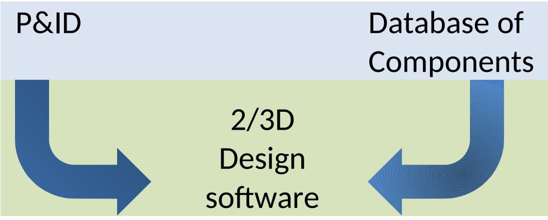


Figure 6 - Typical plant design process

If the standardised module and grid concept is to be implemented, it has been identified that three stage iterative design process is required (Figure 7):

Step 1: Decide how components are grouped into modules
Step 2a: Decide how modules are arranged
Step 2b: Decide how components are arranged within modules

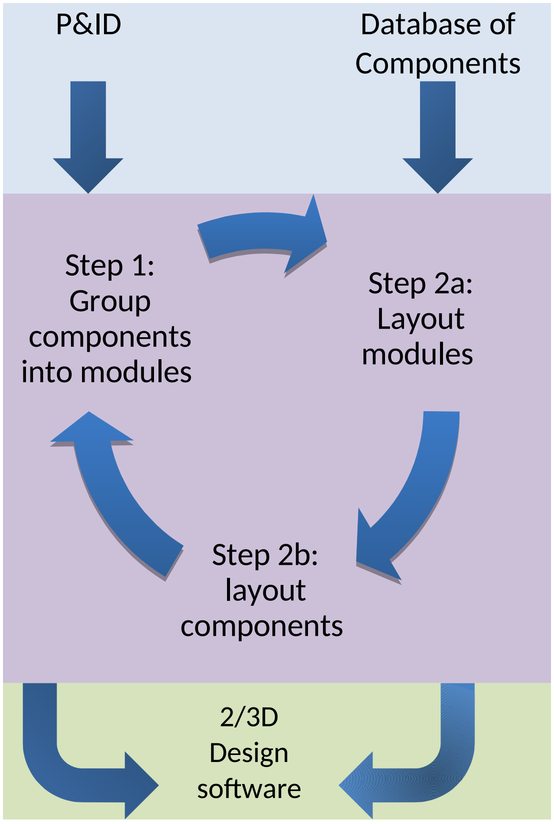


Figure 7 – Standardized balance of plant modules and grid plant design process

As with the typical plant design process (Figure 6), the P&ID is utilized along with the database of components in the first stage. The three stage iterative optimization process then takes place (Figure 7). The iterative loop is required as each stage may affect the output of others. The output then drives and informs the 2/3D plant design.

2.1 Step 1: How to group components into modules (Lapp, 1989)

Lapp (1989) first proposed a method of adapting the Shearon Harris Nuclear Plant (a 900 MW Westinghouse 3-loop design) for modular, assembly area on site (level 3 in the 1-3-8 rule), construction. Within this they grouped systems and components using a matrix reordering technique. Using this method, they highlighted potential savings of 15% in the capital cost of the plant compared to a stick-built plant. The process is outlined in (Figure 8).

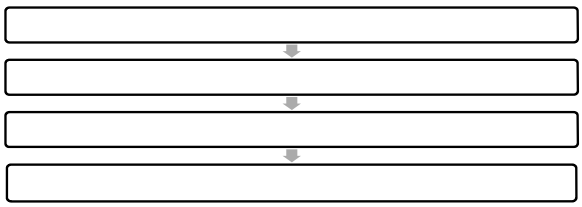


Figure 8 - Lapp (1989) method for grouping components

2.1.1 Step A - Convert P&ID to Design structure matrix

First, the Process and Instrumentation Diagram (P&ID) is converted to a Design Structure Matrix (DSM). The Design Structure Matrix (or later connections penalty matrix) between two components or systems is normally determined from a P&ID as in the example in Figure 9. Using Equation (1), as in Jayakumar and Reklaitis, (1994) the connections from one component or system to the next can be assigned to an *n* by *m* matrix.

$$DSM_{ij} = \{1, \quad ¿ unit\, i ¿ j ¿ 0, ¿ otherwise ¿\}$$ Equation (1)

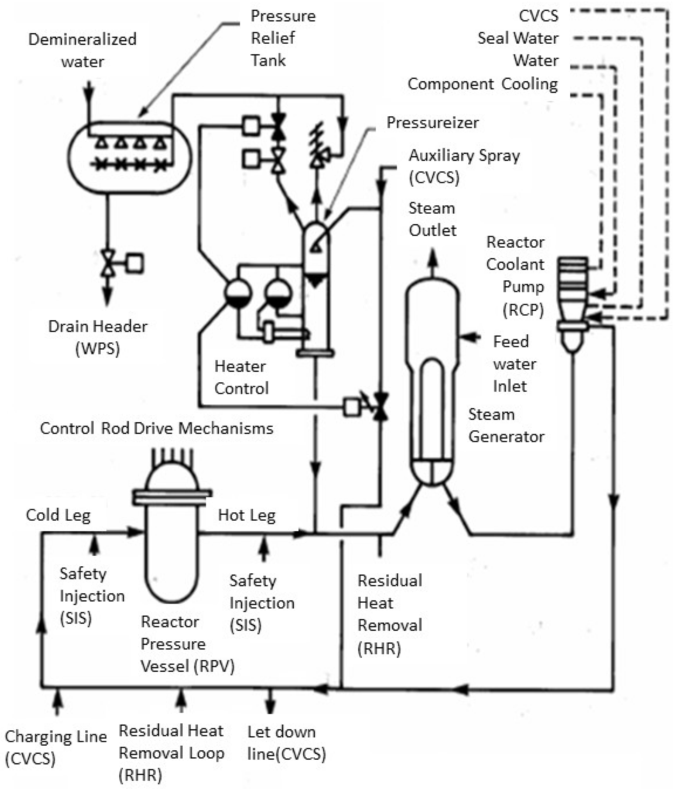


Figure 9 - Example of a Steam Supply system P&ID (adapted from Westinghouse Electric Corporation, 1994)

2.1.2 Step B - Apply Nuclear Specific Connections Penalties

Step B in the process (Figure 8) is to assign the nuclear specific connections penalties from Table 2 to the system connections in the design structure matrix.

Class	Safety Class Penalty (SCP) Description	SCP	PSP
1	Highest rating, for in-containment components directly associated with the primary coolant system.	6	-
2	For components required for emergency purposes.	4	-
3	For components which support class 2 equipment or a primary system.	2	-
NNS	For systems related to non-safety balance of plant functions.	1	-
Class	Pipe Size Penalty (PSP) - Pipe outer diameter	SCP	PSP
S	Small ≥ l0 cm	-	1
M	Medium ≥25 cm	-	3
L	Large ≥46 cm	-	5

Xl	Extra Large ≤46 cm	-	7

Table 2 - Pipe Safety Class And Size Penalty Values from (Lapp and Golay, 1997)

The connections penalty (CP) matrix (Figure 10) for each connection is calculated with equation (2) using the previous connections from the DSM, Safety Class Penalty (SCP) and Pipe Size Penalty (PSP) in Table 2. The SCP and PSP values of Lapp and Golay, Appendix C (Lapp, 1989) are used.

$$CP_{ij} = DSM_{ij} \, x \, PSP_{ij} \, x \, SCP_{ij} \qquad \text{Equation (2)}$$

This is then put into the *n* by *m* system matrix.

2.1.3 Step C - Matrix reordering

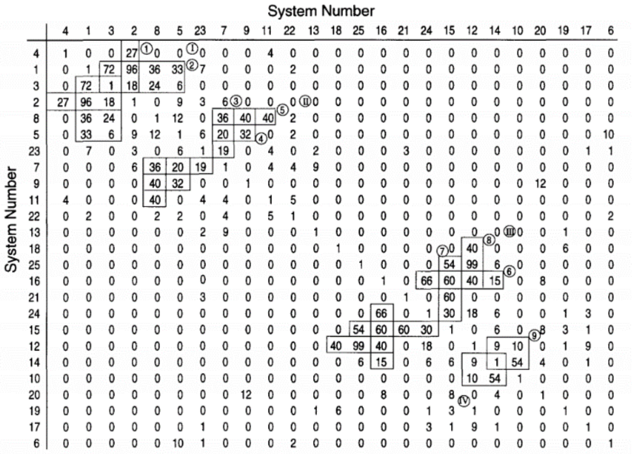
The *n* by *m* system matrix is reordered to group components together, assuming that the matrix's values are non-negative elements. The objective function of the matrix clustering is to maximise the measure of effectiveness (ME), which is defined as:

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

The reordering algorithm is achieved by:

- Multiplying each element CP_{ij} of the matrix by the sum of elements neighbouring it
- The rows or columns are summated to acquire the bond energy algorithm (BEA) value.
- The rows and columns are reordered within the matrix until this reordering maximises value of the BEA.

The final clustered matrix is shown in Figure 10 with the clustering algorithm identifying 4 clusters.



System Number (rows and columns)

	4	1	3	2	8	5	23	7	9	11	22	13	18	25	16	21	24	15	12	14	10	20	19	17	6
4	1	0	0	27	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	1	72	96	36	33	7	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	72	1	18	24	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	27	96	18	1	0	9	3	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	36	24	0	1	12	0	36	40	40	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	33	6	9	12	1	6	20	32	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	10
23	0	7	0	3	0	6	1	19	0	4	0	2	0	0	0	3	0	0	0	0	0	0	0	1	1
7	0	0	0	6	36	20	19	1	0	4	4	9	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	40	32	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0
11	4	0	0	0	40	0	4	4	0	1	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	2	0	0	2	2	0	4	0	5	1	0	0	0	0	0	0	0	0	0	0	0	0	0	2
13	0	0	0	0	0	0	2	9	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	40	0	0	0	6	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	54	99	6	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	66	60	40	15	0	8	0	0	0
21	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	1	0	60	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	66	0	1	30	18	6	0	0	1	3	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	54	60	60	30	1	0	6	0	8	3	1	0
12	0	0	0	0	0	0	0	0	0	0	0	0	40	99	40	0	18	0	1	9	10	0	1	9	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	6	15	0	6	6	9	1	54	4	0	1	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	54	1	0	0	0	0
20	0	0	0	0	0	0	0	0	12	0	0	0	0	0	8	0	0	8	0	4	0	1	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	1	6	0	0	0	1	3	1	0	0	0	1	0	0
17	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	3	1	9	1	0	0	0	1	0
6	0	0	0	0	0	10	1	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Figure 10 – Reordered system matrix to cluster components (Lapp and Golay, 1997)

In this study, the highly grouped systems are then heuristically assigned to modules which are close together, this results in the layout shown in Figure 11.

In future studies, this matrix reordering could be combined with an allocation and packing algorithm to perform this task of assigning components to modules, but the detail was not sufficient in the data for this to be a focus in this case study.

2.1.4 Modified Shearon Harris Nuclear Plant Results (Lapp, 1989)

The study highlighted a potential capital cost savings of 15% with the assembly area on site construction method. The safety related systems in the plant are grouped in top left two clusters:

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

The Residual Heat Removal and Containment Spray module (RHRCS) and Safety Injection System module (SIS) are then located close to containment due to the high connectivity between these systems and systems inside containment (RCS). The Component Cooling Water (CCW) modules are then located close to these. The Chemical and Volume Control System (CVCS) is located near to the waste process building due to its high connectivity.

We converted the floor plans for this plant (Lapp, 1989), (pages 212-244 and figures 6.3a-6.9d) into a representative MATLAB model (Figure 11) for use later in the study. The nuclear island RCS system can be seen within the transparent grey cylinder (Figure 11). The Reactor Cooling System (RCS) is located within here and includes the Reactor Pressure Vessel (RPV), Reactor cooling pumps and Steam Generators. Non connected systems like the heating and ventilation and electrical modules have been omitted.

Located on three sides of the nuclear island are balance of plant systems listed in (Figure 11). When the modules are in this configuration it means that if these systems are connected like the CVCS is connected to the CCW and RHRCS systems, pipework will have to travel all the way around the nuclear island, adding substantial costs to installation. This is especially signification when studies show piping and installation costs in a fluid-process plant can be as much as 20% of the fixed-capital investment according to Peters and K.D. Timmerhaus, (1991).

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	HVAC	CCW Surge Tank	4	

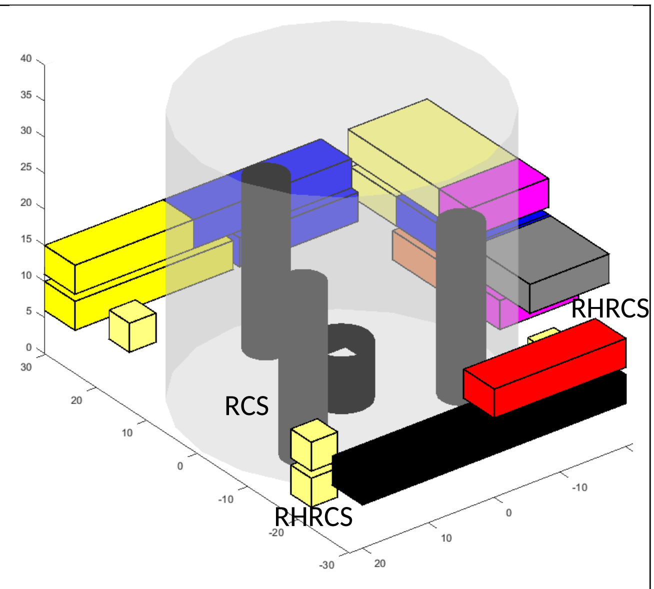


Figure 11 –Shearon Harris Power Plant MATLAB model

3 Step 2a: How modules are arranged (layout optimization)

In this section, the layout optimization for balance of plant modules is outlined (step 2a, Figure 7).

3.1 Case study data

For this paper, we utilise the same case study as (Lapp, 1989) in the Shearon Harris Nuclear Power Plant, a previous modularisation study based on assembly area on site. The data for the power plant is publically available, unlike current designs for SMRs as they are commercial ventures and have not published data/ or given permission to publish data.

SMRs target the use of factory built modules; increasing productivity, quality and requiring less rework to benefit the construction schedule. Although the modules in this study are too large to be transported (6m) it is envisioned that this model could be scaled, and the modules redesigned for transport, to fit any of the SMR technology in the IAEA (2018) Advanced Reactors Information System handbook.

In future, the development of a component allocation and packing algorithm (step 1, Figure 7), would enable SMR developers to design balance of plant modules with their own P&ID and component data for transport requirements. In using this case study, it was found that the information was not detailed enough to provide component geometries for component allocation and component layout. We therefore utilise the same component to module allocation and size from the previous study but also analyse the modules in a standardised grid.

3.2 Remapping the design structure matrix for module optimization

The general process for layout optimization is outlined in Figure 12.

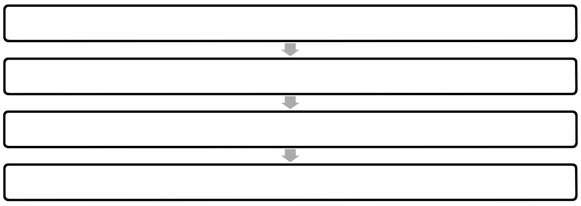


Figure 12 - Method for layout optimization

The first two stages are the same as the method for grouping components in Figure 8. However, the matrix of connections in (Lapp and Golay, 1997) cannot be utilized directly in this study as the connections refer to systems, which can be distributed across many modules (Figure 11). This required the connections matrix to be recreated using “Appendix C MBIVs for Shearon Harris and Shearon Harris II Nuclear Power Plants” (Lapp, 1989) (pages 419-424). There were 19 modules identified in the plant with connections to each other. This results in the following design structure matrix (Figure 13).

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

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

Figure 13 – Revised Connection penalty matrix for the Shearon Harris Power Plant

3.3 Literature Review of Layout optimization

Plant layout is an important aspect of plant design and mistakes can lead to cost increases and accidents (Moran, 2016). It is a highly combinatorial problem and described as NP hard. There are three main methods to solving combinatorial problems: heuristics, optimization algorithms or iterative methods.

Facility layout problems are similar to plant layout problems, considering flows between departments in offices, or manufacturing and assembly. Some of the early work in this field includes (Rosenblatt, 1979) who combines the early work of allocating facilities quantitatively using material handling costs (E.S Buffa, 1964) and qualitative work on subjective closeness ratings (Seehof et al., 1966). Many works have extended this to develop extra capabilities such as considering multi-floor layouts (Bozer et al., 1991). Francis and White, (1974) provided a comprehensive guide to the facility layout and problem for production facilities analyzing material flows, storage, location, networks, single and multi-planar problems.

(Anjos and Vieira, 2017) reviewed three main facility layout problems: row layout, unequal-areas layout, and multifloor layout. They proposed a general formulation for multifloor layout summarize that symmetry remains a key problem in facility layout problems.

3.3.1 Heuristics for plant layouts

Heuristics (rules of thumb, intuitive judgment, and common sense) for plant layouts were first developed to aid in plant design. (Amorese et al. (1977), first looked at using a learning procedure to layout a chemical process unit to minimize the costs of the plant. They found numerical experimentation yields general criteria for the appropriate policy to structure the learning process. (Kern, 1977) developed works to consider implementation of different equipment in a plant.

3.3.2 Mathematical programming approaches

Mathematical programming techniques were then applied to the plant layout problem.

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

Barbosa-Póvoa and Macchietto, (1994) consider a MILP formulation for multipurpose batch plants. The objective function is to minimize the capital costs and to maximize the plant profit. They consider the optimal selection of both the equipment units and the network of connections to satisfy production requirements.

Penteado and Ciric introduced a Mixed Integer Non Linear Programming (MINLP) approach for safe process plant layouts (Penteado and Ciric, 1996). They utilized an objective function to minimise the cost of piping, land cost, financial risk, and device protection cost.

Jayakumar and Reklaitis introduced graph partitioning (Jayakumar and Reklaitis, 1994) for the production of cosmetic grade isopropyl alcohol. They utilized an objective function to minimise connections between components.

Georgiadis & Macchietto applied Mixed Integer Non Linear Programming (MILP) to the chemical process plant layout problem considering allocation of equipment to equal area locations (Georgiadis and Macchietto, 1997) and allocation of equipment to non-equal areas (Georgiadis et al., 1999). The objective function considers pipe, land and pumping costs.

Papageorgiou & Rotstein extended this model to consider a continuous domain single floor MILP model (Papageorgiou and Rotstein, 1998). Patsiatzis & Papageorgiou then extended it further to multi floor (Patsiatzis and Papageorgiou, 2002a) and developed a decomposition and an iterative approach (Patsiatzis and Papageorgiou, 2003). The decomposition approach is largely more accurate and expensive in processing time, while the iterative approach is the reverse. They also suggested an MINLP model by adopting rectangular shapes and rectilinear distances (Patsiatzis and Papageorgiou, 2002b) and another method also considering safety (Patsiatzis et al., 2004).

Guirardello & Swaney studied MILP optimization of process plant layout and added the consideration of pipe routings (Guirardello and Swaney, 2005).

(Park et al., 2011) use MILP to consider safety factors in a multi-floor plant layout problem.

(Han et al., 2013) used MILP to formulate a process layout optimization problem with risk zones. The objective function included pipeline connection cost, land cost and installation cost of the additional protective devices.

(Martinez-Gomez et al., 2015) introduced a MILP problem accounting for future expansions through a multi annual framework also considering economic and safety objectives.

3.3.3 Metaheuristic approaches

Metaheuristic approaches have been proposed to add additional functionality over mathematical programming or to produce a near optimal solution to a problem which would be too computationally time intensive to search fully. A metaheuristic is a higher-level procedure or heuristic which is designed as a partial search algorithm as it samples only part of the entire search area.

Suzuki et al. (1991) proposed an evolutionary algorithm approach for plant layouts as it is difficult to solve costs and preferences simultaneously using MILP. Piping and site costs are considered in the objective function as weighted preferences. Equipment is also grouped together in modules to save calculation time.

More recent methods include Genetic Algorithm approaches for large facility layout problems that may provide a more efficient time solution but are sub optimal (Balakrishnan et al., 2003).

(Xu et al., 2013) improved the genetic algorithm using a hybrid approach and added toxic gas dispersion constraints to the layout problem.

(Alves et al., 2016) consider using Monte Carlo simulation integrated with simulated annealing.

(Latifi et al., 2017) used a bat metaheuristic algorithm to solve an MINLP process plant layout problem with the consideration of toxic release risk and possible scenarios of fire and explosions.

(Palomo-Romero et al., 2017) propose an Island Model for the genetic algorithm to solve the problems of premature convergence, lack of diversity, or high computational cost from different methods.

(Ruiqi Wang et al., 2017) combine works of (R. Wang et al., 2017), which expand work on the Dow's Fire and Explosion Index Method to an industrial area layout optimization method using a genetic algorithm, with (Wu and Wang, 2017) who consider piping implementation for area wide layout, implementing Kruskal’s algorithm for solving the multi-branch pipe network of material flow. The resulting work objective function considers explosion and toxic release safety, material and steam piping cost simultaneously with connection cost. (Wu et al., 2018) add to the area-wide layout design method by considering piecewise steam piping.

(Wang et al., 2018) combine a surplus rectangle fill algorithm with a genetic algorithm to solve the plant design problem. The objective function consists of piping investment cost, pump power cost, land cost, and floor construction cost.

(Lee, 2018) reviews genetic algorithms in operations management and suggests areas for further research.

Most of the work in plant layout optimization has been to consider an objective function of pipe, pumping, connections, safety or land costs. This had been performed in some form of linear programming which is generally achieved in commercial optimization software such as CPLEX or GAMS. More recently, the focus has moved to metaheuristic approaches in genetic algorithms.

Fujita et al., (1994) utilized a hybrid approach to nuclear power plant layout design. A rule based expert system was utilized to generate constraints and a preliminary layout is achieved through constraint-directed search using a depth first search procedure in common LISP with object oriented programming. The positions are then fixed using MILP. The objective function was to minimize the volume of the building.

3.4 Layout optimization method

To analyse the layout of modules in a standardized grid, the problem will be formulated as a facility layout problem. The objective function for this problem is therefore to minimise piping distance between the modules in the standardized modules concept. For future studies, component allocation and module size could be changed, but this is not within the scope of this paper.

The final step is to input the data into the optimization algorithm. Figure 11 shows the number of modules that need to be assigned to locations within the standardized grid concept of Figure 5. To accomplish this, a binary optimization variable y_{ik} matrix is utilized consisting of the number of modules *i* and the number of locations *k*. It allows the modules to be assigned to locations in the standardized grid in Figure 14. The binary optimization variable constraint in Equation (3) specifies that each module *i* must be allocated in one of the given locations *k* (Mathworks, 2018a) (Mathworks, 2018b):

$$\sum_{k=1}^{K} Yik = 1$$ Equation (3)

The constraint in Equation (4) specifies each location may occupy at most one module (Mathworks, 2018a):

$$\sum_{i=1}^{N} Yik \leq 1$$ Equation (4)

To determine the locations of the modules variable expressions are used:

$$X_i = \sum_{i=1}^{N} Xlocations \times y_{ik}$$ Equation (5)

$$Y_i = \sum_{i=1}^{N} Ylocations \times y_{ik}$$ Equation (6)

$$Z_i = \sum_{i=1}^{N} Zlocations \times y_{ik}$$ Equation (7)

To calculate the distances between the modules the following constraints are applied.

$$H_{ij} = \sum_{i=1}^{N} X \times (y_{ik} ¿ - y_{jk}) ¿$$ Equation (8)

$$F_{ij} = \sum_{i=1}^{N} Y \times (y_{ik} ¿ - y_{jk}) ¿$$ Equation (9)

$$V_{ij} = \sum_{i=1}^{N} Z \times \left(y_{ik} ¿ - y_{jk} \right) ¿ \qquad \text{Equation (10)}$$

$$\left(For\, i = 1, \ldots, N-1,\; j = i+1, \ldots, N \right)$$

The objective function for this problem is to minimise piping distance between the modules.

$$minOF = \sum_{i,j,i<j} \left[CP_{ij} \cdot \left(H_{ij} + V_{ij} + F_{ij} \right) \right] \qquad \text{Equation (11)}$$

The model was implemented in MATLAB 2018a using a genetic algorithm (Mathworks, 2018c) default arguments. A genetic algorithm was chosen because it is capable of solving combinatorial problems with multidisciplinary design optimization (Fujita et al., 2014). Furthermore, it can be combined with other algorithms hierarchically (Fujita et al., 2014), which would be useful in future case studies on optimization on components within the module and allocating components to modules.

For the optimization, two scenarios will be studied. These are where the 6m wide balance of plant modules are located on either one or two sides of the nuclear island. The assumption is that distances are calculated from the middle of the module using rectilinear distances. In the standardized grid scenario (Figure 14), a 3m gap is left in between modules to allow for access and shielding requirements. The grid for the allocation of modules was placed at -27m in the y direction relative to the RPV. Floor heights for the Z direction were at 3m, 8m, 13m and 18m.

Height		Width						
		-27	-18	-9	0	9	18	27
	18							
	13							
	8							
	3							

Figure 14 – Standardized grid system representation

4 RESULTS

The objective function total for the original Shearon Harris Power Plant was calculated at 26700. The fixed main safety systems; SIS, RHR, and CS, that are connected to the RCS account for 11786 of the pipe score. This pipe score is fixed because the systems are already in the optimum locations and this was determined in the previous study (Lapp and Golay, 1997). The balance of plant safety systems therefore have a pipe score of 14914.

In the scenario where modules are located on two sides of the nuclear island, both three and four floor layouts were assessed. A three-floor layout was the minimum as a two floor layout does not have enough space for all the modules to be allocated. The four floor layout (Figure 15) resulted in a balance of plant objective function of 9279, whereas the three-floor layout (Figure 16) resulted in a score of 9993.

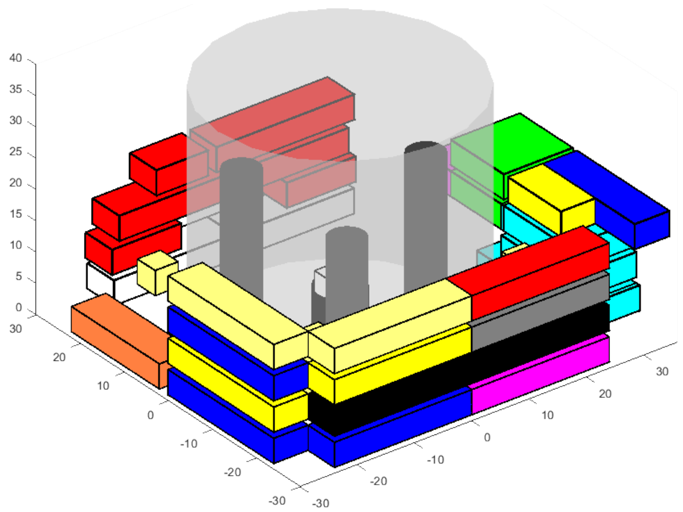


Figure 15 – Four-floor layout for modules located on two sides of the nuclear island

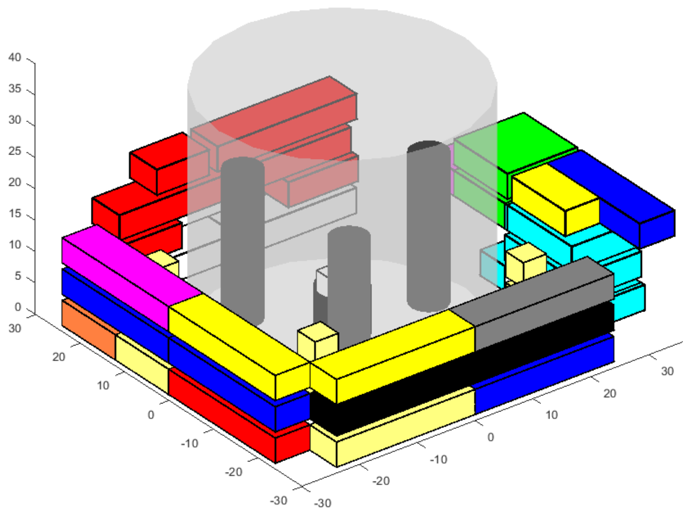


Figure 16 - Three-floor layout for modules located on two sides of the nuclear island

For the three-floor standardized grid scenario (Figure 17), the BOP objective function was 8174, whereas the four-floor layout (Figure 18) was 8036. This represents a significant saving on the original plant, a reduction of 46.1%.

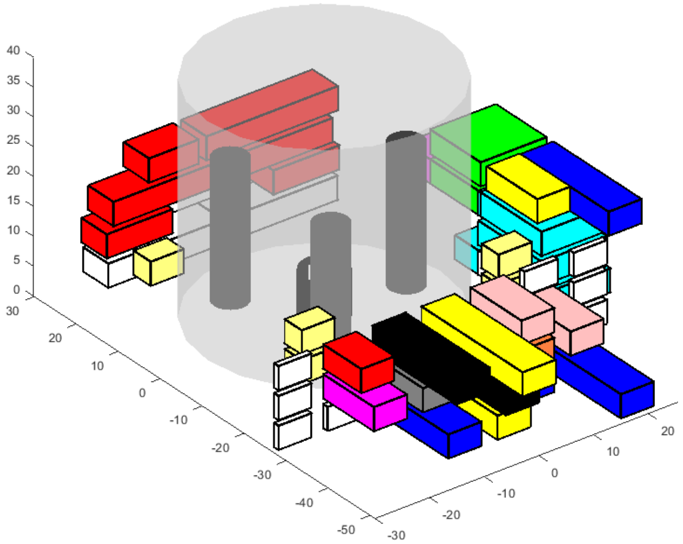


Figure 17 - Three-floor layout for modules located in a standardized grid on one side of the nuclear island

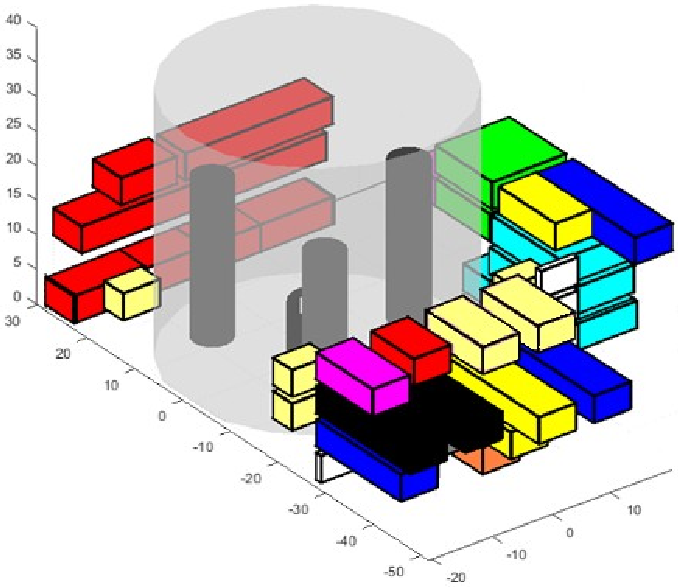


Figure 18 - Four-floor layout for modules located in a standardized grid on one side of the nuclear island

The results of the variations of layouts studied are tabulated in Table 3.

Number of sides	Number of floors	Objective function score	GA generations	GA function counts
Two	Three	9993	53	5021
Two	Four	9279	55	5144

One	Three	8174	67	6946
One	Four	8036	58	5538

Table 3 - Objective Function and Genetic Algorithm performance results for different layouts

5 Discussion

Locating the modules on two sides of the nuclear island design is a similar configuration to the original designs for the plant, where modules were located around all four sides. For the three and four floor layouts in this configuration, the BOP pipework score function was reduced by 37.8% and 33% respectively.

For the standardized grid, three and four-floor layouts were reduced by 37.8% and 46.1% respectively.

Furthermore, this arrangement may lend itself better to modularization, as modules can be easily located within the grid structure and may aid construction scheduling (Lloyd and Roulstone, 2018) and build method (Maronati et al., 2018). This grid arrangement, (integrating the structure, mechanical, electrical and instrumentation into a standardized composite module (Haney, 2012)), lends itself to removing as much as possible of the work offsite to factory build (Lloyd and Roulstone, 2018).

Some areas for further research could include analyzing different sizes of modules for different modes of transport. This would require a method for allocating components to modules (Lapp and Golay, 1997) and more detailed data on component sizes which were not available in this data.

Other methods from the literature could be implemented such as the safety considerations and site location planning. Working on more detailed SMR design data would enable flows between modules and systems and therefore pumping penalty scores could be added for operation.

6 CONCLUSIONS

In conclusion, a module layout optimization model for the Shearon Harris Power Plant was developed. It built upon modularization work performed by Lapp and Golay, (1997) and previous works in plant layout optimization. The literature review highlighted that no optimization has been performed previously for nuclear power plants. The paper assessed two scenarios, with modules located on either one or two sides of the nuclear island. For modules located on two sides, the objective function for Balance of Plant modules was reduced to 9993 and 9279 for the three and four floor layouts respectively. The optimization reduced the objective function for balance of plant modules in a standardized grid from 14914 for the original plant, to 8174 and 8036 for three and four floor layouts respectively, a reduction of 46.2%. The optimization allows for the exploration of thousands of combinations of modules, something which would take years for a manual process.

Research Directions

A literature review on dynamic plant layout optimization (Chandratre and Nandurkar, 2011) recognized that a combination of different algorithms for optimization at various stages of layout planning and implementation would be useful to obtain the most effective performance. Different algorithms such as: Particle Swarm, Simulated Annealing MILP, MINLP, could be assessed.

Component allocation was not studied in this paper as there was not enough definition in the data to obtain component sizes. Further work could investigate this problem which would also enable different sizes of modules to be studied. Another avenue of research could be to study the arrangement of components within modules.

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