UKAEA-CCFE-PR(23)138

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Modular Reactors - What can we learn from modular construction and industrial plant research?

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This is a preprint of a paper submitted for publication in
Nuclear Engineering and Technology

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Acknowledgments

This work was funded by Rolls-Royce Plc, the University of Derby and the UKAEA.

Abstract

New Technologies such as High Temperature Superconducting magnets and advanced computing in Fusion Reactors, Advanced Generation IV Reactor Technologies or Off-Site Modular Construction are exciting developments in low carbon energy. Modular Reactors enable "factory shop build and transport to site" according to the International Atomic Energy Agency who record over 11 commercial "demo" fusion reactors and 40 Advanced Generation IV technology designs in commercial development worldwide. Factory build takes advantage of productivity, environment and equipment improvements to reduce schedules and direct costs. Furthermore, much of the commissioning and qualification can be completed in factories, further reducing risk to schedule delays.

There is a strong background in modular manufacturing and construction in the industrial chemical plant and construction industries. These industries have implemented modular design techniques and construction. Understanding learnings from these industries could benefit Reactor construction by applying these methods. Therefore, the objectives of this review paper are to understand the state of the art in Off-Site Modular Construction and Industrial Modular Chemical Plant Design through a systematic literature review. This research can then be analysed and adapted for use in modular reactor development. Applicable research was highlighted for further work exploration.

keywords

Modular Reactors, Fusion, Off-Site Modular Construction (OSMC), integrated modular design process.

Abbreviations

Advanced Modular Reactor (AMR)s.
Building Information Modelling (BIM)
Mechanical Electrical and Plumbing (MEP)
Off-Site Modular Construction (OSMC)
Process and Instrumentation Diagrams (P&ID)

1 Introduction

New technology developments in Fusion, enabled by new High Temperature Superconducting magnets and advanced computing and through Generation IV technologies has spurred new reactor developments worldwide. Low carbon power is ever more imperative as highlighted in the United Nations Intergovernmental Panel on Climate Change Sixth Assessment Report and recent energy security concerns in Oil and Gas.

Costs can be reduced if there is a strong national government effort to deploy multiple standardised units of the same design as those that have been achieved in South Korea (Gilbert et al., 2017) (Koomey et al., 2017).

Modularisation can reduce costs through transferring work from in situ construction to parallel working. This can be either completing work in an onsite assembly area or off-site in factories, reducing construction schedules and reducing financial risk.. Previous research into modularization in nuclear has focused on adapting large nuclear plants for on-site assembly with very large modules to reduce the critical path (Sutharshan et al., 2011). This is similar to techniques used in the oil and gas industry where remote and weather adverse locations labour is expensive and difficult. Modular construction in oil and gas has shown up to 20% in direct costs savings and up to 50% in schedule reductions (Mignacca et al., 2018).

There is a strong interest in Small Modular Reactors (SMR)s development worldwide. SMRs are smaller than large nuclear power plants, typically less than 300MWe, permitting siting at remote and weather adverse locations. They also frequently embrace integrated nuclear steam supply systems, reactor and steam supply in one module. SMR’s defined as “factory shop built and transported to site” by the International Atomic Energy Agency, record over 30 light water SMR and 40 Advanced Generation IV technology designs in commercial development worldwide. This reduces construction activities and commissioning can be completed in factories. Factory build takes advantage of productivity, environment and equipment improvements to reduce schedules and direct costs. Furthermore qualifying systems in factories before transportation to site, improves quality and further reduces risk. Research conducted on modular nuclear shipbuilding evaluates that manufacturing systems in a factory may be 8 times more efficient than executing the same techniques on site (Barry, 2009)..

Similarly, the construction industry in advanced economies, where labour is expensive, has also seen reduced productivity (Bock, 2015a) over the past few decades.

Thus, an emerging trend in the construction industry is to manufacture parts off the critical path, the sequence of critical activities performed for the project to be completed. These are built off site, in factories, through modular design to reduce schedules and direct costs. Off-Site Modular Construction (OSMC) has significantly boosted efficiency in construction in recent years (Jin et al., 2018) and has witnessed an exponential interest in research over the past decade (Hosseini et al., 2018). Furthermore, a study from shipbuilding estimates that work done in a factory may be 8 times more efficient than performing the same work in situ on site

Therefore this systematic literature review aims to analyse the industrial process plant and OSMC industries research to comprehend and identify what reactor developers may be able to learn and apply for more successful modular reactors deployment.

This paper aims to explore the most forefront research in off-site modular construction and chemical industries, compare this to research in the nuclear industry and discover the application to modular reactors. The aim is to keep the paper reactor technology agnostic. This will be achieved by exploring 4 research questions:

- Understand the most up to date processes, analyses & design methods in industrial process plant and OSMC industries research literature (Section 3).
- What are the considerations and recommendations from these industries research literature (Section 3.6).
- What are the research gaps between these industries and nuclear industry (Figure 12, detailed in Table 2).
- What tools and research can be implemented into the module design development framework for modular reactors (Section 4).

2 Method

The Systematic Literature Review technique as discussed in Jin et al., (2018) and Mignacca and Locatelli, (2020) is used as a basis for this literature review and shown in Figure 1. The research paper exploration was accomplished on 4th May 2023 for the papers presented here.

Scopus was utilised for the search. Concentrating on the Scopus fields: titles “TITLE”, abstracts “ABS” and keywords “KEY”, research articles were identified. Articles concerning keywords with dissimilar semantic connotations were filtered out. The next step is to screen out articles that were not relevant to the research questions by interpreting the abstracts. The research articles were then analysed for their useful content and merit. To account for the replication of the process, the Five distinct searches in Scopus are abridged in Appendix B - Literature search papers.

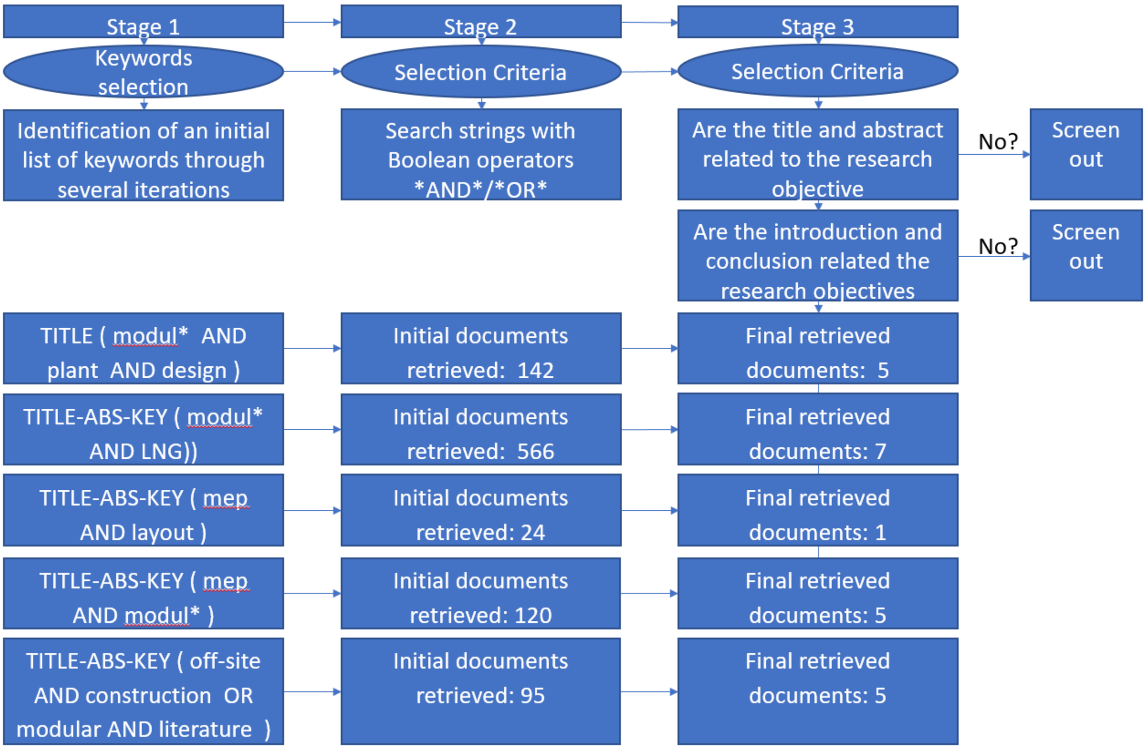


Figure 1 - Systematic Literature Review method adapted from Jin et al., (2018) and (Mignacca and Locatelli, 2020)

3 Results

Using the literature outlined from the search listed in Appendix B - Literature search papers, the outcomes from the literature exploration are debated in section 3. They have been divided into areas based on similar subjects:

- Chemical Plant Industry
    - Cost and schedule reduction examples in industry,
    - Plant expansion decision tools
    - Equipment database generation and selection tools
    - Reusing previous designs
    - Module design
    - Plant layout
- Offsite Modular Construction literature reviews
    - Decision support tools
    - Transportation, logistics and scheduling and supply chain
    - Module and system partition
    - Site Layout
    - Integrating Building Information Modelling (BIM)

3.1 Small scale modular chemical plants

Process plant layout design is a discipline concerning how to position process plant equipment and related structures within a specified physical location, considering interconnections, construction, safety, operation and maintenance (Moran, 2016). Recently, however, due to the low productivity in the construction industry (Bock, 2015b), some chemical process plant research has focused on small scale OSMC. OSMC enables work to be taken off the critical path (minimum time needed to complete a construction project), into factories where productivity, environment, tools and processes are vastly improved compared to working on site. This can be cheaper, faster (66%) (Seifert et al., 2012) and more flexible (Michael Baldea et al., 2017), (Bielenberg and Palou-Rivera, 2019a) than traditional plants.

3.1.1 Cost and schedule reduction examples in industry

(Bramsiepe et al., 2012) provide examples of modular plants in the food processing and biofuels industries future and present future developments. They assess how the industries may be affected by small and (Zeton factory-built (Zeton, 2021)) modular process units (Figure 2). Modular Building Institute, (2013) shows modular construction time can be shortened by 50%.

Figure 2 - Factory-built process plant modules (Bramsiepe et al., 2012) by ((Zeton, 2021)*)*

It was estimated that small modular plants could decrease the construction schedule by over 2 years (66%) and improve value by 35% (Seifert et al., 2012). (Kockmann, 2016) discuss examples of standardised and modular equipment and some aspects of design. Eftimie, (2016) states that modular construction reduced the schedule by up to 25-50% in offshore facilities. Developments in US process intensification and modular construction (Figure 3) were summarised in various industries: pulp & paper handling, chemical manufacture, gas processing and fuels refining (Bielenberg and Palou-Rivera, 2019b). They stress that in future, the two methods could also have a significant impact in water usability processes and carbon capture and utilisation. General Dynamics, (2020) showed the construction schedule could be reduced by 28% in its modular electric boat.

Figure 3 – Modular process plant (Bielenberg and Palou-Rivera, 2019b)

3.1.2 Plant expansion considerations decision tools

A number of decision tools were developed for plant growth: a real options framework methodology for plant growth regarding capability bottlenecks and multiproduct situations (Seifert et al., 2015) and the modular expansions of existing plants (Seifert et al., 2015) and expansion considerations for new plants (Sievers et al., 2016b).

3.1.3 Equipment database generation and selection tools

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 et al., 2014). As well as selection methods for equipment using reusable databases were then developed (Krasberg et al., 2014). A multi-objective evolutionary algorithm was developed to choose component modules for an adaptable modular manufacturing plant with minimal investment costs (Radatz et al., 2019). They highlighted for 50% greater investment costs, 11 times expanded working period can be achieved. Eilermann et al. then presented a method for plant design via module selection and outline. The requisite design responsibility modules are chosen from records and configured for all tasks in the design process from Process Flow Diagrams, Process and Instrumentation Diagrams (P&ID), equipment set and 3D layout tasks (Eilermann et al., 2018). They improve the method to cover more requirements while being more computationally efficient (Eilermann et al., 2019). Whereas a lot of work has been done on modular equipment databases, process flow diagrams, and P&IDs, very little work has been done on 3D layout for small, factory-built process plants (Eilermann et al., 2018). Furthermore, recent research has developed a method to investigate the use of process modules to fit to process system requirements considering the investment and operating costs (Radatz et al., 2021). These modules can then be combined into a larger system module.

3.1.3.1 Equipment database reusing previous designs

The capability of modules as reusable items were discussed (Hady and Wozny, 2010) and a module documentation internet administration software tool called Reuse-Atlas was produced for quality and assurance (Hady and Wozny, 2011). This was achieved using Windows®, Apache™, MySQL®, "PHP: Hypertext Preprocessor" and HTML. Student evaluation showed approval and acceptance of the technique. 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). The revision of process component designs from previous projects were utilised to create appropriate results for new projects (Fleischer-Trebes et al., 2017). A theory for data processing during the whole life cycle of the process industry from laboratory to production was defined (Hohmann et al., 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.

3.1.4 Module Design

Design decision making tools can efficiently and more optimally help in module design. 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%

An approach for assessing modular & non-modular fabrication situations was developed. The "F3" factory concept (Figure 4) was utilised as an example of assessing different production methods as well as the supply chain (Sievers et al., 2016b). This included a set of design guidelines for the process plant. (EU Community Research and Development Information Service, 2013b).

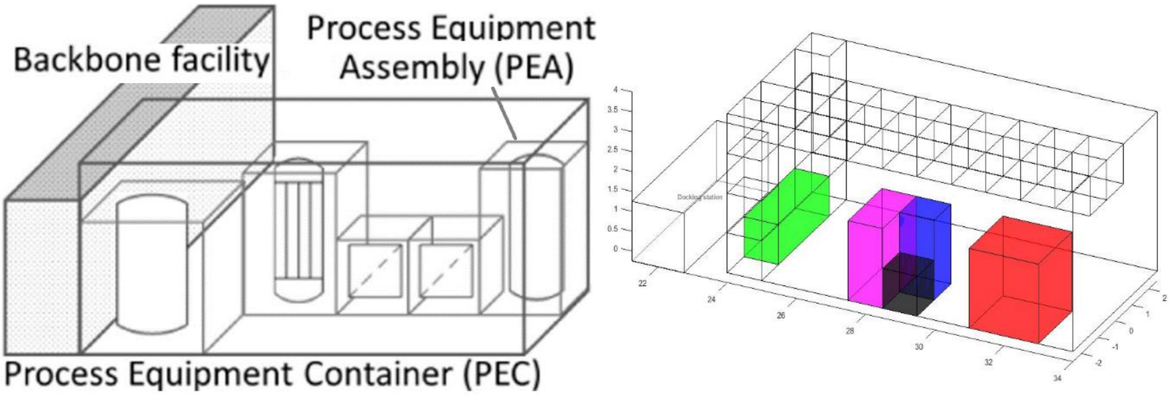


Figure 4 -Illustration of F3 factory modular elements (left) (Sievers et al., 2016b) *and F3 Factory design procedures and specifications for modular, module-based fabrication units characterised and applied in various process component modules (EU Community Research and Development Information Service, 2013b)*

3.2 Plant Layout

The optimal module layout for a generic offshore Liquid Natural Gas liquefaction process was defined (Ku et al., 2014). Although this is a module, it is not a modular design where equipment is located in road transportable, factory-built modules. Optimal module layout research should be considered however to reduce unnecessary pipe and electrical lengths and connection work on site.

A project with Aker Solutions and The University of Norway utilised Technosoft's Adaptive Modelling Language to perform layout optimisation of equipment on an oil rig using a bin packing algorithm (Marthinusen, 2016). Figure 5 shows an offshore rig layout developed using Knowledge Based Techniques through Technosofts Adaptive Modelling Language, (2018a)

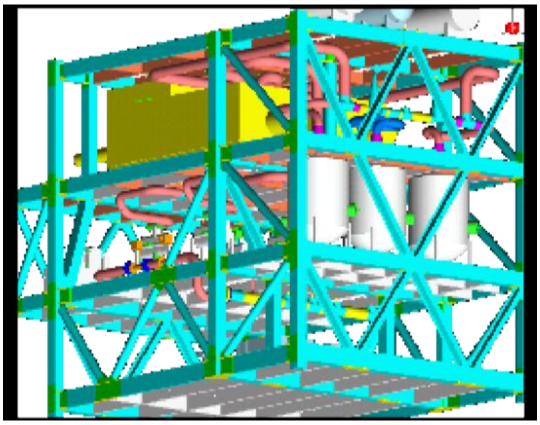


Figure 5 – Offshore Equipment layout performed using Knowledge Based Techniques through ©Technosoft, (2018a) AML

An expert system to arrange a submarine with a multistage optimisation was developed (Kim and Roh, 2016) and also applied to an offshore oil rig design (Ku et al., 2014)(Kim et al., 2015) (S.-K. Kim, Roh, & Kim, 2017), and a surface naval shop (Jung et al., 2018).

3.3 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. Most building areas of a plant utilise Heating, Ventilation and Cooling and MEP services and this is an important aspect to consider in plant design. A search for MEP modules was conducted to understand if similarities between modular MEP design and industrial plants exist.

3.3.1 Offsite Modular Construction literature reviews

The Scientometric literature review analysis performed by Hosseini et al., (2018) and Jin et al., (2018) found that 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 remains under researched (Martinez et al., 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 Robot approaches, construction automation technology, other microsystems technology and service robot systems are currently uniting with BIM (Bock, 2015a).

3.3.2 Decision support tools

There are several research items to consider for project decision tools. 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 et al., 1994). Taking important lessons from previous research where the advantages of modularisation and some commercial plants were summarised in the modular design of smaller-scale plants (Roberts, 2013). An evaluation of the modular method for industrial plant construction projects using the analytical hierarchy process and several evaluation criteria was developed (Choi and Song, 2014) analysing: Physical characteristics of piping, safety in the construction process, transportation of material and module, lifting plan and execution, vendor selection efforts, interface for connection points, procurement plan. They theorised a schedule reduction of 22% and higher quality and safety but highlight more effort in planning, design, assembly processes, procurement, transport and particular attention needs to be paid to interfaces and constructability. They then develop these factors further into a modularization business case analysis model using 5 levels of questions and an estimated cost benefit (Choi et al., 2019). How standardisation and modularisation can be compared and integrated for Modular Industrial Plants was assessed, again listing 10 advantages and 3 disadvantages and providing future research directions (O'Connor et al., 2015). Experience and lessons learned over several recent offsite modular projects were described outlining considerations, requirements, and criteria for module design during marine transportation (Bai et al., 2016). Supporting decisions on oil and gas industrial plant were presented (Bondi et al., 2016). A research framework for stakeholders in off-site manufacturing was developed for future practice and improvement (Hu et al., 2019). A robust empirically based decision-support tool for decision makers and clients was outlined (Goodier et al., 2019) and validated with a mixed methodology incorporating an online survey, semi- structured interviews, a Delphi-style questionnaire and three industry workshops with experienced engineering construction practitioners where 46 drivers and 41 constraints were identified.

Some research focused on expansion Decision support tools. A real options framework methodology for plant growth regarding capability bottlenecks and multiproduct situations was presented (Seifert et al., 2015). Decision tools were also developed to analyse modular expansions of existing plants (Seifert et al., 2015) and expansion considerations for new plants (Sievers et al., 2016b).

3.3.3 Transportation, logistics and scheduling and supply chain

A two-stage stochastic programming model was applied for logistics planning in a residential construction sector project (Hsu et al., 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 et al., 2019). 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 et al., 2016). This Logistics planning and optimisation (Hsu et al., 2018) (Hsu et al., 2019) could be integrated with Scheduling optimisation (Anvari et al., 2016), Crane planning and optimisation (Taghaddos et al., 2018) and plant layout optimisation (Xu and Li, 2012), (Song and Choi, 2014) (Tanabe and Miyake, 2010) (Ku et al., 2014). As well as planning for robotics in off-site modular construction (Yang et al., 2019) and electric autonomous transportation. More research should develop techniques to analyse this part of the construction process to optimise costs, schedules and planning.

3.3.4 Module and system partition

A method to find the optimum selection of module configuration for efficient modular construction. 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 et al., 2017). The method showed efficient results in a residential construction project (Figure 6).

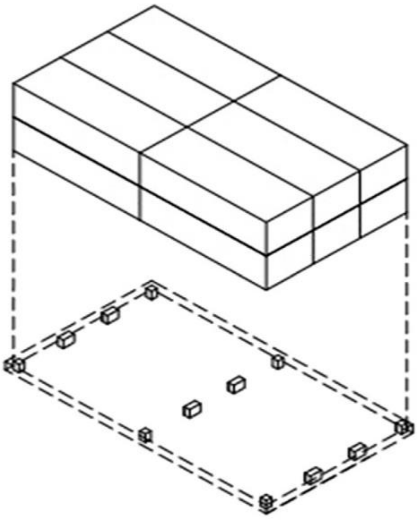


Figure 6 - Modules' foundation design in residential construction by Salama et al., (Salama et al., 2017)

Modular offsite production of fluid systems were analysed, identifying barriers and recommendations for successful implementation (Li et al., 2017), these should be considered in the modular design process such as BIM usage and starting with a threaded coupling mode.

A Monte Carlo tolerance simulation was applied to a preassembled building (Figure 7), highlighting that by using this method to improve tolerances, a major rework probability can be reduced from 100% to 34% likelihood of slight alterations (Rausch et al., 2019).

Figure 7 - Monte Carlo tolerance simulation on a preassembled building to improve tolerances to reduce rework probability (Rausch et al., 2019)

Tserng et al. found that modularising an MEP module (Figure 8) using planning algorithms reduced costs from $66,030 to $19,566 and saved 12 days in the construction schedule (Tserng et al., 2011).

Figure 8 - Fire suppression system decomposition, motor, foam tank and Generator (Tserng et al., 2011)

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

An automated efficient modularisation algorithm combining a Design Structure Matrix, fuzzy logic and Hierarchical Clustering methods were developed (Samarasinghe et al., 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 9).

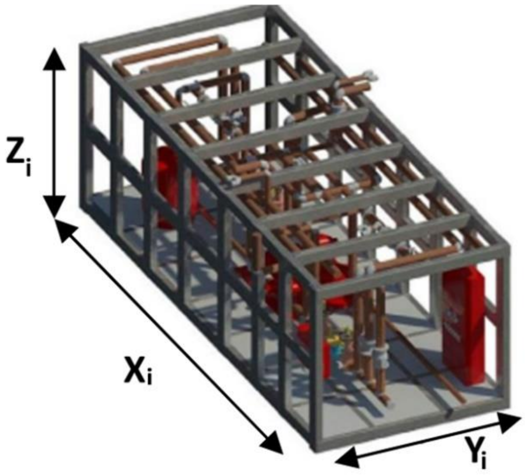
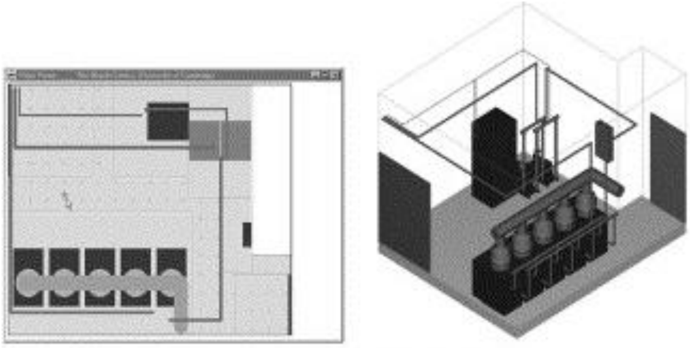


Figure 9 – Technique utilised to calculate dimensions of MEP modules using the equipment coordinates (Samarasinghe et al., 2019)

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



(e) area minimisation

Figure 10 - 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 new concept for standardized large-scale modular LNG plant design was presented (Kobayashi and Oba, 2019) highlighting signification savings in efficiency in design.

3.4 Site Layout

It is important to consider and analyse the optimal layout for construction and design to reduce the amount of pipework, electrical and human operator movement around the plant. A few OSMC research articles consider wider plant layouts (Taghaddos et al., 2018) (Xu and Li, 2012), (Song and Choi, 2014) (Tanabe and Miyake, 2010) (Ku et al., 2014). 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 (Xu and Li, 2012).

A method to automate and optimise crane planning and configuration (Figure 11) was conceived and applied to modular projects in Alberta, Canada (Taghaddos et al., 2018).

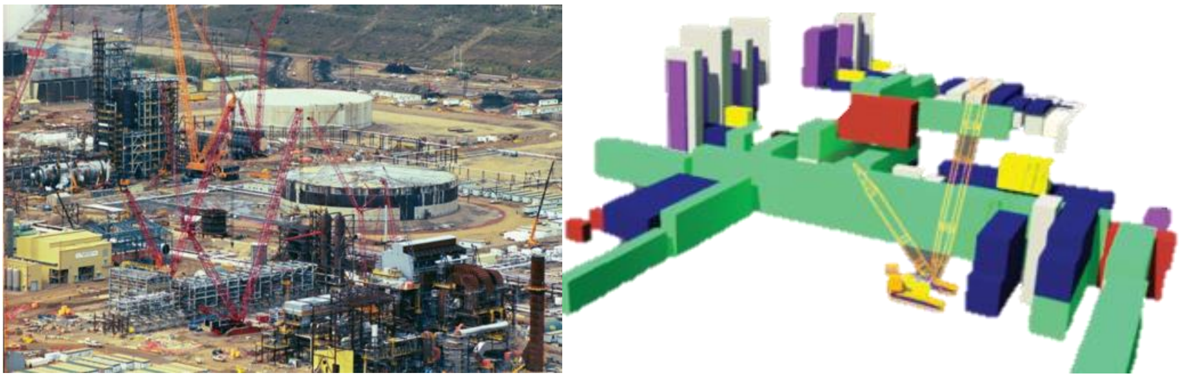


Figure 11 - Optimised crane planning and configuration for a modular project in Alberta, Canada (Taghaddos et al., 2018)

Some research focused on the safety aspects of design, critical for a successful industrial plant industry. A safety design approach for onshore modularized Liquified Natural gas liquefaction plant during the Concept Definition phase was presented (Tanabe and Miyake, 2010). They implemented "the safety critical design basis matrix" which provides "scenarios" to determine the design basis for the emergency systems considering common cause failure by external events. The "hazard-design logical relation tree" identifies the inter-relation between hazards for new applications. The effective implementation of inherently safer design during the design phase of modularized onshore LNG projects was outlined recommending: design options such as separation distance and operational requirements (Tanabea and Miyake, 2016). Consideration of implementing safer designs research should be investigated further for the most up to date methods for application in the industrial plant industry.

Modular manufacturing in shale gas supply chain design and operations was assessed for economic and environmental sustainability and future production (Gao and You, 2017). Utilising a life cycle optimization model, it was concluded Modular manufacturing could improve the economic performance of a shale gas supply chain. However, no impact was found on overall environmental performance, it did lead to more sustainable solutions. Key factors were identified such as drilling schedule, water management, and midstream infrastructure design and planning. 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 (M Baldea et al., 2017). Also discussed are the links between modularisation and process intensification. Process intensification may be useful for reducing the size of systems to fit into transportable modules. Manufacturing is an important consideration in modular design and construction and more research into this area would be required.

Examples of standardised and modular equipment and some aspects of design were outlined (Kockmann, 2016). The flexible design of a liquid heat exchanger was also developed through the deduction of heuristics and a global sensitivity analysis (Radatz et al., 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.

3.5 Integrating BIM

One of the main research areas in offsite modular construction is integrating BIM technologies. Literature reviews found BIM integration was a highly researched area and should be highly considered for modular reactors (Hosseini et al., 2018) (Jin et al., 2018) (Yin et al., 2019), (Martinez et al., 2019) (Bock, 2015a) along with methods for integrating BIM and design (Wang et al., 2016) (Cheng et al., 2020) (Ciribini et al., 2016) (Lee and Kim, 2014).

A pragmatic BIM outline for assimilating the MEP layout across all levels of the design was developed, highlighting early detection of errors, reducing schedules and costs (Wang et al., 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 et al., 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 et al., 2016). Another study found that a sequential BIM coordination approach was about 3x more efficient than a parallel method in a pharmaceutical MEP case study (Lee and Kim, 2014).

Developing a digital twin-concept for smart process equipment assemblies supporting process validation in modular plants could be a useful process for modular reactors (Mädler et al., 2022). Developing and integrating BIM approaches could enable efficient design and cost effective solutions.

3.6 Findings summary

As highlighted in previous nuclear modularisation literature, most of the modular design research in the nuclear industry has focused on converting a standard large nuclear plant for off-site modular construction (Figure 12, detailed in Table 2). This has typically focused on high level design process for large modules not designed for transport. Figure 12 highlights the scarcity of research into areas of modular system design in nuclear research in comparison of important research areas for modular in nuclear research and the industrial chemical plant and OSMC industries, underlining the importance in assessing this research.

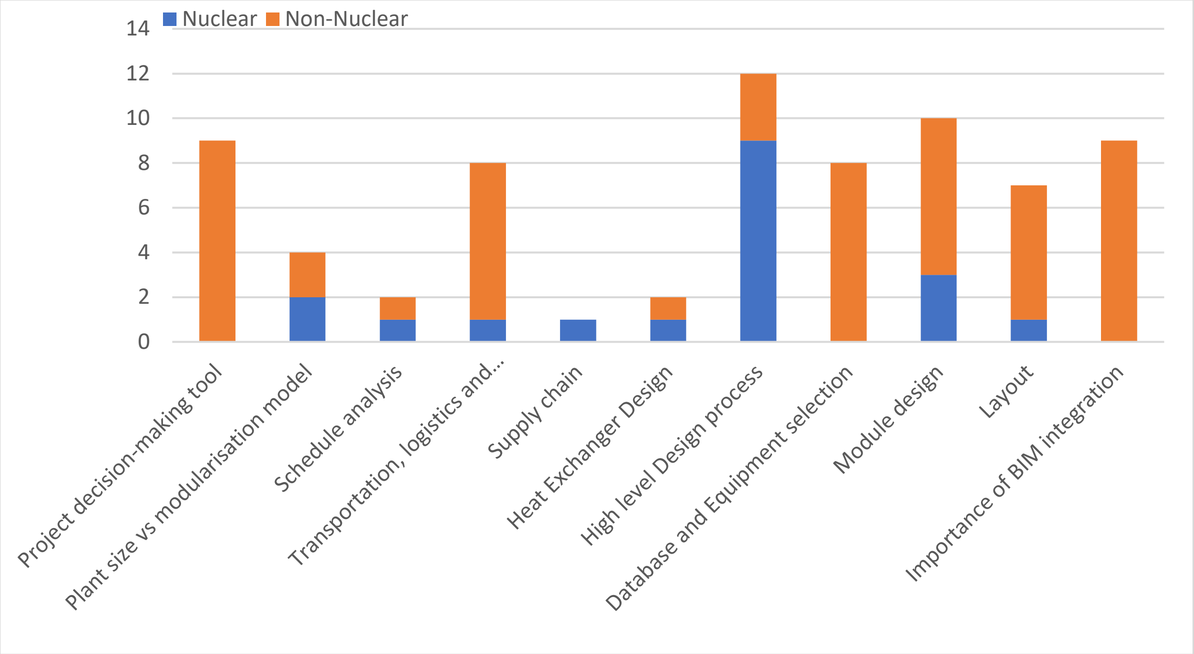


Figure 12 – Comparison of research areas for modular in nuclear research and the industrial chemical plant and OSMC industries.

Both the industrial chemical process plant industry and OSMC highlighted the benefits and significant cost and schedule that moving to a modular approach can bring. However, where industrial chemical process plant industry focused on single modules and equipment selection tools, the OSMC industry research focuses more on the wider site system, including the Transportation, logistics and scheduling and supply chain. Integrating both single module and the site wide approach could bring effective efficiency savings for modular reactors.

A lot of the research highlighted in this literature search has developed Decision support tools (Figure 12). These are very important to stakeholders to make investment decisions and useful to consider for modular reactors vendors.

The module design is very important. A lot of chemical plant industry research develops module databases and selection tools. Equipment selection algorithms can efficiently speed up the process. This enables plant designers to select equipment quickly and efficiently for the required specification for their design. A unified open database for standardised off the shelf equipment (tested, verified, and validated for use in the nuclear industry) would be extremely useful here. This would enable standardised equipment to be used in the nuclear industry, instead of bespoke one-off designs, further reducing costs.

Research articles in the OSMC industry develop wider system methods such as module partitioning methods and module design algorithms which should be prioritised for further analysis and development along with wider integration of module-to-module site wide layout algorithms.

4 Discussion – Towards a modularisation framework?

In Section 3, the literature was categorised according to similar subject areas. This provided the logical steps to move towards a development framework for modularisation as assessing project applicability and defining the build strategy based on location logically come first. Then assessing the plant systems and equipment for modular design. This was developed in conjunction with expert nuclear design engineers. A proposed outline is shown in Figure 13 and discussed in Section 4.

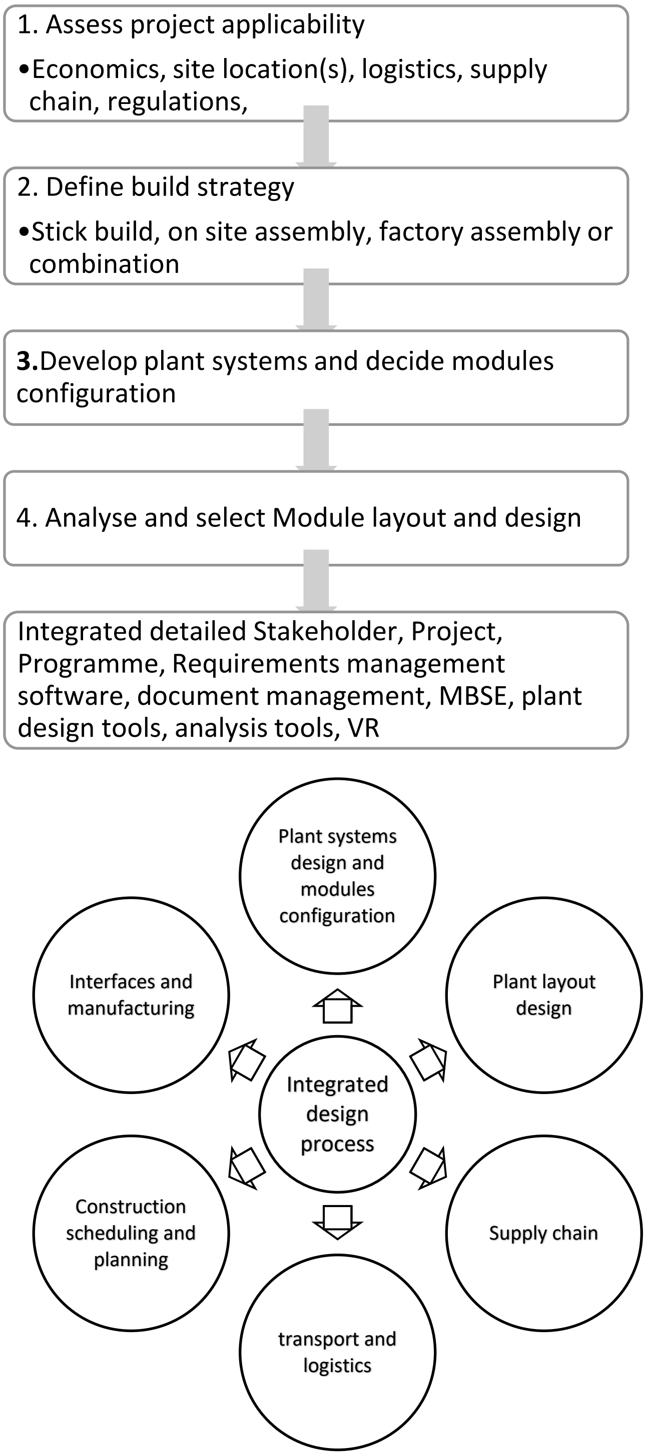


Figure 13 – Towards a modular design methodology?

4.1 Assess project applicability - Decision tools

The first step in a modularisation project is to determine if the project is suitable for modular construction. This will depend on many factors. The size of the plant, location, community stakeholders, supply chain and logistics. The build strategy can then be defined. Some research has focused on project and design decision making tools. Modularisation decision tools were developed for the oil and gas industry, which has mainly focused on large modules for remote and weather adverse locations, and may be useful in deciding on modularisation for a project. Modularisation decision tools may help modular reactor designers, governments and engineering providers decide on whether to use modularisation in reactors and which build method may be best suitable for their location.

Stakeholder analysis methods aid in understanding if the project is suited to modularisation (Choi and Song, 2014), (Choi et al., 2019) (O'Connor et al., 2015) (Bondi et al., 2016)(Mancini et al., 2016) (Goodier et al., 2019) and for stakeholders (Hu et al., 2019). When considering modularisation for a project, these considerations need to be assessed and taken into account. Utilising an assessment method for analysing modularisation for a project would be useful at this stage (Goodier et al., 2019). business decisions were outlined (Mancini et al., 2016) (Bondi et al., 2016), (J. O. Choi et al., 2019) finding the following considerations for oil and gas plants

Companies and projects need to consider if they are building a fleet approach where standardisation leads to learner benefits or if the plant is a one-off prototype, pilot or research plant. Plants with room for expansion or integration with cogeneration options may be developed and should also be a consideration in the design. Depending on this, parts or all of the plant may be stick built, assembled in an onsite assembly area, factory fabricated or a combination of all three. Studies suggest performing work in a dedicated off site factory may be up to 8x more efficient than performing work on site, a heuristic developed when assessing ship construction and performing work in an onsite assembly area may be 3x more efficient than performing the same work in situ (Barry, 2009).

An important consideration for modular reactors is the expansion of existing plants and the potential expansion of new plants for cogeneration such as desalination, building heating and hydrogen production. A couple of research items were highlighted as possible avenues for further exploration here (Seifert et al., 2015) (Seifert et al., 2015) (Sievers et al., 2016b).

A quick assessment of the industry supply chain, with regards to factory manufacture, assembly and warehousing as well as transportation, logistics and scheduling should be conducted.

- Manufacturing facilities and locations (Hsu et al., 2018). (Hsu et al., 2019).

- Lifting/transport equipment
- Build scheduling (Anvari et al., 2016).
- Customs and export requirements
- Government transport requirements for vehicle size, weight constraints & police escorts required.
- Requirements/lead time for permits.
- Community and environmental risks.
- At site transport logistics (Taghaddos et al., 2018).

4.1.1 Transportation, logistics and scheduling and supply chain

Transportation, logistics and scheduling is also an important consideration if you are moving to a factory-based manufacturing strategy. This Logistics planning and optimisation (Hsu et al., 2018) (Hsu et al., 2019) could be integrated with Scheduling optimisation (Anvari et al., 2016), Crane planning and optimisation (Taghaddos et al., 2018) and plant layout optimisation (Xu and Li, 2012), (Song and Choi, 2014) (Tanabe and Miyake, 2010) (Ku et al., 2014). As well as planning for robotics in off-site modular construction (Yang et al., 2019) and electric autonomous transportation. More research should develop techniques to analyse this part of the construction process to optimise costs, schedules and planning.

Transport is an important consideration in modular design (Salama et al., 2017) (Mignacca et al., 2019). The sizes and weights of modules for transportation are outlined in (Moran, 2016) and defined into 6 categories. The key size and weight considerations are: Predressed, Containers (25–30t, 12×2.5×2.5), Skid mounted (60–70t, 14×4×3.4), Onshore modules or preassembled units lifted (300t, 25×15×10) or ground installed (2000t, 40×25×25), Barge mounted and bedded at site (6,000–260,000 t, 184 × 44 × 13.8). The coming availability of electric, autonomous transport may make factory build more economical than current fossil fuel, human driven logistics of today. Within the EU (European Commission, 2008) consideration should be given to the size of transport for each scenario.

Table 1 - EU Framework for abnormal road transport permits

	No permit needed	Long term permit	Corridor (3)
Width	3m	3.5m	4.5m
Overall length	24m	30m	40m
Overall height	Directive 96/53/EC	4.2m	4.4m
Weight	Directive 96/53/EC	80 tonnes	100 tonnes

4.2 Define build strategy

Once a high-level assessment has concluded modularisation may be a good fit for the project, the next step is to understand the build strategy. Further detailed assessments should be conducted into the initial lessons learned from previous projects, supply chain, transportation, logistics and scheduling outlined in the previous section. This could be useful for standardising plants and for guidelines early in the design stage.

Consideration needs to be taken for if modules and systems will be built in factories, assembled in an onsite area or dockyard or stick built. Location is highly important, if the project location has access to the sea, rivers and dockyards, modules can be assembled in factories, then in a dockyard, and finally at site. Construction on land in a factory may also apply to areas without these facilities.

4.3 Develop plant systems and decide the modules configuration

Working with the system design engineers, the next step is to classify and break down modules and systems. Operational analysis should be conducted in conjunction with capital construction costs. Two main considerations are: Designing modules to fit the system or designing the system to fit the modules.

4.3.1 Designing modules to fit the system

For plants with predetermined designs, specialised plant projects and manufacturing plants at low production quantities, investment into an assembly factory would most likely be uneconomic. In this instance, a virtual Factory, whereby the equipment items are positioned into module space frames by the equipment manufacturers, could be adopted. This procedure ensures the demand and expenses for a dedicated assembly factory are abolished. The drawback is adding work on site as there are a higher quantity of discrete modules that are required to be connected on site, or in an on site assembly area. Therefore, this approach might be more appropriate to 'one off' plants (research and prototypes/ pilot plants), where improved learning rates from economies of multiples and additional factory and logistics capital costs would be more than the additional site costs.

4.3.2 Designing the system to fit the modules

The other option is to design the system to fit the modules. Choosing the module size for various design factors such as factory handling, transport and logistics, site construction. Designing the modules to maximise this design requirement enables more work to be performed off site. Standardised module sizes may enable economies of mass production and more efficient construction at site (Figure 3). A combined scheme can perform work in a factory and assemble those modules into a larger module system on site or in a dockyard.

4.4 System design and layout

The next step is to start designing the plant system layout. Working alongside the system design engineers, plant designers should start deciding how to partition and separate the modules. For system designers, utilising modular P&IDs (Uzuner, 2017) may speed up design and increase quality by utilising proven systems. Collaboration across the industry and supply chain could develop these modular process systems to reduce the costs of designing and building a specialised one-off system. Furthermore, the development of automation architecture can help designers with the sys (Hoernicke et al., 2020).

4.4.1 Module and system partition

The modular reactor plant systems need to be partitioned into modules. Research has provided some investigation into this area. A method to find the optimum amount of modules configuration could be useful in this stage of the process. By adapting similar work in this area, this could be applied to the modular reactor process (Salama et al., 2017) (Samarasinghe et al., 2019).

4.4.2 Equipment database generation and selection tools

For deployment in remote and weather adverse locations, modules can be constructed in factories and developed into larger modules either in a shipyard or at site. This larger variety of design options, along with cogeneration abilities, would benefit from the automated equipment database and selection tools developed in the chemical industry. It may be useful for designers to adopt this for quick analysis of systems and design. Equipment selection algorithms can efficiently speed up the process. A unified open database for standardised off the shelf equipment tested, verified and validated for use in the industry would be extremely useful here and selection methods can quickly and efficiently help design.

The following research can be utilised by developers to obtain the optimum designs for their use case scenario (Krasberg et al., 2014), (Krasberg et al., 2014), (Eilermann et al., 2018), (Eilermann et al., 2019), (Eilermann et al., 2018), (Radatz et al., 2021).

4.4.2.1 Equipment database reusing previous designs

Due to shortened project lead times, increasing competitiveness with renewables and between reactor designers and Cogeneration capabilities, it is valuable to consider utilising tools that can quickly and efficiently help reuse designs. Examples of this include; (Hady and Wozny, 2010), (Hady and Wozny, 2011), (Eilermann, 2016), (Eilermann et al., 2017), (Fleischer-Trebes et al., 2017), (Hohmann et al., 2017).

4.4.3 Module Design

Design decision making tools can efficiently and more optimally help in module design such as calculating a near ideal option of module arrangement (Salama et al., 2017), determining modules and separation points (Samarasinghe et al., 2019), algorithms for assembly (Tserng et al., 2011), methodologies for piping (Li et al., 2017), simulation methods for manufacturing analysis (Rausch et al., 2019), manufacturing using applied robotics (Yang et al., 2019) and algorithms for layout planning.

4.5 Layout

It is important to consider and analyse the optimal layout for construction and design to reduce the amount of pipework, electrical and human operator movement around the plant. A few OSMC research articles consider wider plant layouts (Taghaddos et al., 2018) (Xu and Li, 2012), (Song and Choi, 2014) (Tanabe and Miyake, 2010) (Ku et al., 2014). (Kim and Roh, 2016) (Ku et al., 2014)(Kim et al., 2015) (S.-K. Kim, Roh, & Kim, 2017), (Jung et al., 2018), (Marthinusen, 2016).

Some research focused on the safety aspects of design, critical for a successful industrial plant industry. Consideration of implementing safer designs research should be investigated further for the most up to date methods for application in the industrial plant industry.

Process intensification may be useful for reducing the size of systems to fit into transportable modules. Manufacturing is an important consideration in modular design and construction and more research into this area would be required.

4.5.1.1 Equipment design

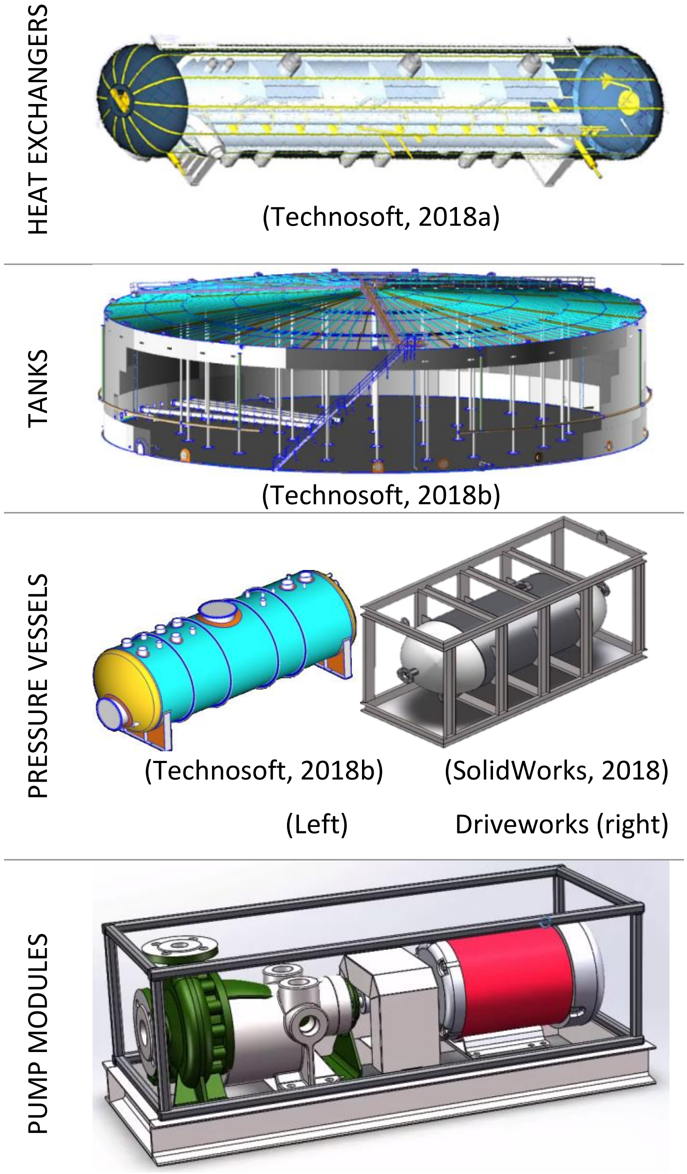
Standardisation could be a useful tool in developing modular reactors from using standardised off the shelf components and equipment to standardised modules that are more easily constructed, facilitating reduced schedules. Examples of standardised and modular equipment and some aspects of design were outlined (Kockmann, 2016) showing efficiency in moving towards commercial off the shelf components, along with flexible designs (Radatz et al., 2017).

Moving a step up from parametric design, the use of design rules to automatically generate equipment designs increases efficiency. For equipment that cannot be acquired or utilised from standardised off the shelf components, 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,
- Reactors

Combine this with a workflow integrator to perform Finite Element Analysis, Computational Fluid Dynamics, cost and manufacturing assessments, concepts could be analysed and developed quickly. The different types of components that have been designed using this method are shown in Figure 16.



(Technosoft, 2018a)

(Technosoft, 2018b)

(Technosoft, 2018b) (Left)

(SolidWorks, 2018) Driveworks (right)

(SolidWorks, 2018) Driveworks

Figure 16 – Components/ Products designed using Knowledge Based Techniques from Technosoft, (2018a) Adaptive Modelling Language and SolidWorks, (2018) Driveworks

4.6 Integrating BIM

One of the main research areas in offsite modular construction is integrating BIM technologies. Literature reviews found BIM integration was a highly researched area and should be highly considered for modular reactors. BIM integration has been highlighted as the most important aspect in design for modular construction. As such, it would be important to consider developing effective BIM technologies for development. Developing and integrating BIM approaches could enable efficient design and cost effective solutions.

5 Conclusion

New technology developments in Fusion, Advanced reactors and off site factory construction methods are an exciting research and development opportunity to help reduce the impact of climate change through decarbonisation. The factory build capability of modular reactors takes advantage of productivity, modern factory equipment, training and lean methods to decrease schedules and costs. Whereas new Fusion and Advanced reactor technologies can benefit from OSMC and automation in the design process. The industrial chemical plant and off-site modular construction industries have successfully implemented this methodology therefore this research analysed associated research to understand if key design learnings could be applied to the design of modular reactors system modules. Several key findings are presented:

Both the industrial chemical process plant industry and OSMC emphasised the benefits and significant cost and schedule savings that shifting to a modular method can offer. The industrial chemical process plant industry focused more on single modules and equipment selection tools. This is compared to the OSMC industry research, which concentrates more on the wider site system, including the transportation, logistics and scheduling and supply chain. Integrating both single module and the site wide approach could bring effective efficiency savings for modular reactors.

The module design is very important. Most nuclear power plant designs focus on adapting system designs into modules. Modular Reactors should focus on adapting the systems into modules maximised for off-site construction. A few research articles highlighted in this paper may aid with this process such as equipment/ module selection, design processes/ guidelines and system/ module partitioning methods. They should be adapted and analysed for modular reactor design as well as layout analysis tools to reduce network flows (pipes, electrical, control and human operators/ maintenance) around the plant.

Modular reactors enable deployment in remote and weather adverse locations and modular reactors can provide co-generation opportunities such as desalination, industrial and domestic heat and hydrogen/ synthetic fuel production. This larger variety of design options would benefit from the automated equipment database and selection tools developed in the chemical industry. Equipment selection algorithms can efficiently speed up the process. This enables plant designers to select equipment quickly and efficiently for the required specification for their design. A unified open database for standardised off the shelf equipment (tested, verified, and validated for use in the nuclear industry) would be extremely useful here. This would enable standardised equipment to be used in the nuclear industry, instead of bespoke one-off designs, further reducing costs.

The move to shop factory build requires more analysis of the supply chain. Research articles selected and presented here may be adapted for this purpose. The importance of BIM is highlighted in most offsite modular construction research. This is not an area that has been explored in nuclear power plant research.

The literature was categorised according to subject area. This was then organised into a logical modular development framework proposal for modular reactors in section 4. Further analysis of the research highlighted for application for modular reactors is recommended. The modular development framework can then be iterated and improved as more information and analysis is completed. Therefore, the recommended further research is:

A. A more detailed analysis of the suitability and effectiveness of the methods highlighted and developing the methods for use in modular reactors (Modularisation stakeholder and cost analysis decision tools, automated equipment database and selection tools, logistics, transportation, planning, scheduling and layout tools and methods).
B. More research is required on logistics, transportation, planning and scheduling to understand what module size might be optimum for an modular reactors. Especially for modules with no transport restrictions (3m wide in the EU) and modules with restrictions (up to 4.5m wide in the EU) which may be able to install more equipment offsite but brings more complicated logistics considerations.
C. Developing integrated BIM methods, an important research area in offsite construction.
D. Research into automated engineering developments for modules be implemented to help speed up and optimise the design process. Algorithms for equipment design, equipment/ module selection, module partitioning and layout to assess different configurations (Lapp and Golay, 1997) as well as safety and construction considerations. Researching and utilising factory manufacturing techniques from automotive, aerospace, shipbuilding industries.
E. Working on an integrated modular design methodology, with integrated optimisation of logistics, transportation, planning, scheduling and plant/ site layout and Virtual/ Augmented Reality tools.

This research is limited by its keywords search. A more detailed analysis of the suitability and effectiveness of the methods highlighted should be conducted.

References

Akagi, K., Murayama, K., Yoshida, M., Kawahata, J., 2002. Modularization Technology in Power Plant Construction, in: 10th International Conference on Nuclear Engineering. ASME, Arlington, pp. 641–647. https://doi.org/https://doi.org/10.1115/ICONE10-22244

Anvari, B., Angeloudis, P., Ochieng, W.Y., 2016. A multi-objective GA-based optimisation for holistic Manufacturing, transportation and Assembly of precast construction. Autom. Constr. 71, 226–241. https://doi.org/10.1016/j.autcon.2016.08.007

Bai, J., Hoskins, S., Hodapp, D., Ma, W., Wisch, D., 2016. LNG facilities module design considerations during marine transportation, in: Offshore Technology Conference, Proceedings. pp. 1216–1226.

Baldea, Michael, Edgar, T.F., Stanley, B.L., Kiss, A.A., 2017. Modular manufacturing processes: Status, challenges, and opportunities. AIChE J. 63, 4262–4272. https://doi.org/10.1002/aic.15872

Baldea, M, Edgar, T.F., Stanley, B.L., Kiss, A.A., 2017. Modular manufacturing processes: Status, challenges, and opportunities. AIChE J. 63, 4262–4272. https://doi.org/10.1002/aic.15872

Barry, K., 2009. Modularization of Equipment for New Nuclear Applications (1021178).

Bauer Germany, H.C., 2011. Modular Design of a Base Load LNG Plant. Int. Gas Union Res. Conf.

Bielenberg, J., Palou-Rivera, I., 2019a. The RAPID Manufacturing Institute – Reenergizing US efforts in process intensification and modular chemical processing. Chem. Eng. Process. - Process Intensif. 138, 49–54. https://doi.org/10.1016/j.cep.2019.02.008

Bielenberg, J., Palou-Rivera, I., 2019b. The RAPID Manufacturing Institute – Reenergizing US efforts in process intensification and modular chemical processing. Chem. Eng. Process. - Process Intensif. 138, 49–54. https://doi.org/10.1016/j.cep.2019.02.008

Bock, T., 2015a. The future of construction automation: Technological disruption and the upcoming ubiquity of robotics. Autom. Constr. 59, 113–121. https://doi.org/10.1016/j.autcon.2015.07.022

Bock, T., 2015b. The future of construction automation: Technological disruption and the upcoming ubiquity of robotics. Autom. Constr. 59, 113–121. https://doi.org/10.1016/j.autcon.2015.07.022

Bondi, A., Magagnini, A., Mancini, M., Micheli, G.J.L., Travaglini, A., 2016. Supporting Decisions on Industrial Plant Modularization : A Case Study Approach in the Oil and Gas Sector, in: International Conference on Industrial Engineering and Operations Management. Kuala Lumpur, pp. 742–753.

Bramsiepe, C., Sievers, S., Seifert, T., Stefanidis, G.D., Vlachos, D.G., Schnitzer, H., Muster, B., Brunner, C., Sanders, J.P.M., Bruins, M.E., Schembecker, G., 2012. Low-cost small scale processing technologies for production applications in various environments-Mass produced factories. Chem. Eng. Process. Process Intensif. 51, 32–52. https://doi.org/10.1016/j.cep.2011.08.005

Cheng, J.C.P., Chen, W., Chen, K., Wang, Q., 2020. Data-driven predictive maintenance planning framework for MEP components based on BIM and IoT using machine learning algorithms. Autom. Constr. https://doi.org/10.1016/j.autcon.2020.103087

Choi, J., Song, H., 2014. Evaluation of the modular method for industrial plant construction projects. Int. J. Constr. Manag. 14, 171–180. https://doi.org/10.1080/15623599.2014.922728

Choi, J.O., O'Connor, J.T., Kwak, Y.H., Shrestha, B.K., 2019. Modularization Business Case Analysis Model for Industrial Projects. J. Manag. Eng. 35, 1–11. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000683

Ciribini, A.L.C., Mastrolembo Ventura, S., Paneroni, M., 2016. Implementation of an interoperable process to optimise design and construction phases of a residential building: A BIM Pilot Project.

Autom. Constr. https://doi.org/10.1016/j.autcon.2016.03.005

Construction Industry Handbook, 2012. . Japan Federation of Construction Contractors, Tokyo.

De La Torre, M.L., Sause, R., Slaughter, S., Hendricks, R.H., 1994. Review and Analysis of Modular Construction Practices. Lehigh University.

Eftimie, C., 2016. How to Efficiently Engineer the Onshore Facilities: Standardized Modularization Drivers, challenges and perspectives in the Oil and Gas industry. Proj Value Deliv.

Eilermann, M., 2016. A methodology to generate modular equipment for an equipment database in module-based plant design, in: Computing and Systems Technology Division 2016 - Core Programming Area at the 2016 AIChE Annual Meeting. AIChE, San Francisco, pp. 310–311.

Eilermann, M., Post, C., Radatz, H., Bramsiepe, C., Schembecker, G., 2018. A general approach to module-based plant design. Chem. Eng. Res. Des. 137, 125–140. https://doi.org/10.1016/j.cherd.2018.06.039

Eilermann, M., Post, C., Schwarz, D., Leufke, S., Schembecker, G., Bramsiepe, C., 2017. Generation of an equipment module database for heat exchangers by cluster analysis of industrial applications. Chem. Eng. Sci. 167, 278–287. https://doi.org/10.1016/j.ces.2017.03.064

Eilermann, M., Schach, C., Sander, P., Bramsiepe, C., Schembecker, G., 2019. Generation of an equipment module database — A maximum coverage problem. Chem. Eng. Res. Des. 148, 164–168. https://doi.org/10.1016/j.cherd.2019.05.055

EU Community Research and Development Information Service, 2013a. Final Report Summary - F^3 FACTORY (Flexible, Fast and Future Production Processes) [WWW Document]. Flexible, Fast Futur. Prod. Process. URL https://cordis.europa.eu/project/rcn/92587/reporting/en

EU Community Research and Development Information Service, 2013b. Final Report Summary - F^3 FACTORY (Flexible, Fast and Future Production Processes) [WWW Document]. Flexible, Fast Futur. Prod. Process.

European Commission, 2008. European Best Practice Guidelines for Abnormal Road Transports. Office for Official Publications of the European Communities, Luxembourg.

Fang, X., Gu, L., Song, F., 2012. Definition and analysis of modularity degree of nuclear power plant construction, in: International Conference on Nuclear Engineering, Proceedings, ICONE. American Society of Mechanical Engineers (ASME), pp. 701–705. https://doi.org/10.1115/ICONE20-POWER2012-55066

Fleischer-Trebes, C., Krasberg, N., Bramsiepe, C., Kockmann, N., 2017. Planning Approach for Modular Plants in the Chemical Industry. Chemie Ing. Tech. 89, 785–799. https://doi.org/10.1002/cite.201600083

Fujita, K., Akagi, S., 1993. Approach to plant layout design based on constraint-directed search. NII-Electronic Libr.

Gao, J., You, F., 2017. Can Modular Manufacturing Be the Next Game-Changer in Shale Gas Supply Chain Design and Operations for Economic and Environmental Sustainability? ACS Sustain. Chem. Eng. 5, 10046–10071. https://doi.org/10.1021/acssuschemeng.7b02081

General Dynamics, 2020. General Dynamics Electric Boat [WWW Document]. Gen. Dyn. Electr. Boat. URL http://www.gdeb.com/ (accessed 5.31.20).

Gilbert, A., Sovacool, B.K., Johnstone, P., Stirling, A., 2017. Cost overruns and financial risk in the construction of nuclear power reactors: A critical appraisal. Energy Policy 102, 644–649. https://doi.org/10.1016/j.enpol.2016.04.001

Goodier, C., Gibb, A., Mancini, M., Turck, C., Gjepali, O., Daniels, E., 2019. Modularisation and offsite in engineering construction: an early decision-support tool. Proc. Inst. Civ. Eng. - Civ. Eng. 172, 3–14. https://doi.org/10.1680/jcien.19.00015

Hady, Ł., Wozny, G., 2011. Modularization within the framework of the course Computer-Aided Plant Design. Comput. Aided Chem. Eng. 29, 1120–1124. https://doi.org/10.1016/B978-0-444-54298-4.50003-9

Hady, Ł., Wozny, G., 2010. Computer-aided web-based application to modular plant design. Comput. Aided Chem. Eng. https://doi.org/10.1016/S1570-7946(10)28115-4

Hoernicke, M., Stark, K., Wittenbrink, A., Bloch, H., Hensel, S., Menschner, A., Fay, A., Knohl, T., Urbas, L., 2020. Automation architecture and engineering for modular process plants - Approach and industrial pilot application. IFAC. https://doi.org/10.1016/j.ifacol.2020.12.1966

Hohmann, L., Kössl, K., Kockmann, N., Schembecker, G., Bramsiepe, C., 2017. Modules in process industry − A life cycle definition. Chem. Eng. Process. 111, 115–126. https://doi.org/https://doi.org/10.1016/j.cep.2016.09.017

Hosseini, M.R., Martek, I., Zavadskas, E.K., Aibinu, A.A., Arashpour, M., Chileshe, N., 2018. Critical evaluation of off-site construction research: A Scientometric analysis. Autom. Constr. 87, 235–247. https://doi.org/10.1016/j.autcon.2017.12.002

Hsu, P.Y., Angeloudis, P., Aurisicchio, M., 2018. Optimal logistics planning for modular construction using two-stage stochastic programming. Autom. Constr. 94, 47–61. https://doi.org/10.1016/j.autcon.2018.05.029

Hsu, P.Y., Aurisicchio, M., Angeloudis, P., 2019. Risk-averse supply chain for modular construction projects. Autom. Constr. 106, 102898. https://doi.org/10.1016/j.autcon.2019.102898

Hu, X., Chong, H.Y., Wang, X., London, K., 2019. Understanding Stakeholders in Off-Site Manufacturing: A Literature Review. J. Constr. Eng. Manag. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001674

Jin, R., Gao, S., Cheshmehzangi, A., Aboagye-Nimo, E., 2018. A holistic review of off-site construction literature published between 2008 and 2018. J. Clean. Prod. 202, 1202–1219. https://doi.org/10.1016/j.jclepro.2018.08.195

Jung, D.Y., Kang, Y.K., You, C.H., 2010. Advanced construction methods for new nuclear power plants, in: American Society of Mechanical Engineers, Pressure Vessels and Piping Division (Publication) PVP. American Society of Mechanical Engineers Digital Collection, pp. 55–59. https://doi.org/10.1115/PVP2010-25369

Jung, S.K., Roh, M. Il, Kim, K.S., 2018. Arrangement method of a naval surface ship considering stability, operability, and survivability. Ocean Eng. 152, 316–333. https://doi.org/10.1016/j.oceaneng.2018.01.058

Kim, K.S., Roh, M. Il, 2016. A submarine arrangement design program based on the expert system and the multistage optimization. Adv. Eng. Softw. 98, 97–111. https://doi.org/10.1016/j.advengsoft.2016.04.008

Kim, K.S., Roh, M. Il, Ha, S., 2015. Expert system based on the arrangement evaluation model for the arrangement design of a submarine. Expert Syst. Appl. 42, 8731–8744. https://doi.org/10.1016/j.eswa.2015.07.026

Kobayashi, K., Oba, T., 2019. New concept for standardized large-scale modular LNG plant design, in: 19th International Conference and Exhibition on Liquefied Natural Gas. Shanghai.

Kockmann, N., 2016. Modular Equipment for Chemical Process Development and Small-Scale Production in Multipurpose Plants. ChemBioEng Rev. 3, 5–15. https://doi.org/10.1002/cben.201500025

Koomey, J., Hultman, N.E., Grubler, A., 2017. A reply to “Historical construction costs of global nuclear power reactors.” Energy Policy 102, 640–643. https://doi.org/10.1016/j.enpol.2016.03.052

Krasberg, N., Hohmann, L., Bieringer, T., Bramsiepe, C., Kockmann, N., 2014. Selection of Technical Reactor Equipment for Modular, Continuous Small-Scale Plants. Processes 2, 265–292. https://doi.org/10.3390/pr2010265

Ku, N.-K., Hwang, J.-H., Lee, J.-C., Roh, M.-I., Lee, K.-Y., 2014. Optimal module layout for a generic offshore LNG liquefaction process of LNG-FPSO. Ships Offshore Struct. 9, 311–332. https://doi.org/10.1080/17445302.2013.783454

Lapp, C.W., Golay, M.W., 1997. Modular design and construction techniques for nuclear power plants. Nucl. Eng. Des. 172, 327–349. https://doi.org/10.1016/S0029-5493(97)00031-9

Lee, G., Kim, J.W., 2014. Parallel vs. Sequential cascading MEP coordination strategies: A pharmaceutical building case study. Autom. Constr. 43, 170–179. https://doi.org/10.1016/j.autcon.2014.03.004

Lee, Y. Il, Lee, U.K., Kim, T. Il, 2010. Modularization technology development and application for NPP in Korea, in: American Society of Mechanical Engineers, Pressure Vessels and Piping Division (Publication) PVP. https://doi.org/10.1115/PVP2010-25533

Li, X., Li, Z., Wu, G., 2017. Modular and Offsite Construction of Piping: Current Barriers and Route. Appl. Sci. 7, 547. https://doi.org/10.3390/app7060547

Lloyd, Clara A., Roulstone, A., 2018. A Methodology To Determine SMR Build Schedule And The Impact Of Modularisation, in: ASME (Ed.), 26th International Conference on Nuclear Engineering ICONE26. ASME, London.

Lloyd, Clara A, Roulstone, A.R.M., 2018. The impact of modularisation strategies on Small Modular Reactor Costs. Icapp 2018.

Lovering, J.R., Yip, A., Nordhaus, T., 2016. Historical construction costs of global nuclear power reactors. Energy Policy 91, 371–382. https://doi.org/10.1016/j.enpol.2016.01.011

Lu, Q., 2013. Research and Application Status of the Modular Technology in Nuclear Power Engineering of CGNPC, in: 21st International Conference on Nuclear Engineering Volume 1: Plant Operations, Maintenance, Engineering, Modifications, Life Cycle and Balance of Plant; Nuclear Fuel and Materials; Radiation Protection and Nuclear Technology Applications. ASME, Chengdu, p. V001T01A001. https://doi.org/10.1115/ICONE21-15004

Lu, Q., Li, Y., Wang, Z., Luo, Y., Qinwu, L., Zengchen, W., 2013. Research and Development of 3D Module Design System in Nuclear Power Engineering, in: 21st International Conference on Nuclear Engineering Volume 1: Plant Operations, Maintenance, Engineering, Modifications, Life Cycle and Balance of Plant; Nuclear Fuel and Materials; Radiation Protection and Nuclear Technology Applications. ASME, Chengdu, p. V001T01A004. https://doi.org/10.1115/ICONE21-15060

Lyons, R.E., Roulstone, A.R.M., 2018. Production learning in a small modular reactor supply chain, in: Proceedings of the 2018 International Congress on Advances in Nuclear Power Plants, ICAPP 2018. American Nuclear Society, pp. 1034–1041.

Mädler, J., Rahm, J., Viedt, I., Urbas, L., 2022. A digital twin-concept for smart process equipment assemblies supporting process validation in modular plants, in: Computer Aided Chemical Engineering. pp. 1435–1440. https://doi.org/10.1016/B978-0-323-95879-0.50240-X

Mancini, M., Micheli, G.J.L., Travaglini, A., Gilardone, G., 2016. Oil & gas industry perception of modularization barriers and impacts, in: IEEE International Conference on Industrial Engineering and Engineering Management. pp. 1595–1599. https://doi.org/10.1109/IEEM.2016.7798146

Marthinusen, I., 2016. The Acquisition and Codification of Knowledge-Based Engineeing.

Martinez, P., Al-Hussein, M., Ahmad, R., 2019. A scientometric analysis and critical review of computer vision applications for construction. Autom. Constr. 107. https://doi.org/10.1016/j.autcon.2019.102947

Medjdoub, B., 2009. Constraint-based adaptation for complex space configuration in building services. Electron. J. Inf. Technol. Constr.

Medjdoub, B., Bi, G., 2018. Parametric-based distribution duct routing generation using constraint-based design approach. Autom. Constr. 90, 104–116. https://doi.org/10.1016/j.autcon.2018.02.006

Medjdoub, B., Chenini, M.B., 2015. A constraint-based parametric model to support building services design exploration. Archit. Eng. Des. Manag. 11, 123–136. https://doi.org/10.1080/17452007.2013.834812

Medjdoub, B., Richens, P., Barnard, N., 2003. Generation of variational standard plant room solutions. Autom. Constr. 12, 155–166. https://doi.org/10.1016/S0926-5805(02)00006-7

Mignacca, B., Alawneh, A.H., Locatelli, G., 2019. Transportation of small modular reactor modules: What do the experts say?, in: International Conference on Nuclear Engineering, Proceedings, ICONE. Japan Society of Mechanical Engineers, Tsukuba, Japan.

Mignacca, B., Locatelli, G., 2020. Economics and finance of Small Modular Reactors: A systematic review and research agenda. Renew. Sustain. Energy Rev. 118, 109519. https://doi.org/10.1016/j.rser.2019.109519

Mignacca, B., Locatelli, G., Alaassar, M., Invernizzi, D.C., 2018. We Never Built Small Modular Reactors SMRs but What Do We Know About Modularization in Construction, in: 26th International Conference on Nuclear Engineering. ASME, London.

Modular Building Institute, 2013. Why Build Modular" [WWW Document]. URL http://www.modular.org/HtmlPage.aspx?name=why_modular (accessed 5.31.20).

Mokhatab, S., Mak, J.Y., Valappil, J. V., Wood, D.A., 2013. 10.4.2 - Modularistion - Advances and Innovations in LNG Industry, Handbook of Liquefied Natural Gas. https://doi.org/10.1016/C2011-0-07476-8

Moran, S., 2016. Process Plant Layout, 2nd ed. Butterworth-Heinemann.

O'Connor, J.T., O'Brien, W.J., Choi, J.O., 2015. Standardization strategy for modular industrial plants. J. Constr. Eng. Manag. 141, 1–10. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001001

Obata, T., Urashima, A., Watanabe, K., Miyahara, T., 2010. Advanced construction technologies for the ohma nuclear power plant reactor building of Electric Power Development Co., Ltd, in: International Conference on Nuclear Engineering, Proceedings, ICONE. https://doi.org/10.1115/ICONE18-30163

Radatz, H., Elischewski, J.M., Heitmann, M., Schembecker, G., Bramsiepe, C., 2017. Design of equipment modules for flexibility. https://doi.org/10.1016/j.ces.2017.04.021

Radatz, H., Kragl, A., Kampwerth, J., Stark, C., Herden, N., Schembecker, G., 2021. Application and evaluation of preselection approaches to decide on the use of equipment modules. Chem. Eng. Res. Des. 173, 89–107. https://doi.org/10.1016/j.cherd.2021.06.021

Radatz, H., Schröder, M., Becker, C., Bramsiepe, C., Schembecker, G., 2019. Selection of equipment modules for a flexible modular production plant by a multi-objective evolutionary algorithm. Comput. Chem. Eng. 123, 196–221. https://doi.org/10.1016/j.compchemeng.2018.12.009

Rausch, C., Nahangi, M., Haas, C., Liang, W., 2019. Monte Carlo simulation for tolerance analysis in prefabrication and offsite construction. Autom. Constr. 103, 300–314. https://doi.org/10.1016/j.autcon.2019.03.026

Roberts, K., 2013. Modular design of smaller-scale GTL plants. Pet. Technol. Q. 18, 101–103.

Salama, T., Salah, A., Moselhi, O., Al-Hussein, M., 2017. Near optimum selection of module configuration for efficient modular construction. Autom. Constr. 83, 316–329. https://doi.org/10.1016/j.autcon.2017.03.008

Samarasinghe, T., Gunawardena, T., Mendis, P., Sofi, M., Aye, L., 2019. Dependency Structure Matrix and Hierarchical Clustering based algorithm for optimum module identification in MEP systems. Autom. Constr. 104, 153–178. https://doi.org/10.1016/j.autcon.2019.03.021

Seifert, T., Schreider, H., Sievers, S., Schembecker, G., Bramsiepe, C., 2015. Real option framework for equipment wise expansion of modular plants applied to the design of a continuous multiproduct plant. Chem. Eng. Res. Des. 93, 511–521. https://doi.org/10.1016/j.cherd.2014.07.019

Seifert, T., Sievers, S., Bramsiepe, C., Schembecker, G., 2012. Small scale, modular and continuous: A new approach in plant design. Chem. Eng. Process. Process Intensif. 52, 140–150. https://doi.org/10.1016/j.cep.2011.10.007

Sievers, S., Seifert, T., Franzen, M., Schembecker, G., Bramsiepe, C., 2016a. Fixed capital investment estimation for modular production plants. Chem. Eng. Sci. https://doi.org/10.1016/j.ces.2016.09.029

Sievers, S., Seifert, T., Schembecker, G., Bramsiepe, C., 2016b. Methodology for evaluating modular production concepts. Chem. Eng. Sci. 155, 153–166. https://doi.org/10.1016/j.ces.2016.08.006

Smith, C.T., Hammeran, J.H., Lockwood, C., 2013. Module Fabrication Strategy for Today's Nuclear Industry 125. https://doi.org/10.1115/icone20-power2012-54818

Song, H., Choi, J., 2014. Evaluation of the modular method for industrial plant construction projects. Int. J. Constr. Manag. 14, 171–180.

Stewart, W.R., Shirvan, K., 2022. Capital cost estimation for advanced nuclear power plants. Renew. Sustain. Energy Rev. 155, 111880. https://doi.org/10.1016/j.rser.2021.111880

Sutharshan, B., Mutyala, M., Vijuk, R.P., Mishra, A., 2011. The AP1000TM Reactor: Passive Safety and Modular Design, in: Energy Procedia. pp. 293–302. https://doi.org/10.1016/j.egypro.2011.06.038

Taghaddos, H., Hermann, U., Abbasi, A.B., 2018. Automated Crane Planning and Optimization for modular construction. Autom. Constr. 95, 219–232. https://doi.org/10.1016/j.autcon.2018.07.009

Tanabe, M., Miyake, A., 2010. Safety design approach for onshore modularized LNG liquefaction plant. J. Loss Prev. Process Ind. 23, 507–514. https://doi.org/10.1016/j.jlp.2010.04.004

Tanabea, M., Miyake, A., 2016. Effective implementation of inherently safer design during design phase of modularized onshore LNG projects. Chem. Eng. Trans. 48. https://doi.org/10.3303/CET1648090

Tserng, H.P., Yin, Y.L., Jaselskis, E.J., Hung, W.C., Lin, Y.C., 2011. Modularization and assembly algorithm for efficient MEP construction. Autom. Constr. 20, 837–863. https://doi.org/10.1016/j.autcon.2011.03.002

Uzuner, 2017. Ein Beitrag zur wissensbasierten Unterstützung bei der Auswahl technischer Ressourcen. Hamburg.

Wang, J., Wang, X., Shou, W., Chong, H.Y., Guo, J., 2016. Building information modeling-based integration of MEP layout designs and constructability. Autom. Constr. 61, 134–146.

https://doi.org/10.1016/j.autcon.2015.10.003

Williamson, M., Townsend, L., 2003. Sizes of secondary plant components for modularized IRIS balance of plant design. Glob. 2003 Atoms Prosper. Updat. Eisenhowers Glob. Vis. Nucl. Energy 605–609.

Wrigley, P., Wood, P., O'Neill, S., Hall, R., Robertson, D., 2021. Off-site modular construction and design in nuclear power: A systematic literature review. Prog. Nucl. Energy 134, 103664. https://doi.org/10.1016/j.pnucene.2021.103664

Xu, J., Li, Z., 2012. Multi-objective dynamic construction site layout planning in fuzzy random environment. Autom. Constr. 27, 155–169. https://doi.org/10.1016/j.autcon.2012.05.017

Yang, Y., Pan, M., Pan, W., 2019. 'Co-evolution through interaction' of innovative building technologies: The case of modular integrated construction and robotics. Autom. Constr. 107. https://doi.org/10.1016/j.autcon.2019.102932

Yin, X., Liu, H., Chen, Y., Al-Hussein, M., 2019. Building information modelling for off-site construction: Review and future directions. Autom. Constr. 101, 72–91. https://doi.org/10.1016/j.autcon.2019.01.010

Yotsuya, T., Miura, J., Murayama, K., Nakajima, A., Kawahata, J., 2004. Design concept of composite module for nuclear power plant construction, in: Proceedings of the International Conference on Nuclear Engineering (ICONE12). pp. 449–452. https://doi.org/https://doi.org/10.1115/ICONE12-49331

Zeton, 2021. Modular Fabrication [WWW Document]. URL https://www.zeton.com/zeton-advantage/modular-fabrication/

Appendix B - Literature search papers

	Search terms				
	TITLE (modul* AND plant AND design).	TITLE-ABS-KEY (modul* AND LNG))	TITLE-ABS-KEY (mep AND layout)	TITLE-ABS-KEY (mep AND modul*)	TITLE-ABS-KEY (off-site AND construction OR modular AND literature)
(Hady and Wozny, 2011),	X				
(Seifert et al., 2012),	X				
(Seifert et al., 2015),	X				
(Eilermann, 2016) (Eilermann et al., 2017)	X				
(Eilermann et al., 2018).	X				
(Eilermann et al., 2019).	X				
(Bramsiepe et al., 2012),	X*				
(Krasberg et al., 2014),	X*				
(Sievers et al., 2016b),	X*				
(Fleischer-Trebes et al., 2017),	X*				
(Hohmann et al., 2017),	X*				
(M Baldea et al., 2017),	X*				
(Uzuner, 2017),	X*				
(Radatz et al., 2017),	X*				
(Radatz et al., 2019),	X*				
(Bielenberg and Palou-Rivera, 2019b).	X*				
(Tanabe and Miyake, 2010)		X			
(Roberts, 2013)		X			
(Ku et al., 2014)		X			
(Gao and You, 2017)		X			
(Tanabea and Miyake, 2016)		X			
(Bai et al., 2016)		X			
(Kobayashi and Oba, 2019)		X			
(Wang et al., 2016).			X		
(Tserng et al., 2011),				X	
(Li et al., 2017),				X	
(Ciribini et al., 2016)				X	
(Cheng et al., 2020),				X	
(Samarasinghe et al., 2019).				X	
(De La Torre et al., 1994),					X
(Medjdoub, 2009),					X
(Xu and Li, 2012),					X
(Song and Choi, 2014),					X
(Lee and Kim, 2014),					X
(Bock, 2015a),					X
(Medjdoub and Chenini, 2015)					X

(Anvari et al., 2016),					X
(Salama et al., 2017),					X
(Taghaddos et al., 2018),					X
(Hsu et al., 2018),					X
(Medjdoub and Bi, 2018),					X
Hosseini et al., (2018)					X
(Jin et al., 2018)					X
(Yin et al., 2019),					X
(Martinez et al., 2019),					X
(Hu et al., 2019),					X
(Choi et al., 2019),					X
(Hsu et al., 2019),					X
(Yang et al., 2019),					X
(Rausch et al., 2019).					X

5.1 Research areas comparison

Table 2 - Comparison of research areas for modular in nuclear research and the industrial chemical plant and OSMC industries.

Research Area	**Nuclear specific from** (Wrigley et al., 2021)	**Chemical Plant Industry and off-site modular construction**
Project decision-making tool	(Lee et al., 2010)	(Seifert et al., 2015). (Sievers et al., 2016b). (Sievers et al., 2016a). (Choi and Song, 2014), (Choi et al., 2019) (O'Connor et al., 2015) (Bondi et al., 2016) (Goodier et al., 2019) and for stakeholders (Hu et al., 2019)
Plant size vs modularisation model	Clara A Lloyd and Roulstone, (2018) Fang et al., (2012)	(Samarasinghe et al., 2019). (Salama et al., 2017).
Schedule analysis	Clara A. Lloyd and Roulstone, (2018)	(Anvari et al., 2016).
Transportation, logistics and scheduling	Mignacca et al., (2019)	(Hsu et al., 2018) (Hsu et al., 2019) (Anvari et al., 2016). (Taghaddos et al., 2018). (Bai et al., 2016). (Bauer Germany, 2011). (Choi and Song, 2014):
Supply chain	Lyons and Roulstone, (2018)	
Heat Exchanger Design	(Williamson and Townsend, 2003).	(Radatz et al., 2017)
High level Design process	(Lapp and Golay, 1997). (Akagi et al., 2002). (Yotsuya et al., 2004). (Obata et al., 2010). (Jung et al., 2010). (Smith et al., 2013). (Barry, 2009). (Lu et al., 2013). (Lu, 2013).	(Sievers et al., 2016b). (EU Community Research and Development Information Service, 2013b) (Bielenberg and Palou-Rivera, 2019b).
Database and Equipment selection		(Hady and Wozny, 2010) (Hady and Wozny, 2011). (Krasberg et al., 2014). (Krasberg et al., 2014). (Radatz et al., 2019). (Eilermann et al., 2018).

Research Area	**Nuclear specific from** (Wrigley et al., 2021)	**Chemical Plant Industry and off-site modular construction**
		(Eilermann et al., 2019). (Eilermann et al., 2018).
Module design	Yotsuya et al., (2004) Obata et al., (2010) Smith et al., (2013)	(Tserng et al., 2011). (Song and Choi, 2014). (Samarasinghe et al., 2019). (Salama et al., 2017). (Medjdoub and Chenini, 2015). (Medjdoub and Bi, 2018). (Medjdoub, 2009). (Li et al., 2017), (Medjdoub et al., 2003), (Rausch et al., 2019). (Yang et al., 2019)
Layout	(Fujita and Akagi, 1993)	(Taghaddos et al., 2018) (Xu and Li, 2012), (Song and Choi, 2014) (Tanabe and Miyake, 2010) (Ku et al., 2014).
Importance of BIM integration		(Hosseini et al., 2018) (Jin et al., 2018) (Yin et al., 2019), (Martinez et al., 2019) (Bock, 2015a). (Wang et al., 2016) (Cheng et al., 2020) (Ciribini et al., 2016) (Lee and Kim, 2014)