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WE NEVER BUILT SMALL MODULAR REACTORS (SMRs), BUT WHAT DO WE KNOW ABOUT MODULARIZATION IN CONSTRUCTION?

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ABSTRACT

The key characteristics of small modular reactors (SMRs), as their name emphasized, are their size and modularity. Since SMRs are a family of novel reactor designs, there is a gap of empirical knowledge about the cost/benefit analysis of modularization. Conversely, in other sectors (e.g. Oil & Gas) the empirical experience on modularization is much greater. This paper provides a structured knowledge transfer from the general literature (i.e. other major infrastructure) and the Oil & Gas sector to the nuclear power plant construction world. Indeed, in the project management literature, a number of references discuss the costs and benefits determined by the transition from the stick-built construction to modularization, and the main benefits presented in the literature are the reduction of the construction cost and the schedule compression. Additional costs might arise from an increased management hurdle and higher transportation expenses. The paper firstly provides a structured literature review of the benefits and costs of modularization divided into qualitative and quantitative references. In the second part, the paper presents the results of series of interviews with Oil & Gas project managers about the value of modularization in this sector.

1. THE VALUE PROPOSITION OF SMALL MODULAR REACTORS

The International Atomic Energy Agency [1] defines Small Modular Reactors (SMRs) as “*newer generation reactors designed to generate electric power up to 300 MW, whose components and systems can be shop fabricated and then transported as modules to the sites for installation as demand arises*” (Page 1). Several SMRs designs, detailed in [1–3], are currently at different stages of development. [4] provides a

summary of the innovative feature of SMRs and describes SMRs as “*reactor designs that are deliberately small, i.e. designs that do not scale to large sizes but rather capitalize on their smallness to achieve specific performance characteristics.*”

Several papers discuss the competitiveness of SMRs vs Large Reactors (LRs) and how SMRs might balance the “diseconomy of scale” with the “economy of multiples” [5–11]. [12,13] analyse specific factors (such as grid characteristics, construction time, financial exposition, modularization, learning etc.) which distinguish SMRs from LR in the evaluation of the capital cost. Once these factors are taken into account, the capital cost is comparable between the two technologies [5,7]. [14] discusses the effects of ‘non-financial parameters’, such as electric grid vulnerability, public acceptance, the risk associated with the project, licensing [15], during the evaluation of the best reactor size for investments in the nuclear sector. For many of these parameters, the authors explain how SMRs show an advantage with respect to LR. SMRs, having the power fractionated are also ideal for cogeneration, as presented in [16–18]. Indeed, one of the key SMRs advantages is the possibility to split a large investment into smaller ones. The construction of a single LR is a risky investment [20]. The construction of SMRs is an investment decision with n degrees of freedom that allows hedging investment risks. The economic merit of flexibility can be calculated using the Real Options (ROs) approach [21].

However, despite the relatively large amount of literature published on SMRs, there is a gap in knowledge on the merit of having “small modular reactors” instead of just “small reactors”. In other words, one of the key challenges for the assessment of SMRs advantages and disadvantages is the lack of empirical information, as no SMRs have been built yet, but

only “traditionally built small reactors”. Therefore, it is necessary to explore the role of modularization in closely related fields, such as large infrastructures creation, and transpose the knowledge back to the nuclear and in particular the SMRs sector. Therefore, this paper addresses the following question: what SMRs in particular and the nuclear sector, in general, can learn about modularization from the infrastructure sector?

The rest of the paper is structured as follows: section 2 summarises the key references about modularization in large infrastructure to show how the transition from the stick-built construction to modularization impacts on the project schedule, budget and risk; section 3 presents the methodology used to collect and analyse data; section 4 shows and discusses the results of interviews with Oil & Gas project managers about the value of modularization in this sector; section 5 concludes the paper.

2. MODULARIZATION IN INFRASTRUCTURE: LESSON LEARNED

Several papers and reports, hereby described, deal with the costs and benefit of modularization. This section is divided into two subsections to show the qualitative and quantitative references. Qualitative references represent most of the studies.

2.1 Qualitative references

- **Schedule**

The impact of modularization on the project schedule is widely discussed in the literature. Understanding and planning the criticality of the project schedule is one of the decision-making factors that must be considered before the beginning of the modular construction [22]. Habibullah et al. [23] studied and compared modular design and Gravity Base Structure concepts to that of the traditional stick-built plant, in particular, the land-based large individual modules and the Liquefied Natural Gas (LNG) process facilities installed on a Gravity Base Structure. One of the main conclusions of the study is that the modularization reduces the construction schedule. Ikpe et al. [24] examined the modularization of projects in the Alberta Oil & Gas industry. The research methodology implemented was qualitative and involved interviews with seventeen industry practitioners. According to the authors, modularization has excellent potential to reduce the schedule overruns and improve the performance of the project. Moreover, in the construction of offshore Floating Production System, after the transition to modularization, most of the operators were able to reduce the schedule without delay from the start till the first oil extraction [25]. It is interesting the case of Yamal LNG Project, that is the construction of a liquefied natural gas plant for production, treatment, liquefaction, storage and export of LNG from South Tambey condensate gas field. It is the world’s largest modularised LNG Project, and it respected the schedule [26,27]. Considering that an analysis of data from 318 industrial megaprojects [28] shows that the vast majority of megaprojects might be viewed as a failure when considering adherence to schedule and budget as well as benefits in

operation, it wasn’t trivial that Yamal LNG Project respected the schedule. There are several references [29–32] which define the schedule compression as one of the key characteristics of the modularization, but the critical point is to understand why. De La Torre [29] explains its causes and states: “*the reduced schedule is caused by:*

- 1) *performing the design and procurement simultaneously,*
- 2) *working in parallel,*
- 3) *increasing the control of schedule (Wells, 1979),*
- 4) *higher productivity from the permanent workforce in fabrication shops,*
- 5) *the opportunity to train operators at fabrication shops rather than on-site (Wells,1979)”.*

- **Cost**

A considerable amount of literature has been published on the cost variations caused by the transition from the stick-built construction to modularization. The key point is to understand where the changes are, where the modularization determines a cost reduction and where a cost increase. According to Musa et al. [32], modularization can reduce the labour and material cost but can increase the transportation cost. Moreover, design and engineering phases require additional man hours and, consequently, a cost increase [29,33]. On the other hand, through high-quality materials and factory quality assessment (QA)/ quality control (QC) management and control, modularization determines a cost saving [32]. According to Jameson [30], modularization can reduce the labour cost but only if the off-site labour cost is less than the on-site one. This often happens for the following reasons:

- The cost of tools, supervision, training etc. is higher on-site than in a shop environment;
- Some areas have a labour cost higher than some yards located in a more economical environment.

The possibility to produce modules off-site increases the quantity and diversity of potential fabricators for a project and, consequently, the increase of competition that can determine a reduction cost [28]. Eftimie [34] states that a modular method is an alternative approach of doing engineering that aims to minimise the total installed cost and optimise the return on investment, sanctioning the standardisation for similar projects in the future. Standardisation is at the origin of a more efficient supply, construction and operations and it enables suppliers and utilities to more rapidly benefit from the learning economies [35]. Another essential characteristic of the modularization is the possibility to achieve economy of scale in production [36]. Moreover, one of the implications of the studies explained in the previous section is the reduction of the project cost [23,24]. De La Torre [29] concludes that despite the increased cost listed above, most modular construction projects show savings in installed costs over conventional construction.

- **Risk**

According to 5th Edition of the PMBOK® Guide [37], project risk is “*uncertain event or condition that, if it occurs, has a positive or negative effect on one or more project objectives such as scope, schedule, cost, and quality. A risk may have one or more causes and, if it occurs, it may have one or more impacts*”. According to De La Torre [29], the increased risk is

one of the disadvantages of the modularization, and it is related to the necessity of expertise, the interdependency of activities, and the lack of adaptability to variations. Moreover, previous studies evaluating the modular construction in offshore Oil & Gas projects have highlighted that risks are mainly due to poor planning and poor detailed engineering [38,39]. The life cycle of Offshore Oil & Gas projects is characterised by eight phases, in which the risks are continuously assessed [40]. Cost and schedule estimates for Oil & Gas projects are commonly set up during Front End Engineering Design (FEED) and managed over the implementation phase [41]. Moreover, changes during the project may contribute to significant implications on the cost of the entire project cycle [42,43]. These changes are related to risk associated with modularised projects in Oil & Gas megaprojects [44,45]. On the other hand, Jameson [29] explains a characteristic of modularization which leads to a reduction in the safety risk: “*Shifting work into a controlled shop environment generally benefits the overall safety risks of a project. In addition, large vertical structures can be constructed in the horizontal by use of modularization. This limits the amount of vertical work at elevation and can decongest areas that, by their nature, possess a riskier work environment*”. However, according to Shahtaheri et al. [46], several sectors of construction are shifting away from the stick-built method in the use of modularization due to its advantages, despite the constraints and risks that may impact its benefits.

2.2 Quantitative references

• Schedule

The Modular Building Institute is an association formed by manufacturers, contractors, and dealers working in the modular building sector. The organisation emphasises the benefit of modularization in the definition of modularization itself: “*a process in which a building is constructed off-site, under controlled plant conditions, using the same materials and designing to the same codes and standards as conventionally built facilities but in about half the time*” [47]. Also Shelley [48] indicates that modular construction can shorten construction time by 50%. Instead, Hesler [49] states that “*in-depth studies have shown that modular power plants show schedule savings approaching 40%*”. In the case study “*High-rise Building in Wolverhampton*”, it was estimated a saving of 45% in the construction period [36]. Moreover, Choi & Song [38] estimated schedule for stick-built and modular method relative to the construction of an underground machine room for a high-rise residential building. This study concludes that the traditional approach takes about nine months and the modularization about seven months. Therefore, it is possible to estimate a schedule saving of 22.2%. Efrimie [34], instead, focused on offshore facilities. According to the data owned by the author: “*reduced schedule (up to 25-50%): yard fabrication allows early procurement of critical equipment and maximized parallel works (workshop vs field civil work/site preparation); yard work can start before obtaining a site permit. Short schedules are important when required to market products rapidly [...]*”. Another example of an offshore project that adopted modularization is the Delta House FPS in the Gulf of Mexico [25,50]. The Delta House

began the project well before the arrival of any data (such as volume, specific pressure, temperature, and production). Conversely, most of the FPS projects use the conventional developmental approach, wherein drilling tests the wells and the reservoir composition is analysed before the design and construction phase. With the use of standardisation and modularization, the Delta House was able to finish their project successfully in about three years after the construction of the facility started. Comparing to other platforms in the Gulf of Mexico, the Delta house project was roughly completed 2-3 years earlier [50,51]. Considering that the construction time of offshore FPS projects using the traditional development cycle is 5-7 years [25], it is possible to estimate a saving of at least 28.6% in the construction period. Another specific case study is the General Dynamics Electric Boat [52]. Electric Boat is the prime contractor and lead design yard for the U.S. Navy's Virginia-class attack submarines. According to the company “*Improvements in construction performance will reduce construction span from 84 months to 60 months. This is being achieved through greater use of modular construction, pushing as much work as possible into a manufacturing setting where it can be done more efficient.*”. Therefore, it is possible to estimate a saving of 28.6% in the construction period. Most of the references analysed report a schedule saving between 40% and 50%. On the other hand, two case studies in two different sectors show the same value of schedule saving, 28.6%. Figure 1 summarises the quantitative information about the schedule.

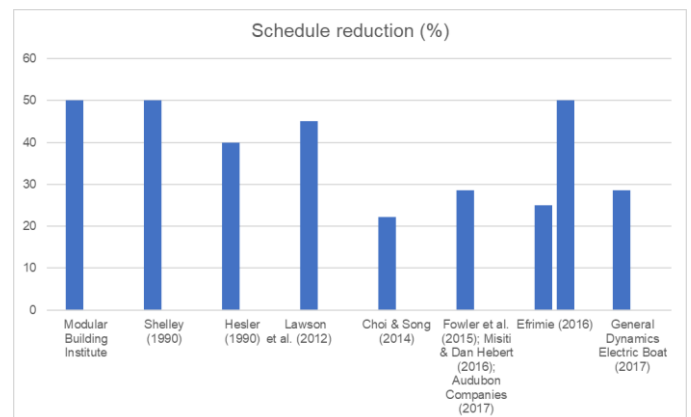


Figure 1: Schedule reduction determined by the transition from the stick-built method to modularization

• Cost

This section summarises the quantitative references about the cost variations determined by the transition from the stick-built method to modularization. Hesler [49] states that “*in-depth studies have shown that modular power plants show capital cost savings of 20 % or more*”. He explains that the engineering costs involved in the first modular construction project are usually greater because of inexperience. In particular, the first modular design “*can be 50-60% more than conventional construction design, particularly if the job is done well. This, of course, is only 50-60% more (than conventional construction design) or 12% of the total installed cost.*”. Shelley [48] shows that, in some cases, a reduction of capital costs by up to 20% is possible. Therefore, Shelley [48]

and Hesler [49] agree on a capital cost saving of 20 % or more. Tatum et al. [53] evidence other significant benefits of the modularization. They state that it has been estimated that the modular engineering concept can save up to 10% of the total cost of a facility, cut on site labour by 25%, and reduce the plot [working] area by 10% to 50%. Parkingson & Short [54] show other examples of reduced costs through modular construction. In particular, they show that John Brown of John Brown Engineers & Constructors Inc. stated that savings of at least 7% of the total contract amount were obtained by using modular construction methods rather than conventional methods for over 40% of the process facilities for the Sullom Voe Oil Terminal in the Shetland Islands. Jameson [29] analysed a gasoil hydrotreater modular project located in North America. According to the author, modularization determined a cost saving of \$ 12.5-million on an approximately \$ 70-million project. Therefore, a cost saving of 17.8%. On the other hand, Glaser et al. [33] state that the additional man-hours required for design and engineering of a modular construction project increase the design and engineering cost by approximately 10%. Because of the effort needed to evaluate and select vendors, fabricators, and fabrication shops, and to administer contracts, the cost associated with procurement increases by 20% in modular construction projects, while the costs of the fabrication and transportation activities increase by approximately 17% and 13%, respectively. Instead, Kliewer [55] cites an engineering cost increase of 15%. Moreover, Shelley [48] shows that the transportation cost is about 1-2% of the value of the module. Figure 2 below summarises the quantitative information about the cost saving.

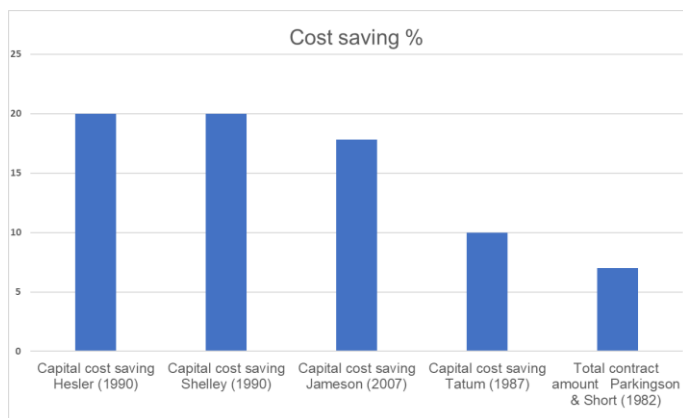


Figure 2: Cost saving determined by the transition from the stick-built method to modularization

2.3 Summary

Both qualitative and quantitative references show that the schedule reduction is one of the implications of the modularization. There are examples in several sectors, and the percentage can change from one to another one, but also within the same. Therefore, it should be assessed for each project individually. However, the references analysed show a maximum schedule reduction of 50%, a minimum of 22.2% and an average schedule reduction of 37.7%. At the same time, both qualitative and quantitative references show how modularization determines several cost variation. Design and engineering phase, procurement and transportation become

more complicated than in the stick-built method, determining a cost increase. Nevertheless, the references analysed show a maximum capital cost saving of 20%, a minimum of 7% and an average cost saving of 15%.

3. RESEARCH METHODOLOGY

This section is concerned with the methodology used for the study explained above. Table 1 below provides a summary of the main research elements of this study.

Research Question	How modularization in offshore Oil & Gas projects impacts project cost and schedule?
Research Design	Inductive, exploratory study that implements a survey approach.
Sampling Strategy	Purposive and snowball sampling.
Data collection	Qualitative data collected through semi-structured interviews.
Data Analysis	Pilot-coding, content analysis through inductive coding.
Supplements	NVivo Pro

Table 1: research methodology, layout adapted from Bititci et al. [56]

3.1 Research Design and Research Method

The deductive approach and the inductive one are the primary research approaches. The deductive approach uses existing theory to develop a hypothesis and then tests it for validity. On the contrary, the inductive does not formulate a hypothesis at the beginning of the research [57]. The inductive approach has been selected, in consideration of the research question that aims to explore a phenomenon, identify the patterns and contribute to new generalisations [58,59]. Furthermore, this research design is categorised as an exploratory study. Based on Saunders et al. [60], qualitative research works in unity with interviews that consist of open-ended questions. Semi-structured interviews have been selected. This method allows open questions to be flexible in acquiring in-depth knowledge from the interviewees' responses [61].

3.2 Sampling strategy and Data Collection

The sampling strategy is based on the research design, access and representativeness of population [62]. For this research study, two sampling techniques are combined: the purposive sampling and the snowball sampling. The purposive sampling allows to be selective in choosing participants for the study. The participants targeted are senior project managers that worked on offshore Oil & Gas projects in Norway. The reason to choose this sample is that the concept of modularization in offshore Oil & Gas projects began to develop from around 40 years [63] and the Norwegian industry is one of the most advanced in the world in this sector. The snowball sampling is a technique in which the existing subject study propose other subjects who might become part of the sample. The advantage is the possibility to interview candidates that are hard to reach, mainly since the research focuses on a closed network industry. Data for this study were collected through interviews held in Norway, all being conducted face-to-face except for one phone-interview, with a total of 6 in-depth interviews with

leading experts. Discussions focused on the participants roles and company background, experience from offshore projects, extent and view of modularization, further discussing related issues and examples. In all interviews, English was used to communicate. English is considered the second language in Norway, with participants in an industry that adopts it as its working language. Table 2 presents an overview with details of the six interviews, taking into consideration the anonymity of the interviewees.

No.	Date	Duration	Current position	Activity
1	6 th June 17	35 mins	Engineering Manager	E & P
2	9 th June 17	75 mins	Engineering Manager	EPC
3	12 th June 17	70 mins	Engineering Manager	EPC
4	20 th June 17	60 mins	Director	Supplier
5	23 th June 17	70 mins	Vice president	Supplier
6,7	6 th July 17	60 mins	Discipline lead & Senior engineer	Concept & Design

Table 2: Overview of interview participants

Other data was collected in the process of setting up for interviews, such as phone calls and emails that discussed the research topic and its objectives. For instance, a conference call with both participants 1 and 2 occurred over a month before the face-to-face interview. It was initially arranged to brief participants more on the research question and discuss modularization before the formulation of the questions for the interview. Data collection is divided into two stages. In the first, the interview questions were put to the test by interviewing the first two participants, as pilot-test interviews. In the second stage, the other five participants were questioned based on the lessons learned from the previous ones. A key point is the engagement of the participants and several follow-up questions to attain elaborate answers and explore developing aspects relevant to the research question. This includes implementing the laddering technique to ask ‘why’ questions and ask participants for example [64].

3.3 Data analysis

A key point of research is the data analysis, which aims to finish the research work by drawing logical conclusions from obtained data [65]. Figure 3 below summarises the data analysis plan of this study.

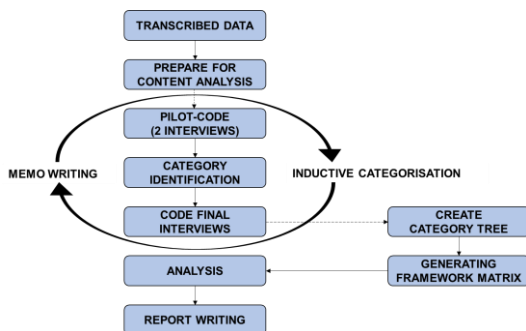


Figure 3: Data analysis plan

From the data collection stage, the interview transcripts were documented and each data content (six interviews transcript

and notes) were thoroughly read and understood. NVivo Pro, a Computer-assisted Qualitative Data Analysis Software was employed to facilitate the analysis of data. Following the guideline set by Saldaña [66] in his coding manual, there are two cycles of coding. The first starts by reading the interview transcripts and summarising in a word or two each section of data into ‘nodes’ that represent different categories or themes. Further, the second cycle focuses on outlining the codes and reorganising the long initial list based on thematic similarity. Furthermore, the coding of the transcribed data is executed in two stages following a similar arrangement to the data collection. The initial phase includes pilot-coding the first two interviews using the cycles explained above. Following the second cycle of coding, a rough representation of the categories and sub-categories is formulated, and preliminary relationships were identified. The last stage proceeds to coding the final interviews using the initial stage categories for guidance. Throughout the process of coding, categories and sub-categories were rearranged, combined and titled appropriately based on the accumulated knowledge of the data. The following Figure 4 shows the final organising categories based on collected data.

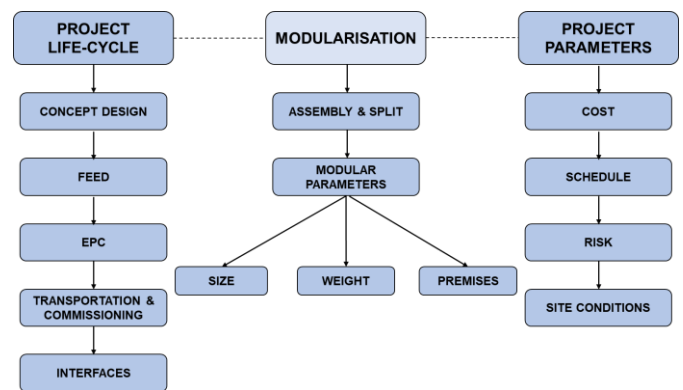


Figure 4: Category tree

The root category, Modularization, gives a unique perception of the offshore Oil & Gas sector. The branching category, Project parameters, presents the identified interrelations between modularization and the primary project constraints. The last branching category, project life-cycle, is divided to show the determining offshore Oil & Gas phases.

4. FINDINGS AND DISCUSSION

This section summarises the findings and discusses the results of interviews in relation to the literature.

4.1 Modularization

This core category mainly focuses on defining modularization from the perspective of the participants. All of them agreed on its importance in the context of offshore projects. Most interviewees expressed modularization as the split of a project into various scopes or modules. As participant 3 articulated: “...to take the complete project and split it into functional parts and split the scope. It could be internally...we prepare several modules that are fabricated as separate units, and then they are assembled on a later stage of the project. Or it could be split up into several scopes...other parties have other

modules from the different parts of the whole project". Participant 5 pointed out a key benefit of modularization as: "the good thing about modularization of the equipment is that you can change out parts...then without having any downtime for the rig you can replace that... otherwise you have to do all retrofit work offshore". Furthermore, the phases that determine the modular approach were mentioned by participant 6: "... we need to decide on the modularization as part of the concept, pre-FEED and FEED". Hence, these early phases represent the crucial stage which impacts the project most.

4.2 Schedule

• Extract from the interviews

Participants always acknowledge a direct relation between schedule and cost. Participant 2 explained: "to compress a schedule that itself will have an extra cost due to overtime and additional personnel costs". Participant 3 highlighted the importance of the control of the schedule: "the schedule is very much controlled...it's one of the largest lifting vessels in the world ...therefore it's not an alternative to reschedule, so things need to be finished on that day". Another aspect of having large modular offshore projects split and spread out is pointed out by Participant 2: "the difficulty of managing site teams and communications is both time consuming and costly of course to have onsite follow-up of all these different sub-projects"

• Discussion

A critical variable identified is the reduction of the project schedule. The shorter execution time influences the increase in costs since contractors, subcontractors and suppliers focus on delivering on time. These results support previous research that reflects on the impact of project duration on the cost performance [39,67,68]. Empirical evidence shows the constraints posed by the final transportation and lifting plan of these enormous modules are critical. Hence, the cost overruns can increase significantly for the EPC contractor as the schedule is very controlled. These results are in agreement with findings on the effect of scope delay on overall project commissioning [69]. On the other hand, it is interesting to note the excellent practice in the industry, where studies are performed on schedule performance issues upon project completion, providing lessons learned for similar future projects. The nuclear sector needs to familiarise with these lifting practices, particularly for SMRs built not on the coast.

4.3 Cost

• Extract from the interviews

As a result of the follow-up on modular parameters that impact cost, participant 6 made this statement: "Weight is directly linked to cost...if you have an idea of the weight of steel you can just multiply the ratio number for cost and you get quite an accurate price range actually". On the other hand, when asked about the impact of modular construction on the cost of procurement, participant 5 stated: "you will have a more efficient and cost-effective procurement and fabrication, I think". Other responses to this point included participant 2

statement: "...you have more complex logistics...and typically you have misunderstandings of how and where various components are to be delivered, who shall purchase what. So, I would say ... procurement is more complicated and reduced in quality due to the modularization". As for the cost of transporting modules compared to the overall project cost, participant 4 stated for small modules: "when you come to big cranes ... it can be up to 10% of the cost of product".

• Discussion

The empirical findings presented the direct relationship between weight, size, production capacity and cost. A similar relation and the importance of taking into account for the cost are documented in the literature [69]. However, the authors [69] don't consider design factors such as the met-ocean data required for the early design of floaters and semisubmersibles. The results presented that this design parameter influences the size of the hull which causes a definite increase in cost. Further, increase in weight affects fabrication costs due to additional steel, massive lift cranes, engineering costs and shipping costs. On the other hand, the relationship between risk of rework and increase in cost is reported in the literature [40,44]. The current study found that factors of rework risk impact cost due to lack of early involvement, the complexity of planning and interface handling. These results support the idea of developing interface management to better control risks [45]. A significant finding is that the modularization reduces in some instances the risk of rework. The results suggest, having smaller modules as units that can be removed or replaced would decrease the high costs of rework and enable cost savings. A key point for the nuclear sector would be to establish the exact size of the module(s), balancing the economies of scale with the learning process acquired by building a series of modules.

4.4 Risk

• Extract from the interviews

The participants illustrated several types of risk. Participant 2 stated: "due to the extreme focus of let's say, turnover time. I think the risk of under engineering or poorly planned engineering...are the most critical". Further, participant 3 presented an example related to modular parameters: "there is a risk that maybe your assumption in the beginning was a module 20x20 meter and hopefully that will be enough space to house all the equipment and all the functionality you put in. But, if it turns out you cannot fulfil the requirements within the space, then you will have a very big problem". Additionally, the schedule is linked to many risks. Participant 6 stated: "Usually delay is a risk, for instance these topside modules built, even if it's on the same yard, it's still different locations and it needs to be timed correctly, needs to be finished at the right time because maybe you have one block that goes in before you have the outer one installed". Moreover, participant 5 presented the risk of rework: "...the equipment should be incorporated in the 3D model, when that fits together you start to do the construction...if the actual equipment isn't 100% identical with the drawings then...your assembling doesn't fit together. You have to do some

rework...that should be in a small workshop not at a yard, an...you hold back maybe the whole fabrication”.

- **Discussion**

Previous studies evaluating the modular construction in offshore Oil & Gas projects have highlighted that risks are mainly due to poor planning and poor detailed engineering [38,39]. The empirical results presented the risk of not fulfilling the weight and capacity requirements due to poor detailed engineering and lack of communication among the parties in the EPC phase. On the other hand, findings present the risk of delays due to weather conditions to be critical for topside modules, since they require special large transport vessels. However, delays are not regarded for smaller modules that can be transported by commercial container ships for instance. Construction in the nuclear sector has often been affected by huge risks leading to overbudget and delay. If modularization will be able to offset some of these risks, it would be possible to have more investors confident to embark in nuclear projects. However, a key point will always be to properly allocate the different risks to the stakeholders better able to handle them. Novel solutions, like the usage of SPE, should be carefully investigated [70].

4.5 Project Life Cycle

- **Extract from the interviews**

- **Concept Design**

The relationship between the project characteristics of offshore Oil & Gas projects and modularization starts with the concept phase. Appropriate decisions made during the early design impact cost as stated by participant 7: *“To get robustness, to get a good start, if you do a lot of changes in the later phases it might be more expensive you have to redo a lot of things...”*. Moreover, the decision made on lifting of modules may impact the modular design, participant 3 elaborated: *“you have to decide early for instance how to install this, shall this be an offshore installation with lifting or do you install the modules on the yard with skidding, that will affect the design of the modules”*.

- **Front End Engineering Development**

When asked about complications that develop during the FEED phase, participant 6 related to module layout: *“for instance you add all the different sizes of piping and you will see that thing will increase in size...when you get to really do things in detail you will see the actual required space and not the assumption we made early on”*. Participant 5 argued about FEED with an example: *“we had one project they have done FEED phase and the quality was not good enough, so the whole platform needed to be reinforced or increased in size and weight, that affects everything, the cost and schedule...”*.

- **Engineering, Procurement and Construction**

Following the concept phase and FEED phase, the company developing the concept is usually not involved anymore. Participant 7 stated: *“we have done engineering up to a certain degree, and then the detailed contractors do the detailed engineering”*. About the selection of EPC format, participant

1 said: *“normally the main hurdle is actually to have all the engineering in place before you start construction. I think that’s actually where most companies or projects fail”*. The reason behind this problem is illustrated by participant 3: *“all projects that we have been involved with have a very tough timeframe and...you are normally forced to start fabrication early, even when it’s still a lot of remaining issues to be resolved in the engineering phase”*.

- **Transportation and Commissioning**

The complete overview of transportation of different modules till the commissioning of the final offshore platform is presented from a project by Participant 3: *“to reduce offshore work that is very expensive...they assemble it as one unit...and transport it to the field...that is cost efficient”*. On the other hand, transportation arrangements act as constraints that influence key milestones in the project. Participant 5 mentioned this remark: *“you might be building the hull at the yard and then you have the milestone to take the hull further for topside integration. Then you have a certain milestone ... to just transport the vessel ...”*. Conversely, the delay may come from the transport or lifting vessel. Participant 1 stated: *“...we were two months delayed on the offshore installation of the module, that was actually due to harsh weather west of Africa...”*. Most participants agreed on the impact of transportation, yet participant 4 stated: *“our equipment, it’s smaller, it’s not big structures, they are small and can maybe go into a container and they can go on fast going vessels, they maybe don’t need special transport”*.

- **Interfaces**

This matter was stressed upon by both participants from the EPC company, as participant 3 explained: *“Because you might have several engineering companies for systems engineering, you have several companies for fabrication, you can have several subcontractors ... the number of interfaces are increasing your risk”*. Moreover, the communication and integration between the various parties during the early project phases was acknowledged by participant 6: *“... the different disciplines have direct contact with the disciplines if we have a major client in UK or US ... I need to have a contact person for my relevant discipline for the site”*. Further, participant 7 followed with this statement: *“And in later phases, it might be required to work in integrated teams”*. Participant 2 talked about an example to explain how to mitigate the impact of the interface: *“to handle all the interfaces ...that was a modularised project, the demand for engineering phase was that all participants shall be co-located at a physical location...to counter the adverse effects...5 or 10 teams with separate scopes that should be integrated”*.

A key problem for the nuclear industry has often been related to start the construction, still without a detailed design completed. For instance, in the case of Olkiluoto 3 the regulator said *“The schedule of Nuclear Island is now about four years behind the original plan. Main reasons for this delay are: [...] – inadequate completion of design and engineering work prior to start of construction. – lack of experience of parties in managing a large construction”* [71]. Also *“making design as early as needed for smooth construction, & qualifying the new design features and*

technologies” were key points raised by the regulator [71]. As clearly presented in the Oil & Gas sector, modularization would be a key driver here. It could exacerbate these aspects if not properly management (e.g. poor detailed design), but could also be the “silver bullet” if the designed is improved and optimised in the case of “series production”. Again, SMRs would be an attractive proposition only if a multitude of identical units will be manufactured, commissioned and operated.

4.6 Key takeaways for the nuclear sector

A key result of the research reveals the actual importance of vendor selection, for the timely inclusion of modules, interface information and freezing critical modular parameters. Moreover, early engagement of suppliers and regulators during FEED phase is recommended to improve information sharing and decrease the impact of conceptual premises that affect the project life-cycle further. This is consistent with findings that show the impact of early decisions on modular construction projects [22,72]. Furthermore, empirical results presented the size and complexity of projects, which increases interdependence of interfaces among project scopes and increases risk. Under this perspective, SMRs might have a clear advantage respect to larger GWe scale reactors. Small projects are usually fast-paced and, in several instances, engineering and construction overlap causes an increase in requirements for interface handling. Failure to fulfil such requirements will impact installation and functionality of the whole module. Similar findings are documented in the literature. According to Love & Edwards [40], initiation of construction before engineering is completed causes risk of rework. Moreover, as the yard contractor subcontracts smaller modules as equipment packages to the supplier, further the supplier may subcontract the fabrication to distant sites to reduce costs. Although this particular notion is not specified in the presented literature, theory highlighted the crucial factors in EPC phase influencing the risk of rework due to the dispersion of the project team [40]. The literature on modularization of plants focuses on the impact of interfaces handling in terms of cost overruns, for instance, due to rework or other technical risks [38,40]. Nonetheless, as the empirical findings stated, if requirements for critical parameters such as weight and size exceed the specified range in the construction phase, then changes lead to extreme cost overruns for contractors causing, in certain case bankruptcy. In the nuclear sector, where the number of “qualified contractors” for a certain task is usually small, this might become a key risk.

The empirical findings show that contractors adopted concurrent planning and partnering with experienced subcontractors and suppliers. The theory recognises these as factors that enable the success of modular construction projects through the experience of contractors [43,72]. However, empirical findings present a limitation of these applied enablers, that is the discontinuity through projects phases due to the use of different contractors and consultants from one step to the next, or gap among the parties within one step. According to Olaniran et al. [73], implementation of integration teams would assist in improving the continuity and effective communication. An interesting empirical finding to point out is the recent measure taken by the main client in the

Norwegian industry, that is the implementation of large integration teams at one location. This presents a development in client leadership in order to improve cost and schedule performance of modular projects, through the management of execution risks, delay avoidance and continuity through project phases. Otherwise, the repercussion according to empirical evidence has increased in costs for the topside contractor due to the interdependence of assembly on other modules, further increase of delay risk on schedule due to the critical transport and lift milestones for offshore delivery.

5. CONCLUSION

A keyword in “Small Modular Reactors” is “Modular”. Despite many studies and papers discuss the economics of SMRs very few of them provide a sensible analysis of the modularization aspect. The key reason is that SMRs are a novel type of reactors, therefore historical data are not available. This paper addresses this gap in knowledge analysing modularization in other types of infrastructure. It describes, through a literature review analysis, how modularization in infrastructure impacts on the project schedule, cost and risk. Moreover, this paper summarises and discusses the results of interviews with Oil & Gas project managers about the value of modularization in this sector. Schedule reduction and cost saving can be considered as two of the key advantages of the transition from the stick-built method to modularization in infrastructure. On the other hand, the increased risk as one of the key disadvantages. Therefore, the aim of this paper is to show what we know about modularization in infrastructure on three key project parameters: schedule, cost, and risk.

The results of the literature review analysis and of the interviews suggest that the evaluation of the transition to modularization in infrastructure requires the consideration of several variables. However, the empirical evidence presented in this paper confirm the merit of modularization. This doesn’t imply that the transition from the stick-built method to modularization in the nuclear sector will determine the same consequences. However, SMRs in particular and the nuclear sector in general can learn from modularization in the infrastructure leveraging the experience accumulated over the year. “Learning the right way to do modularization” will be a key success factor for the deploy of SMRs.

REFERENCE

- [1] IAEA. "Advances in Small Modular Reactor Technology Developments". 2016.
- [2] Locatelli G, Mancini M, Todeschini N. Generation IV nuclear reactors: Current status and future prospects. *Energy Policy* 2013;61:1503–20.
- [3] IAEA. *Advances in Small Modular Reactor Technology Developments. A Supplement to: IAEA Advanced Reactors Information System (ARIS)*. Vienna: 2014.
- [4] Ingersoll DT. Deliberately small reactors and the second nuclear era. *Prog Nucl Energy* 2009;51:589–603.
- [5] Carelli MD, Locatelli G, Mycoff CW, Garrone P,

- Mancini M, Ricotti ME, et al. Competitiveness of small-medium, new generation reactors: a comparative study on capital and O&M costs. 16th Int. Conf. Nucl. Eng., vol. 4, Orlando, Florida, USA, May 11–15, 2008; ASME; 2008, p. 1–8.
- [6] Locatelli G, Mancini M. A framework for the selection of the right nuclear power plant. *Int J Prod Res* 2012;50:4753–66.
- [7] Boarin S, Locatelli G, Mancini M, Ricottia ME. Financial case studies on small- and medium-size modular reactors. *Nucl Technol* 2012;178:218–32.
- [8] Locatelli G, Bingham C, Mancini M. Small modular reactors: A comprehensive overview of their economics and strategic aspects. *Prog Nucl Energy* 2014;73:75–85.
- [9] Boarin S, Mancini M, Ricotti M, Locatelli G. 10 – Economics and financing of small modular reactors (SMRs). In: Carelli MD, Ingersoll DT, editors. *Handb. Small Modul. Nucl. React.*, Elsevier; 2015, p. 239–77.
- [10] Trianni A, Locatelli G, Trucco P. Competitiveness of small-medium reactors: A probabilistic study on the economy of scale factor. *Int. Congr. Adv. Nucl. Power Plants 2009, ICAPP 2009*, vol. 1, 2009.
- [11] Locatelli G. Fusion: Go small to go fast. 25th Int. Conf. Nucl. Eng. ICONE 2017; Shanghai; China; 2 July 2017 through 6 July 2017; Code 131175, vol. 5, American Society of Mechanical Engineers (ASME); 2017.
- [12] Carelli MD, Petrovic B, Mycoff CW, Trucco P, Ricotti ME, Locatelli G. Smaller sized reactors can be economically attractive. *Soc. Fr. d’Energie Nucl. - Int. Congr. Adv. Nucl. Power Plants - ICAPP 2007*, "The Nucl. Renaiss. Work.", vol. 5, 2007.
- [13] Carelli M, Garrone P, Locatelli G, Mancini M, Mycoff C, Trucco P. Economic features of integral, modular, small-to-medium size reactors. *Progress in Nuclear Energy. Prog Nucl Energy* 2010;52:403–14.
- [14] Locatelli G, Mancini M. The role of the reactor size for an investment in the nuclear sector: An evaluation of not-financial parameters. *Prog Nucl Energy* 2011;53:212–22.
- [15] Sainati T, Locatelli G, Brookes N. Small Modular Reactors: Licensing constraints and the way forward. *Energy* 2015;82:1092–5.
- [16] Carelli MD, Garrone P, Locatelli G, Mancini M, Mycoff C, Trucco P, et al. Economic features of integral, modular, small-to-medium size reactors. *Prog Nucl Energy* 2010;52:403–14.
- [17] Locatelli G, Boarin S, Pellegrino F, Ricotti ME. Load following with Small Modular Reactors (SMR): A real options analysis. *Energy* 2015;80:41–54.
- [18] Locatelli G, Boarin S, Fiordaliso A, Ricotti M. Load following by cogeneration: Options for small modular reactors, gen IV reactor and traditional large plants. 25th Int. Conf. Nucl. Eng. ICONE 2017; Shanghai; China, vol. 3, American Society of Mechanical Engineers (ASME); 2017.
- [19] Locatelli G, Fiordaliso A, Boarin S, Ricotti ME. Cogeneration: An option to facilitate load following in Small Modular Reactors. *Prog Nucl Energy* 2017;97:153–61.
- [20] Brookes NJ, Locatelli G. Power plants as megaprojects: Using empirics to shape policy, planning, and construction management. *Util Policy* 2015;36:57–66.
- [21] Locatelli G, Pecoraro M, Meroni G, Mancini M. Appraisal of small modular nuclear reactors with “real options” valuation. *Proc Inst Civ Eng - Energy* 2017;170:51–66.
- [22] Azhar S, Lukkad MY, Ahmad I. Modular v. Stick-Built Construction: Identification of Critical Decision-Making Factors. 48th ASC Annu. Int. Conf. Proc., United State: the Associated Schools of Construction; 2012.
- [23] Habibullah A, Lardi P, Passmore M. LNG Conceptual Design Strategies. WorleyParsons 2009.
- [24] Ikpe E, Kumar J, Jergeas G. Analysis of Modularization Compared to Total Project Cost in Alberta Oil and Gas Projects. *Glob Adv Res J Manag Bus Stud* 2015;4:pp 116-120.
- [25] Misiti A, Dan Hebert P. Modular Construction in the Oil and Gas Industry. *GlobalSpec* 2016.
- [26] YOUR INDUSTRY NEWS. <http://www.yourindustrynews.com/> 2017. http://www.youoilandgasnews.com/yamal+lng+granted+state+permission+to+commission+first+lng+train_146567.html (accessed December 5, 2017).
- [27] LNG WORLD NEWS. <http://www.lngworldnews.com/> 2014. <http://www.lngworldnews.com/technip-confirms-yamal-lng-deal/> (accessed November 20, 2017).
- [28] Merrow EW. *Industrial Megaprojects: Concepts, Strategies and Practices for Success*. John Wiley & Sons; 2011.
- [29] Torre MLD La. A review and analysis of modular construction practices. Lehigh University, 1994.
- [30] Jameson PH. Is modularization right for your project ? 2007.
- [31] Musa MF, Yusof MR, Mohammad MF, Mahbub R. Characteristics of Modular Construction : Meeting the Needs of Sustainability and Innovation. 2014 IEEE Coll oq Humanit Sci Eng 2014:216–21.
- [32] Musa MF, Yusof MR, Mohammad MF, Sahidah N. towards the adoption of modular construction and prefabrication in the construction environment : a case study in malaysia 2016;11:8122–31.
- [33] Glaser L., Kramer J, Causey E. Practical Aspects of Modular and BargeMounted Plants,. *Chem Eng Prog* 1979;75:49–55.
- [34] Eftimie C. How to Efficiently Engineer the Onshore Facilities: Standardized Modularization Drivers, challenges and perspectives in the Oil and Gas industry. *Proj Value Deliv* 2016.
- [35] David PA, Rothwell GS. Standardization, diversity and learning: Strategies for the coevolution of technology and industrial capacity. *Int J Ind Organ* 1996;14:181–201.
- [36] Lawson RM, Ogden RG, Bergin R. Application of Modular Construction in High-Rise Buildings. *J Archit Eng* 2012;18:148–54.

- [37] Project management body of knowledge. 2013.
- [38] Choi J, Song H. Evaluation of the modular method for industrial plant construction projects. *Int J Constr Manag* 2017;14:171–80.
- [39] Zidane YJT, Stordal KB, Johansen A, Van Raalte S. Barriers and challenges in employing of concurrent engineering within the Norwegian construction projects. *Procedia Econ Financ* 2015;21:494–501.
- [40] Love PED, Edwards DJ. Curbing rework in offshore projects: systemic classification of risks with dialogue and narratives. *Struct Infrastruct Eng* 2013;9:1118–35.
- [41] Burke R. *Project management: planning and control techniques*. New Jersey, USA 2013.
- [42] De Meyer A, Loch CH, Pich MT. Managing project uncertainty: from variation to chaos. *MIT Sloan Manag Rev* 2002;43:60.
- [43] Choi JO, O'Connor JT, Kim TW. Recipes for Cost and Schedule Successes in Industrial Modular Projects: Qualitative Comparative Analysis. *J Constr Eng Manag* 2016;142:4016055.
- [44] Olaniran OJ, Love PED, Edwards DJ, Olatunji O, Matthews J. Chaos Theory: Implications for Cost Overrun Research in Hydrocarbon Megaprojects. *J Constr Eng Manag* 2017;143:5016020.
- [45] Shokri S, Haas CT, G. Haas RC, Lee SH. Interface-management process for managing risks in complex capital projects. *J Constr Eng Manag* 2015;142:4015069.
- [46] Shahtaheri Y, Rausch C, West J, Haas C, Mohammad N. Risk Mitigation through Tolerance Strategies for Design in Modularization. 1st Int. Conf. Ind. Constr., 2015.
- [47] Modular building institute. [Http://www.modular.org/](http://www.modular.org/) 2017. http://www.modular.org/HtmlPage.aspx?name=why_modular (accessed November 28, 2017).
- [48] Shelley S. Making inroads with modular construction. *Chem Eng* 1990;August:30–5.
- [49] Hesler W. Modular Design - Where It Fits. *Chem Eng Process* 1990;October:76–80.
- [50] Audubon Companies. *Fast-Track Platform Success: The Story Behind Delta House Fps*. Audubon Co 2017.
- [51] Fowler RL, Zimmermann EC, Leimkuhler JM, Mullett C, Cooley B, Paternostro B, et al. Delta House Project Overview. *Offshore Technol. Conf., Offshore Technology Conference*; 2015.
- [52] General Dynamics Electric Boat. *General Dynamics Electric Boat | Business Centers* 2017.
- [53] Tatum C, Vanegas J, Williams J. Constructability improvement using prefabrication, preassembly, and modularization. 1987.
- [54] Parkinson G, Short H. For more plant projects the word is: go modular. *Chem Eng* 1982;November:66–9.
- [55] Kliewer VD. Benefits of Modular Plant Design. *Chem Eng Prog* 1983;79:58–62.
- [56] Bititci U, Cocca P, Ates A. Impact of visual performance management systems on the performance management practices of organisations. *Int J Prod Res* 2016;54:1571–93.
- [57] Thomas RM. Blending qualitative and quantitative research methods in theses and dissertations. Corwin Press; 2003.
- [58] Saunders MNK. *Research methods for business students*, 5/e. Pearson Education India; 2011.
- [59] Bryman A, Burgess P. *Business research methods*. Oxford University Press, USA; 2015.
- [60] Saunders M, Lewis P, Thornhill A. *Research Methods for Business Students*. 6th ed. Harlow: Pearson Education Limited; 2012.
- [61] Rubin HJ, Rubin IS. *Qualitative interviewing: The art of hearing data*. Sage; 2011.
- [62] Bryman A. *Social Research Methods*. 4th ed. New York: Oxford University Press; 2012.
- [63] Bjørnstad S. *Shipshaped: Kongsberg industry and innovations in deepwater technology, 1975-2007*. 2009.
- [64] Easterby-Smith M, Thorpe R, Jackson PR. *Management and business research*. Sage; 2015.
- [65] Merriam SB. *Qualitative research and case study application in education*. San Francisco: Jossey-Bass Publishers; 1998.
- [66] Saldaña J. *The coding manual for qualitative researchers*. Sage; 2015.
- [67] Olaniran OJ, Love PED, Edwards D, Olatunji OA, Matthews J. Cost Overruns in Hydrocarbon Megaprojects: A Critical Review and Implications for Research. *Proj Manag J* 2015;46:126–38.
- [68] Yun S, Choi J, de Oliveira DP, Mulva SP. Development of performance metrics for phase-based capital project benchmarking. *Int J Proj Manag* 2016;34:389–402.
- [69] Rui Z, Li C, Peng F, Ling K, Chen G, Zhou X, et al. Development of industry performance metrics for offshore oil and gas project. *J Nat Gas Sci Eng* 2017;39:44–53.
- [70] Sainati T, Locatelli G, Brookes N. Special Purpose Entities in Megaprojects: empty boxes or real companies? *Proj Manag J* 2017;48.
- [71] Symposium US. *Lessons for the next NPP projects, as learned from the Olkiluoto 3 construction experiences* Jukka Laaksonen Director General Radiation and Nuclear Safety Authority -STUK 2011.
- [72] O'Connor JT, O'Brien WJ, Choi JO. Critical Success Factors and Enablers for Optimum and Maximum Industrial Modularization. *J Constr Eng Manag* 2014;140:4014012.
- [73] Olaniran OJ, Love PED, Edwards D, Olatunji OA, Matthews J. Cost Overruns in Hydrocarbon Megaprojects: A Critical Review and Implications for Research. *Proj Manag J* 2015;46:126–38.