THE IMPACT OF MODULARISATION STRATEGIES ON SMALL MODULAR REACTOR COST

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Small Modular Reactors (SMRs) based on established light-water technology have gained a lot of attention from the nuclear industry; however, the potential that SMRs have to reduce the cost of nuclear construction has been under-studied. Modularisation is a cost reducing mechanism where a SMR power plant is subdivided into smaller units, or modules. These modules can be produced offsite in a controlled environment, potentially offering cost reductions that offset their apparently higher capital costs.

This paper will investigate the effects modularisation and standardisation might have on SMR capital costs. Modularisation and standardisation not only reduce direct and indirect costs, respectively, but also enable activation of other cost-reducing mechanisms, such as shifting construction work from site to a factory, transferring learning between tasks, and achieving economies of multiples. It will show that constructing a SMR using the same methods as current large reactors is not economically feasible and will demonstrate how modularisation reduces SMR capital costs.

The primary constraints on module size are imposed by weight and height transport limitations, linking reactor size to ease of modularisation. This leads to an analysis of which SMR components and structures should be targeted for modularisation in order to achieve optimal cost benefits.

I. INTRODUCTION

Historically, large nuclear reactors (LRs) have experienced severe budget and schedule overruns. The industry has welcomed SMRs based on proven light water reactor technology for their potential to reduce both the very high construction costs and long build schedules of traditional LRs. There are a number of strategies that SMRs might employ to bring about these cost and schedule reductions, including modularisation, standardisation, and production learning. The process by which a SMR is built, however, must be radically different from the current LR construction process, otherwise SMRs will fall victim to the issues that have plagued LR projects, particularly since the capital costs for nuclear power plants contribute about 70% of the total Levelised Cost of Electricity [1].

A recent paper by Ganda *et al.* [2] analyses LR construction cost data from a number of US sources, including historical data and construction cost estimates. One of the sources Ganda discusses is a summary of US historical construction cost data that is presented in the 1987 Energy Economic Data Base Programme (EEDB) Phase IX Update Report [3]. Ganda finds that it is important to consider both direct and indirect costs in cost analyses because the contribution of indirect costs to the total construction cost is non-trivial. This work by Ganda is central to establishing baseline LR construction costs.

Carelli *et al.* [4] develop a SMR cost estimation model based on specific cost-power scaling, where the cost of a single SMR is determined using scaling exponents and is then reduced using a series of multiplicative cost-savings related to SMR unit co-siting, replication and standardisation (achieving learning), financial aspects (smaller units are easier to finance as they can be built in stages), and various design-specific solutions. Carelli estimates that, when SMRs take full advantage of all these cost-reducing strategies, the specific capital cost of a SMR will be 1.05 times that of a reference LR. This paper also uses the cost-power scaling approach previously used by Carelli in [4] but considers a serial SMR build strategy, focussing on the cost reduction factors that will be common to all SMRs of a single chosen design (that is, modularisation and standardisation) and ignoring potential site-specific cost reductions.

Work by Abdulla *et al.* [5] presents a qualitative study in which the authors interview 16 nuclear industry experts (vendors, regulators, engineers) to obtain an estimate of the cost of building a SMR plant. Abdulla finds that the estimates vary by a factor of 2.5, and a new 225 MWe SMR plant could cost between \$3,200/kWe and \$7,100/kWe (in 2013 US dollars) [5]. While this paper develops specific SMR costs based on the EEDB LR cost data and Carelli's power scaling rules, the results from the parametric model presented in this paper are generally consistent with Abdulla's findings. Moreover, the cost-reduction methods identified by Abdulla's study, such as factory fabrication of units and a reduced SMR construction schedule, are central to the cost reductions in the work presented here.

I.A. Modularisation Principles

Modularisation is the process by which a large, complicated product is broken down into smaller building blocks, or modules, according to a set of limiting constraints. SMRs have a unique opportunity to leverage the benefits of modularisation as a build technique because of their smaller physical size. The SMR modules can be constructed away from the nuclear construction site; this could be either in a shop, factory, or module assembly building, making parallel construction activities possible and greatly improving productivity. In the case of SMRs, transportation logistics impose dimensional and weight constraints on the modules.

One additional design philosophy that is essential for successful modularisation is standardisation. Standardisation targets the indirect costs associated with building a nuclear power plant by removing much of the repeated upfront design work and by leveraging higher learning to reduce both schedule and, by extension, cost. This is achieved through simplification of the construction, testing, and commissioning procedures. This paper assumes a standard reactor system design and that components and modules are similarly standard wherever that is possible.

While modularisation directly offers one-off productivity benefits, it also acts as an enabler for continuous learning. Implementing standardised, modular construction into a nuclear build programme will help facilitate a streamlined supply chain and off-site module build will potentially increase production learning rates. Rosner and Goldberg [6] present a review of the scope for making SMRs competitive across larger programmes of standard reactors; this is accomplished through production learning and economies of volume. A parametric study conducted by Chen *et al.* [7] investigates the effect of production learning on specific SMR components. These studies highlight the importance of modularisation and standardisation for maximising production learning benefits, as well as designing the factory and supply chain for optimising the conditions for production learning. Analysis and discussion of these further benefits is outside the scope of this paper but has been discussed in other work at the University of Cambridge [8].

Designing a specific modularisation scheme for a nuclear power plant is a challenge. The shipbuilding industry, where modular design and build is the norm, provides some interesting information on the general principles and practice of modular construction, but data on specific modularisation schemes are not publicly available. Stone & Webster [9] developed a modularisation scheme for a 790 MWe LR on behalf of the US DoE. The Stone & Webster report provides a highly detailed analysis of modularisation and is useful for establishing a modularisation scheme for reactors of various sizes. It assesses each part of the nuclear power plant (NPP) and identifies how best to design each component as a module. A summary of the feasible modules is given in Stone & Webster Table 4-1 (pp 145-146). The key information used in this paper is:

- **Type** of each module (including precast concrete structures, structural steel, liner modules, etc.);
- **Location** where the modules are to be used (reactor containment, turbine hall, etc.);
- **Quantity** of modules that are required, together with the module weight and dimensions (length, width, and height).

Stone & Webster also identify that transportation logistics limit the modularisation scheme. It is clear that feasible transport logistics will be of greater importance for SMRs that are intended to be produced in volume; producing greater numbers of modules increases the value of easy and straightforward transportation logistics. Although the age of the Stone & Webster report is a drawback, it provides a useful baseline for the work presented here, as it describes a modularisation scheme for a NPP that is, to our knowledge, the only one of its kind published.

II. PROBLEM SETUP

This paper seeks to determine the benefits, in terms of cost, of modularising SMR nuclear power plants of different sizes. It uses transport constraints on the proposed modules to define what module dimensions are feasible. SMR construction cost is the primary focus of this work, and is captured using the concept of overnight capital cost. Although operating and maintenance costs for SMRs are important to through-life economics, capital costs are nonetheless predominant and modularisation will primarily target these construction costs.

The following terms are important to the argument:

- **Modularisation** refers to dividing NPP structures, equipment, and/or components into modules, or 'building blocks', manufactured in a purpose-built factory, shop, or on-site module assembly building. Off-site modules are transported to the nuclear site for installation and assembly. Modularisation introduces a set of one-off productivity improvements that serve to reduce direct costs [10, 11].
- **Standardisation** refers to adopting a single SMR design and, within that design, using as many common components, modules, and equipment items as possible. Standardisation reduces indirect costs.
- **Degree of Modularisation (DoM)** is defined by the authors as the fraction of direct site costs, associated with the construction of a specific component, that are moved to a factory. In theory, DoM values can range between 0, for a stick-built plant, and 1, for a plant in which every structure is modularised.

- **Effective Modularisation** is again defined by the authors as the net fraction of direct site costs transferred from the construction site to the production facility, for the whole plant. Effective Modularisation is useful because it gives an indication of the extent of modularity for the whole plant.

III. SMR MODULARISATION MODEL

An overview of the SMR modularisation model used in this paper is given here; further details of the data used, and the accompanying sources, are provided in the corresponding subsections.

A. A SMR baseline cost breakdown is determined using the detailed reference LR breakdown from EEDB [3] and applying specific cost-power scaling laws. The specific cost-power scaling relationship used is shown in Equation (1), where *Specific Cost* is the capital cost of construction, in 2017 \$/kWe, *Power* is the rated power output of the reactor, in MWe, and α is the scaling exponent, from [4]. The subscript *i* refers to the particular reactor under consideration and the subscript *EEDB* refers to the reference data used from [3]. Using the scaled SMR cost breakdown, a variable Degree of Modularisation (DoM) is set up to allow a fraction of site costs to be moved to a factory.

$$Specific\ Cost_i = Specific\ Cost_{EEDB}\left(\frac{Power_i}{Power_{EEDB}}\right)^{(\alpha-1)} \quad (1)$$

B. The cost reductions that can be attributed to modularisation and standardisation are determined according to a set of rules from [12] and are applied to the scaled cost breakdown from Equation (1). These are essentially a set of multiplicative factors that have a net cost-reducing effect; the magnitude of which is dependent on the DoM.

C. The Stone & Webster modularisation scheme is used to modularise a range of reactors. The number of modules in a reactor is held constant and the weight of each module for a given reactor is scaled relative to the Stone & Webster reference design, according to Equation (2). The variable *Power* refers to the rated power output of the nuclear reactor, in MWe, and *n* is the scaling exponent. The subscript *S&W* is for the reference Stone & Webster plant and *i* is for the new reactor plant. From this, the linear dimensions (length/width/height) of the module were then determined (square root for 2-D modules and cube root for 3-D modules). Constraints imposed by the transportation logistics were next applied to each module to determine which modules are feasible (transportable) and which are not (non-transportable). This sets a practical maximum DoM for a given reactor.

$$Weight_{\ i} = Weight_{\ S\&W}\left(\frac{Power_{\ i}}{Power_{\ S\&W}}\right)^{n} \quad (2)$$

D. Alternative modularisation schemes are considered by further division on the Stone & Webster module dimensions. The transport feasibility and maximum DoM are re-calculated according to the established criteria.

III.A. Baseline Cost Breakdown

This paper uses a parametric approach to estimating SMR capital costs by applying power scaling laws to the available LR data, similar to the method used by Carelli [4], as described earlier. This paper is, however, concerned with the structure of the construction costs, both direct and indirect, and the effects modularisation and standardisation have on reducing these costs. The only available data that exist at the necessary level of detail are the data analysed by Ganda [2] and published by the US Energy EEDB Phase IX Update Report [3]. The EEDB data are from actual LR builds in the US, taken from annual reports published between 1977 and 1987, although costs reported here have been inflated to 2017 United States dollars. The data are structured by work type and cost type (labour, equipment, or material) and forms the most comprehensive and detailed data set available. This paper uses the median data from 1987, which provides cost data for an average 1144 MWe PWR reactor built in the United States. As Ganda notes, historical US-based data will not necessarily be representative of global experience today. Changes in regulation, location, labour markets, and material costs over time will impact how accurately the inflated 1987 average costs represent the cost of reactors built today. Analysing these influences is beyond the scope of this work, although Berthelemy and Rangel [13] provide a thorough discussion of these factors. This data set does, however, provide a consistent baseline for comparative studies of different construction strategies for LRs and SMRs.

To obtain a cost breakdown for a reference stick-built SMR plant, the available EEDB cost data was scaled using specific power-cost scaling according to Equation (1). This provides a detailed cost breakdown for a range of reactors outputs between 150 MWe and 1500 MWe by applying scaling exponents to the different types of cost, according to the exponential factors in Table I. It is worth mentioning that this model is applying scaling laws beyond the limits of existing data; therefore, the accuracy of the results cannot be calibrated or confirmed against real values.

TABLE I. Two-Digit Code of Account headings [3]and corresponding scaling exponents [4].

Two-Digit Code of Account Heading	Exponent, α
21 - Structures and Improvements	0.59
22 - Reactor/Boiler Plant Equipment	0.53
23 - Turbine Plant Equipment	0.83
24 - Electric Plant Equipment	0.49
25 - Miscellaneous Plant Equipment	0.59
26 - Main Condenser Heat Rejection System	1.06

III.B. Modularisation and Standardisation

The relationship between cost savings and modularisation are based on guidelines published by the EMWG (2007) in Chapter 11: Estimating Factory-Produced Modular Units [12]. Some rules for standardisation-related cost savings have also been developed to reflect reductions in the indirect costs that arise as a result of modularisation-enabled standardisation. These have been developed based on EMWG guidelines and expert opinion, in conjunction with the EEDB definition of what each category includes.

- **Time based** indirect cost categories are affected by the length of the reactor build schedule. SMR costs are reduced proportionally to the SMR schedule reduction, which is indirectly a function of modularisation.
- **Modularity based** indirect cost categories are directly affected by the influence of modularisation on direct labour hours. The same percentage reduction of total direct costs, achieved through modularisation, is applied to these indirect costs.
- Finally, **standardisation** of the SMR facility (that is, building the same SMR design across multiple sites and plants) will directly impact detailed design work, reducing these costs by 80% through removal of work not repeated for a standardised design.

III.C. Transportation Constraints on Modularisation

The reference modularisation scheme from Stone & Webster [9] is used for data on module type, quantity of modules needed, as well as module weight, width, length, and height. The Stone & Webster report shows that transportation is the largest constraint on modules and will therefore limit how modular a nuclear power plant can be. The transport constraints for SMRs are applied to a scaled version of the modularisation scheme for the 790 MWe reactor. The physical size of structures is related to the power output of the reactor power plant. From the relative geometries of small and large power plants, module size is assumed to follow an exponential, instead of a linear, scaling form. Stone & Webster module weights are scaled according to Equation (2). This model uses Carelli's cost weighted average scaling exponent as a proxy for size scaling (n = 0.64), as it is reasonable to expect that the direct costs (which are comprised of material and labour accounts) are a reflection of the size difference between a SMR and a LR.

The transport logistics of the reactor modules is developed according to the UK-specific criteria described in Table II. This work identifies three possible categories, called Transport Envelopes, into which modules can fall based on their weight and/or dimensions. Transport Envelope 1 is a straightforward road transport scenario, with specific transport limitations; the module is the size of an ISO container (or less). Transport Envelope 2 is the routine 'relaxation' of the weight and length limits in Envelope 1 but still allows for accessible and relatively straightforward transport in most of the UK (and likewise continental Europe); the idea here is to use purpose-built vehicles to make use of the additional freedom available. Transport Envelope 3 is for any modules that exceed the limits in Envelope 2 and essentially means the modules cannot be transported by road (at least in the UK) and means the component cannot practically be modularised.

TABLE II. Transportation envelopes for NPP modules based on UK road transport limitations [14].

Transport Envelope	Weight (MT)	Length (m)	Width (m)	Height (m)
1	28.8	12.032	2.34	2.292
2	47	27.4	4.3	3.2
3	>47	>27.4	>4.3	>3.2

Once the quantity and size/weight of SMR modules is calculated, the distribution of these modules into the three transport envelopes defined in Table II can be determined. The maximum Degree of Modularisation is taken to be the percentage of modules, by number, that fit in either Envelope 1 or 2. The remaining modules are considered 'un-modularisable' as the excessive weight or dimensions make transport by road nearly impossible. It should be mentioned that it is expected there will be a small number of very large items that cannot be modularised according to the scheme set forth here (for example the reactor pressure vessel, steam generators, turbine generators, and polar crane). The transportation analysis presented here is developed for the high volume of structural and equipment transport and the constraints are not intended to apply to special one-off equipment transport needs.

III.D. Modularisation Schemes

Fig. 1 shows the maximum percentage of modules, by number, that can be transported by road for a range of reactor powers. The module weight and dimensions are based on scaling the Stone & Webster module scheme using a scaling exponent of $n = 0.64$ in Equation (2). As expected, the model shows that smaller reactors have a greater number of modules that fit within the transport limitations, making modularisation more feasible for SMRs (particularly for the M&E, liner, and reinforcing steel categories). Fig. 1 also indicates that structural modules, if designed according to the Stone & Webster scheme, are generally not transportable and therefore most structural elements cannot be modularised. This translates to 564 modules, of a total 1417 proposed by the Stone & Webster modularisation scheme, which cannot be transported for any size of reactor. Of these, 379 modules are precast concrete (which cannot be transported because weight is the limiting factor) and 185 modules are structural steel (where width is the limiting factor).

In order to increase the number of modules that fit in Transport Envelope 1 and/or 2, it will be necessary to change the modularisation scheme developed by Stone & Webster. There are two ways this can be accomplished.

- **Module Subdivision:** break the existing modules down further, so they are easier to transport. The total modularised weight in each category remains the same, but each module dimension (width, length, height) – and therefore the quantity of modules – changes by a certain Module Division Factor (see Table III). With this strategy, modules become smaller and therefore more likely to fit in the defined transport envelopes. The drawback to this is that there will be a greater number of modules to transport, the more subdivided the original scheme becomes.
- **Module Extension:** modularise different structures and components to those considered by Stone & Webster. This is particularly relevant for SMRs, which may, because of their smaller size, have increased potential for modularisation in various structures or components that Stone & Webster did not consider feasible for the 790 MWe reference reactor.

Fig. 2 shows the maximum Degree of Modularisation, which is equivalent to the percentage of modules by number that can be transported, for a range of reactor powers. The Stone & Webster modules are scaled using an exponent of $n = 0.64$ in Equation (2), and a Module Division Factor of 2.0 is applied. Comparison of Fig. 1 and Fig. 2 shows how further module subdivision increases the percentage of transportable modules.

TABLE III. Relationship between module subdivision and the number of modules required for an NPP.

Module Division Factor	Total number of modules
(Stone & Webster scheme)	1417
1.50	3373
2.00	6324
3.00	15705

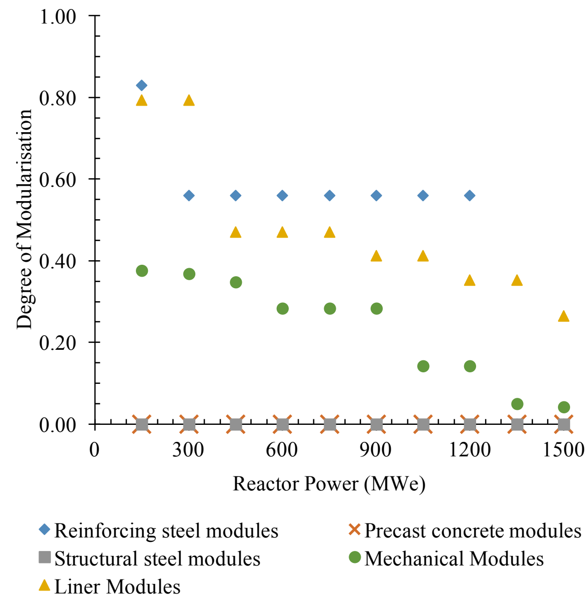

Fig. 1. Maximum Degree of Modularisation attainable from the original Stone & Webster scheme.

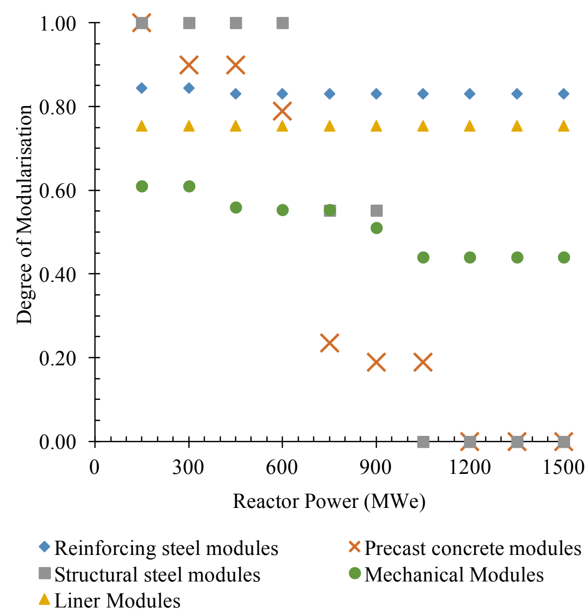

Fig. 2. Maximum Degree of Modularisation attainable when a Module Division Factor of 2.0 is applied to the Stone & Webster scheme.

IV. SMR MODULARISATION SCHEMES

Two modularisation schemes will be considered. In the first, the original Stone & Webster scheme is used and modules are not subdivided beyond the Stone & Webster proposal, as shown in Fig. 1. In the second, the module dimensions proposed by Stone & Webster (length, width, height) are divided by a factor of two, as shown in Fig. 4. In both cases, the maximum degree of modularisation for any system or category is determined by the fraction of modules that can be transported in Envelope 1 and/or 2 (as in Figs. 1 and 2). In both these schemes, the extent to which modularisation is applied to the SMR plant can be varied by varying the DoM between 0.0 and the maximum transportable percentage of modules. In all cases modularisation is applied to the full plant equally (M&E systems, civil structures, and equipment).

Figs. 3 and 4 show the specific capital cost of construction, in 2017 $/kWe, relative to reactor power, in MWe. Modularisation extends to the full reactor plant, including structural elements as well as M&E systems. The model in Fig. 3 uses the original Stone & Webster modularisation scheme; in Fig. 4 the original Stone & Webster module dimensions are halved. For comparative purposes, each chart shows a reactor cost curve corresponding to a stick-built reactor with no standardisation. This must be differentiated from a reactor that has no modularisation (DoM = 0.0) but is built as part of a standardised programme and therefore has reduced development, licensing, and design costs.

As expected, subdividing modules further, as shown by comparing Figs. 3 and 4, is a beneficial modularisation strategy to implement, as it increases the maximum DoM that can be achieved. This means, of course, that a greater fraction of site costs can be shifted to a factory, resulting in greater one-off productivity benefits but also increasing the cost share that can achieve continuous, learning-related benefits. In both cases, there is a point at which modularisation reaches a maximum benefit and further modularisation has little effect. For the case in Fig. 3; this happens at DoM = 0.4 and in Fig. 4 this happens at DoM = 0.8 (or DoM = 0.6 for power outputs exceeding 750 MWe).

Figs. 3 and 4 show how modularising reactors becomes more difficult as the power output increases. For a given modularisation scheme, the module size increases with reactor power, thus decreasing the maximum achievable DoM. For modularisation of the structural elementsjh to be fully effective, however, Fig. 4 shows that the modules need to be further subdivided so a greater number of modules are transportable. The cost implications are significant. The minimum cost of a 300 MWe SMR, when both structures and M&E are made in modules, again to a maximum DoM of 60% is $7,040/kWe. This drops to $5,720/kWe when the modules dimensions are halved, and the plant is modularised to a maximum DoM of 80%. Given the transport constraints and Module Division Factors above, it is apparent that a DoM of 60% will provide worthwhile one-off productivity benefits for all reactor sizes; however, the corresponding Effective Modularisation (that is, the net fraction of site costs that are shifted to a factory) will depend on the reactor power output. The cost benefits of modularisation and further module subdivision are summarised for a 300 MWe SMR and 1000 MWe LR in Table IV and illustrate the significant impact modularisation has on cost.

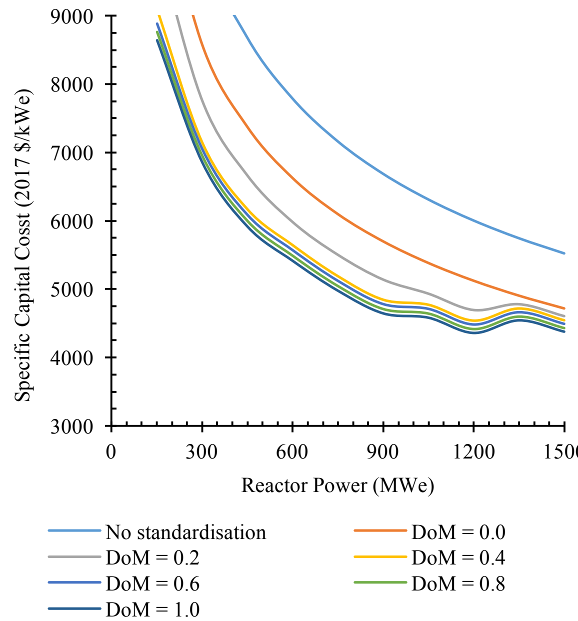

Fig. 3. Specific capital cost of construction relative to reactor power for the original Stone & Webster scheme.

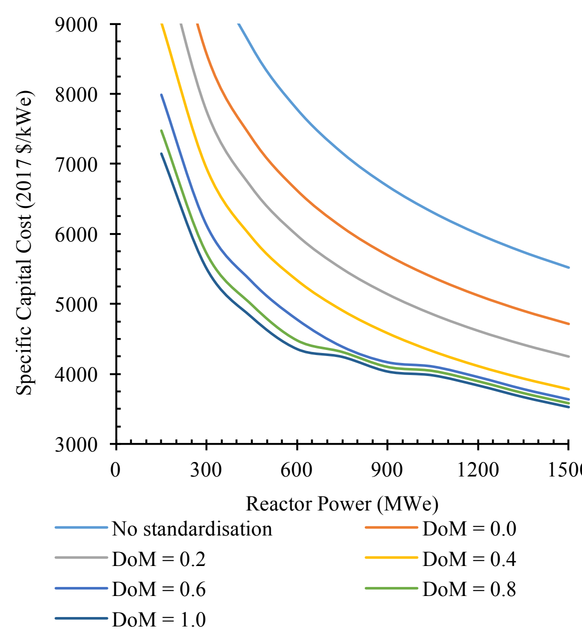

Fig. 4. Specific capital cost of construction relative to reactor power when a Module Division Factor of 2.0 is applied to the Stone & Webster scheme.

TABLE IV. Comparison of modularisation schemes for a 300 MWe SMR and a 1000 MWe LR. The value in brackets is the corresponding Effective Modularisation (M_{eff}) the net fraction of site costs moved to a factory.

	SMR 300 MWe	LR 1000 MWe
No standardisation No modularisation	\$10,100/kWe	\$6,300/kWe
Standardised No modularisation	\$8,570/kWe	\$5,370/kWe
Standardised Max. modularisation	\$7,040/kWe (M_{eff} = 0.35)	\$4,700/kWe (M_{eff} = 0.18)
Standardised Max. modularisation Module subdivision (half)	\$5,720/kWe (M_{eff} = 0.66)	\$4,100/kWe (M_{eff} = 0.46)

It is important to point out the importance of production learning in relation to modularisation. Modularisation and standardisation both offer one-off productivity improvements that reduce SMR cost; however, a range of continuous benefits can also provide significant cost savings over the course of a SMR programme. Modularisation enables factory build, meaning higher factory learning rates could be achieved, further reducing construction costs. Indeed, since the achievable DoM values are higher for smaller reactors, the cost share that can achieve learning benefits is larger and may also lead to greater cost reduction. In this context, modularisation may also offer strategic benefits, where the fact that modularisation enables increased learning is what drives the modularisation decision. Analysis of this effect is outside the scope of this paper but learning rates and supply chain considerations have been discussed in [8].

V. FUTURE WORK AND CONCLUSIONS

This paper develops a simple economic model to investigate the strategies for cost reduction of small nuclear power plants by adopting modular construction. It also highlights the importance of considering transportation-related constraints when developing these strategies. Ultimately, the findings presented here are intended to help guide SMR designers and vendors as to what decisions they make regarding modularisation of the SMR power plant, as well as helping identify what the expected economic and logistic implications might be. This paper suggests that fully modularising the SMR plant is necessary to achieve the maximum cost reduction; however, this comes with the additional need to further subdivide the modules so that transport constraints can be met. Given these conditions, the necessary DoM for a SMR that will provide significant construction cost reduction is 60%; the effort required for further modularisation is not considered worth the small additional cost benefit.

This work so far has relied on the notion of a variable Degree of Modularisation, which is as yet an abstract concept and is tied to cost fractions only. The next stage of this work will be to identify what components and specific modular strategies should be adopted in order to achieve the necessary overall Effective Modularisation.

This work also points out the importance of transportation in setting bounds on the modularisation strategy. The next step is to consider the possibility of developing a modularisation scheme that is extended beyond that considered by Stone & Webster. SMRs may have additional scope for modularisation because of their reduced size. Here too it will be important to perform case studies identifying specific structural and M&E modular solutions that are deemed feasible for a SMR power plant. Future work should also investigate the economic costs introduced by different production learning rates and scenarios, as well as transport options and the potential implications module transport has on reactor lead-time and project scheduling.

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