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Review Article

Modular reactors: What can we learn from modular industrial plants and off site construction research

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ABSTRACT

New modular factory-built methodologies implemented in the construction and industrial plant industries may bring down costs for modular reactors. A factory-built environment brings about benefits such as; improved equipment, tools, quality, shift patterns, training, continuous improvement learning, environmental control, standardisation, parallel working, the use of commercial off shelf equipment and much of the commissioning can be completed before leaving the factory. All these benefits combine to reduce build schedules, increase certainty, reduce risk and make financing easier and cheaper.Currently, the construction and industrial chemical plant industries have implemented successful modular design and construction techniques. Therefore, the objectives of this paper are to understand and analyse the state of the art research in these industries through a systematic literature review. The research can then be assessed and applied to modular reactors.The literature review highlighted analysis methods that may prove to be useful. These include; modularisation decision tools, stakeholder analysis, schedule, supply chain, logistics, module design tools and construction site planning. Applicable research was highlighted for further work exploration for designers to assess, develop and efficiently design their modular reactors.

1. Introduction

Due to the climate crisis, as outlined in the United Nations Intergovernmental Panel on Climate Change Sixth Assessment Report and recent energy security concerns, Modular Reactors are once again being more strongly considered and extensively explored for deployment worldwide. However, industries in the US and some European countries have struggled to build new reactor power plants on time and within budget [1,2] especially over the last few decades. Recently, at Vogtle, Sanmen, and Haiyang, the AP1000 has been delayed and is over budget with construction ceasing at VC Summer. The EPR is years behind schedule and over budget at Olkiluoto, Flamanville, and Hinkley point C, and the ITER fusion plant in France is in a similar situation. The ABWR project at Wylfa was also cancelled due to funding and commitment concerns from the UK Government. However, as achieved in South Korea, costs can be reduced if there is a strong national government effort to deploy multiple standardised units of the same design [3,4].

Modularisation can reduce direct and indirect costs through reduced construction schedules. Previous research into Modular Reactors has focused on adapting large Reactors for on-site assembly with very large modules to reduce the critical path [5]. This is similar to the techniques used in the oil and gas industry where, in 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 [6].

Similarly, the construction industry in advanced economies where labour is expensive has also seen reduced productivity [7] 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

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Abbreviations

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

factories, through modular design to reduce schedules and direct costs. Off-Site Modular Construction (OSMC) has significantly boosted efficiency in construction in recent years [8] and has witnessed an exponential increase in research over the past decade [9].

New modular factory-built methodologies implemented in the construction and industrial plant industries may bring down costs for Modular Reactors. The benefits of using modular factory-built methodologies for Modular Reactors can be through:

- **Increased productivity:** Through improved equipment, tools, quality, shift patterns, training, continuous improvement, environmental control, and parallel working. For example, using specialised equipment and tools can help to improve the efficiency of construction activities. Lessons learned can also be applied from other manufacturing industries.
- **Reduced costs:** The use of factory build, commercial off-the-shelf equipment and standardization can help to reduce direct costs.
- **Reduced schedule:** By allowing for more efficient construction activities and parallel working.
- **Increased certainty:** By reducing the risk of delays and cost overruns via better equipment and learning.
- **Reduced risk:** A factory-built environment can help to reduce risk by reducing the potential for accidents and injuries.
- **Easier and cheaper financing**: By providing lenders with a more predictable and secure investment.
- **Factory commissioning**: Additionally, the ability to complete much of the commissioning work in the factory can help to reduce overall costs, schedules, reduce uncertainty and reduce risk.

Worldwide, there is a strong interest in developing Modular Reactors. Small Modular Reactors, defined as “factory shop built and transported to site” by the International Atomic Energy Agency, have recorded over 30 light water SMR and 40 Advanced Generation IV technology designs in commercial development worldwide. These SMRs are smaller than large reactor power plants, typically less than 300Mwe to allow for factory build and transport, and permit siting at remote and weather adverse locations. They also frequently embrace the reactor, pressurizer and steam generators in one integrated module. Research conducted on Modular Reactors for submarines evaluates that manufacturing systems in a factory may be 8 times more efficient than executing the same techniques on site [10]. Economic assessments also predict that Modular Reactors can be competitive with renewable sources [2,11–14].

Therefore, this systematic literature review aims to comprehend, analyse, and identify successful methods in the industrial process plant and OSMC industries. This research can then be assessed and applied for more successful Modular rRactors deployment. This will be achieved by exploring 4 Research Questions:

- RQ1: What are the the most up to date processes, analyses & design methods in industrial process plant and OSMC industries research literature.
- RQ2: What are the considerations and recommendations from these industries research literature.
- RQ3: What are the research gaps between these industries and Modular Reactor power plant industry.
- RQ4: What tools and research can be implemented into the module design development framework for Modular Reactors.

2. Method

The Systematic Literature Review technique as discussed in Jin et al. [8] and Mignacca and Locatelli [11] is used as a basis for this literature review and shown in Fig. 1. The research paper exploration was accomplished on 4th September 2023 for the papers presented here.

Scopus was utilised for the search. Concentrating on the Scopus fields: titles “TITLE”, abstracts “ABS” and keywords “KEY”, only research articles were identified. Articles concerning keywords with dissimilar semantic connotations were filtered out. The next step was 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 A - Literature search papers.

3. Results

Using the literature outlined from the search listed in Appendix A - Literature search papers, the outcomes from the literature exploration are debated in this 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; and plant layout.

Offsite Modular Construction literature reviews: decision support tools; transportation, logistics and scheduling and supply chain; module and system partition; site layout; and 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 [15]. Recently however, due to the low productivity in the construction industry [16], some chemical process plant research has focused on small scale OSMC. This can be cheaper, faster (up to 66 %) [17], and more flexible [18–20] than traditional plants.

3.1.1. Cost and schedule reduction examples in industry

Provide examples of modular plants in the food processing and

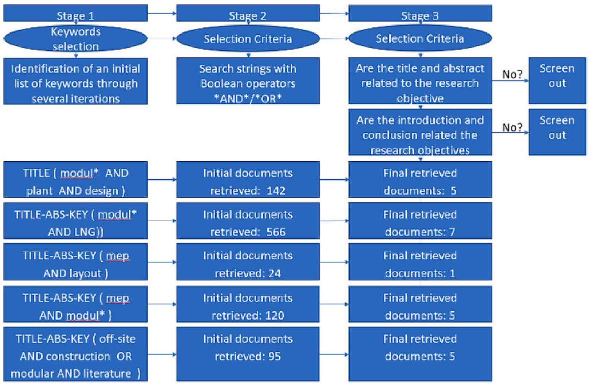

Fig. 1. Systematic Literature Review method adapted from Jin et al. [8,11]

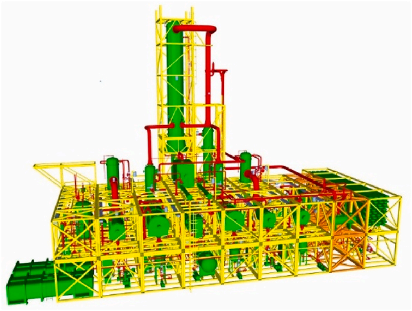

Fig. 2. Factory-built process plant modules [21] by ([22]).

Fig. 3. – *Modular process plant* [26].

biofuels industries present and future developments to be aware of. Examples of modular plants in the food processing and biofuels industries demonstrate current and future developments to be aware of [21]. They assess how the industries may be affected by small (Zeton factory-built [22]) and modular process units (Fig. 2). Modular Building Institute [23], shows modular construction time can be shortened by 50 %.

Small modular industrial plants could decrease the construction schedule by over 2 years (66 %) and improve value by 35 % [17]. Examples of standardised and modular equipment, including some aspects of design have been discussed [24]. Eftimie [25] states that modular construction reduced the schedule by up to 25–50 % in offshore facilities. Developments in US process intensification and modular construction (Fig. 3) were summarised in various industries; pulp & paper handling, chemical manufacture, gas processing, and fuels refining [26], emphasising that in the future, the two methods could also have a significant impact in water usability processes and carbon capture and utilisation. General Dynamics [27] showed the construction schedule could be reduced by as much as 28 % in its modular electric boat.

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 [28] and the modular expansions of existing plants [28] and expansion considerations for new plants [29].

3.1.3. Equipment database generation and selection tools

A computer-assisted selection methodology was created for reactor equipment, returning favourable technical equipment and configuration in the early phases of the design [30]. From this, selection methods for equipment using reusable databases were then developed [30]. A multi-objective evolutionary algorithm was developed to choose component modules for an adaptable modular manufacturing plant with minimal investment costs [31]. The algorithm highlighted that for 50 % greater investment costs, 11 times the 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 [32]. These improve the method to cover more requirements while being more computationally efficient [33]. 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 [32]. 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 [34]. 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 was discussed [35] and a module documentation internet administration software tool called Reuse-Atlas was produced for quality and assurance [36]. This was achieved using Windows®, Apache™, MySQL®, "PHP: Hypertext Preprocessor", and HTML, and 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 [37]. The generated heat exchanger modules could cover 59 % of the contemplated engineering functions [38]. The revision of process component designs from previous projects were utilised to create appropriate results for new projects [39]. A theory for data processing during the whole life cycle of the process industry from laboratory to production was defined [40]. Reusable modules, organised module databases, and innovative techniques for module election and configuration were analysed, highlighting how 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 [41]. 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, as a result the project brought about: improved space-time-yield up by 100x; 20 % enhanced capability; 20 % expanded fabrication yield; decrease in: solvent usage by up to 100 %; 50 % site; 60 % equipment demand; reaction/processing period by 10x, and actions up to 30 %.

An approach for assessing modular and non-modular fabrication situations was developed. The "F3" factory concept (Fig. 4) was utilised as an example of assessing different production methods as well as the supply chain [29]. This included a set of design guidelines for the process plant [42].

3.2. Plant layout

The optimal module layout for a generic offshore Liquid Natural Gas liquefaction process was defined [43]. Although this is a module, it is not a modular design where equipment would be located in road-transportable, factory-built modules. Optimal module layout research

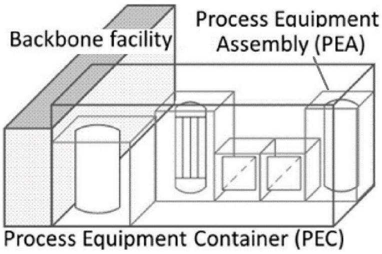

Fig. 4. -Illustration of F3 factory modular elements (left) [29] and F3 Factory design procedures and specifications for modular, module-based fabrication units characterised and applied in various process component modules [42].

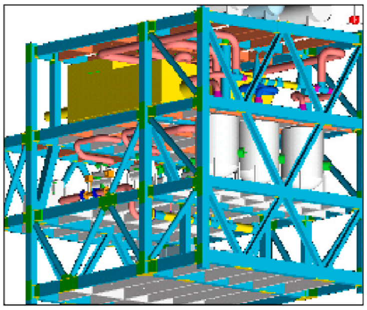

Fig. 5. Offshore Equipment layout performed using Knowledge Based Techniques through ©Technosoft, (2018a) AML.

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 [44]. Fig. 5 shows an offshore rig layout developed using Knowledge Based Techniques through Technosofts Adaptive Modelling Language (2018a).

An expert system to arrange a submarine with a multistage optimisation was developed [45] and also applied to an offshore oil rig design [43,46] (S.-K. Kim, Roh, & Kim, 2017), and a surface naval shop [47].

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 as most building areas of an Modular Reactor 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. [9] and Jin et al. [8] 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 [48], 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 [49]. A literature review into construction automation highlights automation in construction is still in the early phases and is yet to experience larger adoption. They found that Single-Task Construction Robot approaches, construction automation technology, other microsystems technology, and service robot systems are currently uniting with BIM [7].

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 these highlighted several techniques to apply to ensure success [50]. The advantages of modularisation and important lessons in some commercial plants were summarised in the modular design of smaller-scale plants [51]. An evaluation of the modular method for industrial plant construction projects using the analytical hierarchy process and several evaluation criteria was developed [52] 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 plans. They theorised a schedule reduction of 22% and higher quality and safety, highlighting the need for more effort in planning, design, assembly processes, procurement, and transport, as well as that particular attention needs to be paid to interfaces and constructability. They then developed these factors further into a modularisation business case analysis model using 5 levels of questions and an estimated cost benefit [53]. Furthermore, 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 [54]. Experience and lessons learned over several recent offsite modular projects were described outlining considerations, requirements, and criteria for module design during marine transportation [55]. Also, supporting decisions on oil and gas industrial plants were presented [56], as well as the development of a research framework for stakeholders in off-site manufacturing for future practice and improvement [57]. A robust empirically based decision-support tool for decision makers and clients was outlined [58] 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 [28]. Decision tools were also developed to analyse modular expansions of existing plants [28] and expansion considerations for new plants [29].

3.3.3. *Transportation, Logistics, Scheduling and Supply Chain*

A two-stage stochastic programming model was applied for logistics planning in a residential construction sector project [59]. They then added the selection of optimal warehouse locations and applied the technique to a school dormitory construction project, showing significant efficiency savings [60]. 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 [61]. This logistics planning and optimisation [59,60] could be integrated with Scheduling optimisation [61], Crane planning and optimisation [62] and plant layout optimisation [43,63–65], as well as planning for robotics in off-site modular construction [66] and electric autonomous transportation. More research should develop techniques to analyse this part of the construction process to optimise costs, schedules, and planning [67].

3.3.4. *Module and system partition*

A method to find the optimum selection of module configuration for efficient modular construction, consisting of a design structure matrix method to calculate a near ideal option of module arrangement using 5

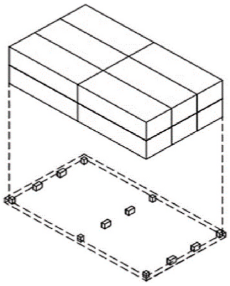

Fig. 6. Modules' foundation design in residential construction by Salama et al. [68].

Fig. 7. Monte Carlo tolerance simulation on a preassembled building to improve tolerances to reduce rework probability [70].

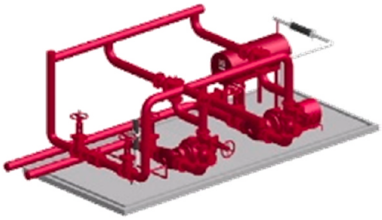

Fig. 8. Fire suppression system decomposition, motor, foam tank and Generator [71].

indicators, was proposed in another study. This included; a shipment of prefabricated modules to the construction assembly site, connections of modules onsite, related cost, project concrete foundation, and crane operating condition [68]. The method showed efficient results in a residential construction project (Fig. 6).

Modular offsite production of fluid systems were analysed, identifying barriers and recommendations for successful implementation [69] which 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 (Fig. 7), highlighting that by using this method to improve tolerances, a major rework probability can be reduced from 100 % to a 34 % likelihood of slight alterations [70].

Tserng et al. found that modularising an MEP module (Fig. 8) using planning algorithms reduced costs from $66,030 to $19,566 and saved 12 days in the construction schedule [71].

A schedule saving of 22.2 % was approximated for the construction of a modular underground machine room in a tall residential building [64] 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 [72]. 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 (Fig. 9).

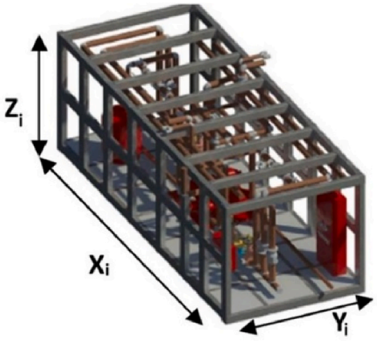

Fig. 9. Technique utilised to calculate dimensions of MEP modules using the equipment coordinates [72].

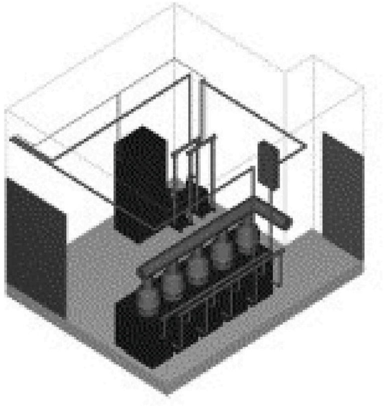

Fig. 10. Production of variational essential plant room solutions [73].

Object-based CAD constraint logic programming to aid in the design of a low-pressure hot water plant room (Fig. 10) was developed, considering selection, sizing, layout, and pipe routing [73]. Design time was estimated to be reduced by around 10–20 %. This was then improved in later works [74,75].

Medjdoub applied a similar technique to a ceiling mounted fan coil system via designing, sizing, and layout planning [76]. A new concept for standardized large-scale modular LNG plant design was presented [77] 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 [43,62–65]. 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 [63].

A method to automate and optimise crane planning and configuration (Fig. 11) was conceived and applied to modular projects in Alberta, Canada in another study [62].

Some research focused on the safety aspects of design, critical for a successful industrial plant industry. A safety design approach for an onshore modularized [78] Natural gas liquefaction plant was presented during the Concept Definition phase [65]. 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 [79]. 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 [80]. Utilising a life cycle optimisation model, it was concluded modular manufacturing could improve the economic performance of a shale gas supply chain. Although 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 were appraised based on the value concentration of feedstock assets, an innovative system of measurement, and markets [18,19]. Also discussed were the links between modularisation and process intensification,

Fig. 11. Optimised crane planning and configuration for a modular project in Alberta, Canada [62].

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

Examples of standardised and modular equipment, as well as some aspects of design were outlined in a research study [24]. The flexible design of a liquid heat exchanger was also developed through the deduction of heuristics and a global sensitivity analysis [81]. The design was compared to the original design, and it has 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. Several literature reviews found that BIM integration was a highly researched area and should be highly considered for Modular Reactors [7–9,48,49] along with methods for integrating BIM and design [82–85].

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 [82]. 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 [83]. The BIM implementation for the Italian Public Pilot Project developed an interoperable Industry Foundation Classes based process, achieving sophisticated model, code checking, and evaluating the 4D BIM construction phase. It showed that a shared stakeholder BIM management is required with collaboration needing to be improved for effective implementation [84]. Another study found that a sequential BIM coordination approach was about 3x more efficient than a parallel method in a pharmaceutical MEP case study [85].

Developing a digital twin-concept for smart process equipment assemblies supporting process validation in modular plants could be a useful process for Modular Reactors [86]. Developing and integrating BIM approaches could enable efficient design and cost-effective solutions.

3.6. Findings summary

As highlighted in previous Modular Reactor literature, most of the modular design research in this industry has focused on converting a standard large reactor power plant for an on-site assembly area (Fig. 12, detailed in Table 2). This has typically focused on high level design process for large modules and not designed for transport. Fig. 12 highlights the scarcity of research into areas of modular system design in reactor research when compared to the industrial chemical plant and OSMC industries, underlining the importance in assessing this research.

Both the industrial chemical process plant industry and OSMC highlighted the benefits, with significant cost and schedule reductions that moving to a modular approach can bring. However, where the 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.

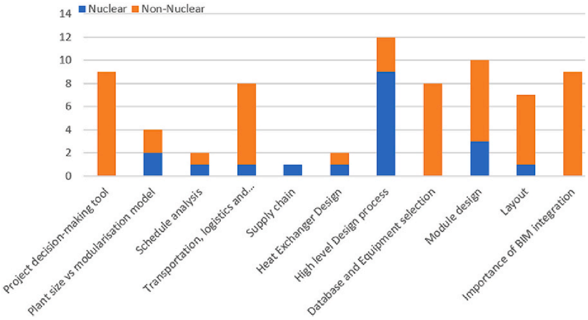

Fig. 12. Comparison of research areas for modular in reactor power plant research and the industrial chemical plant and OSMC industries.

Both industries highlighted decision support tools (Fig. 12) as an important area. These are very important to stakeholders to make investment decisions and useful to consider for Modular Reactor vendors.

The module design is very important. A lot of chemical plant industry research develops module databases and selection tools, demonstrating how 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 Modular Reactor industry) would be extremely useful here. This would enable standardised equipment to be used in the Modular Reactor power plant 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

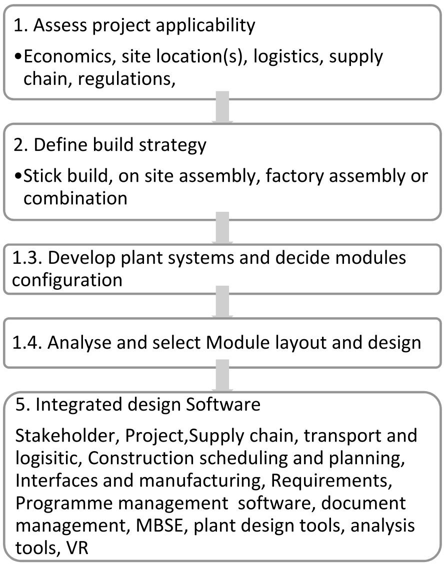

Fig. 13. Towards a modular design methodology.?.

subject areas, providing the logical steps required to move towards a development framework for modularisation. Assessing project applicability and defining the build strategy based on logical location are considered first, followed by assessing the plant systems and equipment for modular design. This was developed in conjunction with expert reactor plant design engineers. A proposed outline is shown in Fig. 13 and discussed in Section 4.

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 such as; the size of the plant, location, community stakeholders, supply chain, and logistics, after which the build strategy can then be defined. Modularisation decision tools were developed for the oil and gas industry, which has mainly focused on large modules for remote and weather adverse locations [53,56,87]. Modularisation decision tools may help Modular Reactor vendors, governments, and engineering providers decide on whether to use modularisation in Modular Reactors, and which build method may be best suitable for their location.

Economic analysis would be useful at this stage to understand if the project is feasible [2,11–14,88].

Stakeholder analysis methods would aid in understanding whether the project is suitable for modularisation [52–54,56,58,87] and stakeholders [57]. 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 [58].

Plants with room for expansion or integration with cogeneration options, such as desalination, building heating, and hydrogen production may be developed [28,28,29] and should also be a consideration in the design. Companies and projects need to consider if they are building a multi fleet approach where standardisation leads to learner benefits or if the plant is a one-off prototype, pilot, or research plant. Depending on this, parts or all of the plant may be either stick built, assembled in an onsite assembly area, factory fabricated, or a combination of all three.

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 particularly for: manufacturing facilities and locations [59,60]; lifting/transport equipment; build scheduling [61,89,90]; customs and export requirements; government transport requirements for vehicle size, weight constraints & police escorts required; requirements/lead time for permits; community and environmental risks; and At site transport logistics [62].

4.1.1. Transportation, Logistics, Scheduling and Supply Chain

Transportation, logistics, and scheduling [91] is also an important consideration if you are moving to a factory-based manufacturing strategy [92]. Logistics planning and optimisation [59,60] could be integrated with scheduling optimisation [61,89,90], crane assembly planning [62], and plant layout optimisation [43,63–65], as well as planning for robotics in off-site modular construction [66], and electric autonomous transportation. Further research should aim to develop techniques to analyse this part of the construction process to optimise costs, schedules, and planning.

Transport is an important consideration in modular design [68,93]. The sizes and weights of modules for transportation are outlined in Ref. [15] 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), and barge mounted and bedded at site (6000–260,000 t, 184 × 44 × 13.8). The coming availability of electric and autonomous transport may make factory builds more economical than the current fossil fuel human driven logistics of today. Within the EU [94], consideration should be given to the size of transport for each scenario (Table 1).

Table 1
EU Framework for abnormal road transport permits.

	No permit	Long term permit	Corridor (3)
Width	3 m	3.5 m	4.5 m
Length	24 m	30 m	40 m
Height	96/53/EC	4.2 m	4.4 m
Weight	96/53/EC	80 T	100 T

4.2. Define build strategy

Once a high-level assessment has concluded that 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, including those regarding 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.

A decision needs to be taken on which parts of the system will be built in factories, assembled in an onsite area, 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 construction [95,96] capital costs estimation analysis [97]. 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 [98], 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. However, there are a higher quantity of discrete modules that would be 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, and site construction [99]. 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 [100] and more efficient construction at site (Fig. 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 [101]. 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 [102] 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 system [103].

4.4.1. *Module and system partition*

The Modular Reactor plant systems need to be partitioned into modules and 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 [68,72,104].

4.4.2. *Equipment database generation and selection tools*

For deployment in remote and weather adverse locations, reactor plant system 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 [30,30,32,32–34].

4.4.2.1. Equipment database reusing previous designs. Due to shortened project lead times, increasing competitiveness with renewables and between Modular Reactor vendors and Cogeneration capabilities, it is valuable to consider utilising tools that can quickly and efficiently help reuse designs. Examples of this include; [35–40].

4.4.3. *Module design*

[105] Design decision making tools can efficiently and more optimally help in module design [67,95,104,106–109], such as calculating a near ideal option of module arrangement [68], determining modules and separation points [72], algorithms for assembly [71], methodologies for piping [69], simulation methods for manufacturing analysis [70], manufacturing using applied robotics [66], 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 [43,43,45,46,62–65] (S.-K. Kim, Roh, & Kim, 2017), [44,47,110–117].

Some research focused on the safety aspects of design which iscritical 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 reactor plant system modules. Manufacturing is an important consideration in modular design and construction and more research into this area would be required.

4.5.1. *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 in [24] showing efficiency in moving towards commercial off the shelf components, along with flexible designs [81].

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: Reactors, Pumps, Tanks, Pressure vessels, and Heat exchangers, etc. Combine these with a workflow integrator to perform Finite Element Analysis, Computational Fluid Dynamics, as well as cost and manufacturing assessments, the concepts could be analysed and developed quickly. The different types of components that have been designed using this method are shown in Fig. 14.

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

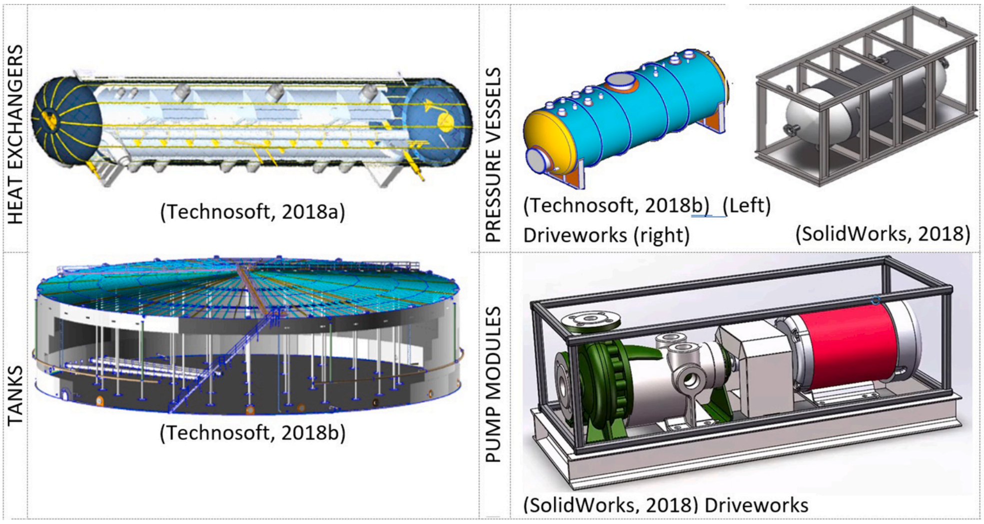

Fig. 14. Components/Products designed using Knowledge Based Techniques from Technosoft, (2018a) Adaptive Modelling Language and SolidWorks, (2018) Driveworks

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 technologies and methods in modular construction are an exciting research and development opportunity to design new Modular Reactors 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. 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 and method learnings could be applied to the design of reactor plant 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 large reactor 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.

Smaller 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 as 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 reactor power plant industry) would be extremely useful here. This would enable standardised equipment to be used in the Modular Reactor power plant 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 Modular Reactor 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 a Modular Reactor, especially for modules with no transport restrictions (3 m wide in the EU) and modules with restrictions (up to 4.5 m 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 [118] as well as safety and construction considerations. Researching and utilising factory manufacturing techniques from automotive, aerospace, and 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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.net.2023.09.029.

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