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DEALING WITH COMPLEXITY IN MODULAR CONSTRUCTION

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Abstract: *Offsite modular manufacturing opens new avenues in productivity and builds quality. Investments in the delivery of pre-assembled modular solutions have been made to meet demand and optimise production and contracting activities. Applications of modularity span from residential housing to industrial plants. Modularity, however, does not come alone. Complexity is inherent to engineered systems or even designed into them. This paper draws on responses from five senior executives, and desk-based research to explore issues of complexity in modular construction. Key findings are: 1. there is a linear and sequential relationship between those who design, engineer and operate modular buildings; 2. to enhance communication and feedback, the construction industry is keen to explore the benefits of systems approaches. The paper contributes by identifying the issues that underlie complexity in the delivery of modular infrastructure projects to lay the foundation for a Systems Engineering framework to address them.*

Key Words: ***Complexity; Construction; Infrastructure; Modular Manufacturing; Systems Engineering***

1. INTRODUCTION

Modularity is an efficient design strategy [1]. Investments in the delivery of pre-assembled modular solutions have been made to meet demand and optimise production and contracting activities. The smartphone in the hands of the user is a bespoke and customised experience – it shows the potential of standardising what is not seen and customising what is seen. Offsite modular manufacturing opens up new avenues for productivity and builds quality [2]. It is now deeply written into industrial strategy in many countries, for example in the UK [3].

Growing interest in offsite modular manufacturing in construction builds on a significant trajectory of research [4-6], with applications of modularity spanning from residential housing [7] to industrial plants [8]. There is the potential for standard processes and both standard and customised components, where the finishes can be customised and those things that are not seen by the end-user can be fully standardised. Greater control over work conditions bring advantages: worker safety, quality assurance, speed, productivity, reduction of waste, traceability of materials.

Modularity, however, does not come alone. Complexity is inherent to engineered systems or even designed into them [1, 9]. The objective of the paper is to identify the issues that underlie complexity in modular infrastructure projects and thus, lay the foundation for a Systems Engineering framework to address them.

2. LITERATURE

2.1. Complexity

In the built environment, complexity can be found in four different types [10]: (1) The physical/technical networks bear an inherent complexity owing to the vast number of technical elements. (2) The actors that develop and use the infrastructural networks act in their own. (3) The physical network and the actors collectively form an interconnected complex network (i.e. socio-technical setting). (4) Infrastructure interconnectedness creates a network of distributed infrastructures that interact with each other, although originally, they were designed as distinct.

Networked infrastructures, such as those for transport of people and goods and for provision of telecommunication, water and energy services, are prime examples of socio-technical systems [11]. Socio-technical systems are systems that exhibit both physical and social complexity. Infrastructure systems are complex systems in view of their combined social, economic and physical complexity [12].

In [13], it is argued that cities like London have been treated as systems for fifty years, but only in the last two decades has the focus changed from aggregate equilibrium systems to more evolving systems whose structure emerges bottom-up. Complexity sciences helped change the paradigm to one which treats cities as emergent phenomena generated through a combination of hierarchical levels of decentralised decision, action [13] and control [14].

Along these lines, civil infrastructure calls for a need to reframe from component (e.g. single project) to systems. In [15], complex projects are regarded as complex adaptive systems emphasising their changing nature. Operations research, systems engineering and project management represent different approaches to this increasing complexity of systems.

A systems approach and Systems Engineering, which brings with it a greater emphasis on testing (verification and validation) in order to understand overall performance and interdependencies and tolerances between different components, is committed upfront in the design process [16, 17].

2.2 Modularity

The lean approach [18] is a pull, rather than push approach that emphasises customisable designs using standard components. In mature sectors, such as construction, systemic innovation is harder than innovation in particular modules [19, 20, 21]. Recent work suggests that offsite modular manufacturing requires more integrated practices [22] and advanced supply chain strategies [23] so that emergent dependencies can be managed.

Construction companies should be quite careful because, inherently, with modularisation, what they might be doing is introducing more connections and new interdependencies. The oxymoron with modulariastion is that, to a point, companies modularise to minimise dependencies between different modules and achieve simplicity through offsite repeatability. But because there is a whole modularised system in place, they actually, unintentionally, introduce more complexity. Balancing between that is one of the chalenges.

The same phenomenon is observed in manufactiring. Firms pursue modularity in the design of product family architectures, however, modularity is not a dichotomous property of a product, as different types of modularity can be embedded into a product family architecture [24]. Also, the complexity of component families outsourced to suppliers and the geographical proximity of component family suppliers affect the extent to which the product variety–operational performance trade-off can be mitigated through modularity [24].

From a complex systems engineering perspective, modular manufacturing requires more than just tools. The problem will not be solved through a ‘run the tool, get the answer’ process, but requires understanding of the nature of complexity and how to deal with volatility and deep uncertainty. Thus, tools needed are those that will enable this understanding first.

Under the same notion, [25] argue that the procurement process in the construction industry is complex and not standardised, adding thus to the complexity and the cost of the entire project. To exploit the potential of reducing cost, suppliers need to understand the complexity that lies in the purchasing routines of their buyers and thus foster and optimise the direct link to their buyers.

Understanding and studying complex systems and processes requires a holistic perspective [26] and systems engineers’ toolkits (e.g. CoSMoS project[1]; CSEI[2] Systems Engineering Toolkit for Infrastructure) should include a wide range of methods and processes to address environmental and system complexity in appropriate and useful ways [27]. There is a large and rapidly expanding literature on networks, complexity and complex adaptive systems that can guide complex systems engineering practice.

3. METHODS

This work was part of a larger project, the aim of which is to examine the applicability and potential advantages of systems engineering in the delivery of a modular reactor project through the development of an exhaustive and sophisticated *Systems Engineering toolkit*.

Data collection was, (1) first, through in-depth interviews with five senior executives (see Table 1) that have experience of modular construction. These interviews had a dual purpose, the first was to get feedback on a toolkit for Systems Engineering that is still under development; the second was to explore issues of complexity in modular construction. Each interview was taped and transcribed leading to 72 pages of transcript for analysis (from 3.6 hours of audio). (2) A second source of data is the written and oral evidence given to the House of Lord's inquiry on offsite manufacturing for construction[3]. We analysed both the interviews and the secondary data in relation to issues of complexity in modular production processes.

Table 1. *Interviews with senior executives*

	Role	Experience
1	Project Technical Leader	32 years (construction company)
2	Partnership and Innovation Leader	27 years (construction company)
3	Director, Nuclear Business Leader	24 years (consultancy and engineering services firm)
4	Leadership Graduate Engineer	11 years (power and propulsion systems company)
5	Mechanical/ Electrical/ Plumbing Lead	7 years (construction company)

[1] Described the characteristics of a process that enables engineers to understand, engineer and validate the complex system and then model and simulate it (Andrews et al. 2010).

[2] http://www.imperial.ac.uk/systems-engineering-innovation - the toolkit is available upon request

[3] https://www.parliament.uk/business/committees/committees-a-z/lords-select/science-and-technology-committee/news-parliament-2017/off-site-manufacture-inquiry-launch/

4. FINDINGS

General findings (Section 4.1) and findings related to complexity (Section 4.2) were produced by the four interviews, whilst the benefits of offsite manufacture (Section 4.3) as well as the dilemma between offsite and conventional construction (Section 4.4) were supported by the oral evidence given to the House of Lords.

4.1. General findings

Key findings are: 1. there is a linear and sequential relationship between those who design, engineer and operate modular buildings; 2. to enhance communication and feedback, the construction industry is keen to explore the benefits of systems approaches.

Each of the three partner companies we interviewed is in charge of: earth works and civil structural design works; the reactor and reactor system design; and the construction of the power plant. There is also a turbine provider that were not included in the interviews because they are not involved in the modular construction.

Based on the interviews, modular construction needs a very *collaborative working* environment. However, the majority of the interviewees raised the issue of siloed working in a manner that the three partner companies do not have a formal special purpose vehicle nor joint venture.

In support to the above observation, the interviewees pointed to the different backgrounds of the partner companies. One of the partners, for instance, specialises in defence and is regulated from a security point of view, which does not apply to the other two members of the partnership. Moreover, the tools they use are not specifically geared to infrastructure projects. As an example, they use the PLM (product lifecycle management) process or PBOM (preliminary bill of materials). The former is a product process used to bring new aero-engine blades or engines to the market. Reffering to the latter, it is essentially the parts list for the power station and originates from product development. Both of them are, for instance, less mature in the cooling water system tunnels, which are of high importance in the construction of modular reactors.

Regarding *communication*, the programme is reliant on people and their natural desire to collaborate and integrate, which is not consistent accross the programme. At the design stage, predictions and assumptions are made, and requirements are defined in order to proceed with the next stages of the project. But in practice, the process is not linear at all. It is rather usual, especially in big projects, that changes are made later in the design, construction or even commissioning and operation. However, according to the interviewees, it is never flashed back through the system to understand the true impact of those changes throuhgout. The key is to find a way to integrate the different systems, processes and people, to develop designs and ensure that single-discipline and multi-disciplinary solutions are integrated. This, by itself, adds to the complexity of the programme.

In an attempt to *coordinate their efforts*, the partners have introduced internal and external maturity reviews, as an opportunity for senior stakeholders and influencers external to the project to suggest changes as early as possible in the project. Shortly before the maturity reviews, there is a series of installation reviews within each of the three companies, which fundamentally is the coming together of all the systems designs. Currently, this is the form of collaboration that happens on a daily basis and through sharing information and knowledge. The integration review is a chance to pull all the designs together and make sure that the whole suggested solution is integrating. The interviewees also pointed to the potential of Building Information Modelling (BIM), as an intelligent 3D model-based process that gives architecture, engineering, and construction professionals the insight and tools to more efficiently plan, design, construct, and manage buildings and infrastructure. At the moment, one of the partner companies maintains a Team Centre that manages the different CAD designs.

Yet, there is still a long way to go before systems integration is fully and succesuffly achieved. As an evidence to this, the interviewees posed the following questions: What physical information needs to be shared across the interface betweeen the various design teams? How can we ensure that designs are coordinated?

4.2. Findings related to complexity

According to the senior executives (see Table 1), modular construction can be looked at in two ways; that is, *modular concrete* and the *modularisation of the process plant* (e.g. water systems, emergency systems), or any other building constructed with modular practices. Modular concrete is complex in a sense that it is big in volume and drives cost, labour and time. To deal with the complexity of the modular process, the number of the systems shall be decreased. This means that the systems shall be standardised and modularised in a way that makes them easier to install, commision, operate, maintain and ultimately decommision.

Other factors that add to the the complexity of modular buildings in construction are the *law and the corresponding regulatory approvals*. This poses the constraint that construction companies have to get all the major changes sorted out before going into the real heart of the regulatory approval process. The same applies to the nuclear industry, even to a greater extent.

There is also a need to *deliver economies of volume*. The aim is to replicate across a fleet, rather than just have single bespoke plants, production lines or modules. This will simplify complexity, but only on a long-term basis. Flows in offsite construction are quite different from car manufacturer flows, for instance. Currently, the three companies have decided on bespoke designs, which are going to be modular, but are waiting to be signed off, meaning that the factory is sitting empty. With a possible increase in the demand for modular infrastructure, this may change in the future.

All in all, complexity in modular construction is about bringing *different objects, different products, different trades, different skills* together and synchronising them at the same time.

4.3 Four high-level benefits of offsite manufacture

1. Provide value to clients and end-users through *improved quality and a shorter construction period*. Quality can be improved through a more rigorous attention to testing in the offsite environment. KPMG research finds increased costs for one-off offsite, but financial net savings of 7% due to a shorter construction period, which allows buildings and infrastructure to come into service quicker. Ultimately, where the government is involved in procurement, this is about value to tax-payers through better quality of schools, hospitals and homes.
2. Use *platform-based design strategies*, in construction as in other industries. There are particular opportunities and challenges around this as use of computational techniques can automate the more repetitive design generation processes. Offsite manufacture for construction can benefit from new forms of data-science.
3. *Improve sustainability*, as there is greater traceability of products through the supply chain and the potential to make demountable systems. This provides new opportunities to consider the circular economy.
4. *Foster regional innovation ecosystems* around offsite construction. In the UK, there is the potential to promote employment outside of the south east and to retain and grow UK expertise.

4.4 Offsite or conventional manufacture?

One of the key questions is: What factors are likely to influence clients, architects, design engineers, contractors and the supply chain in deciding whether to choose offsite manufacture?

We cannot change technologies of production systems without changing business and procurement models. Other sectors (e.g. technology companies/ i-phone; car industry; aerospace) have transformed by understanding platforms, modules, high-value manufacture, new service models: As we have learnt from other industries, some companies will fail to make the transition.

Construction is a manufacturing process that needs to be improved, but systemic innovation is difficult in this sector, as there is no central systems integrator and hence it requires different stakeholders in the process to collectively change.

The current structure of the industry in the UK impedes innovation; with low margins, focus on consultancy hours and cash flow, and a range of vested interests in the status quo. However, according to oral evidence given to the House of Lord's, there are lots of good recent examples of digitally-enabled offsite manufacturing practices in this industry.

Clients (public and private) play a role here; fundamentally, if clients are asking for the wrong things, they can't be surprised when they don't get what they want. Contractors are brought on board too late in design work; meaning projects are designed twice - once in-situ, then with offsite manufacturing processes. *There is a need to spend enough time framing the problem.* Changing how the government makes investment decisions is important.

4.5 Drawbacks of offsite manufacture for construction

From the interviews it is concluded that *complexity* is one of the main downsides. But construction is complex anyway. "Suppliers, manufacturers, designers, contractors, users are all being brought into a big box and need to be dealt with as one system"[4]. It is the nature of this specific kind of construction that makes it more complex. The difference between modular and conventional construction is that engineers need to fix the design much earlier on.

More *decisions need to be made upfront in a project*, tolerances need to be understood and designers need to have a greater understanding of manufacturing, assembly, maintenance and operation activities, and to be able to consider these in the design process. Using platform approaches (as discussed above), more solutions can have tested components and design attention can be focused to customisation of options. There is a need to *consider structural stability and safety in all temporary conditions through the build process.*

There is *less flexibility as resources are committed*: Many contractors do not directly employ the labour on the construction site giving them a lot of flexibility. Offsite construction needs capital investment in fabrication equipment and materials, which makes it less easy for firms to upscale and downscale production in response to cycles in demand and so there is greater need for certainty in the forward order book.

Academia seeks to remedy those drawbacks. There is substantial university research in other countries, such as the Digital Fabrication work in ETH Zurich[5]. There is excellence also in the UK, but this needs to be promoted to keep the industry internationally competitive in the medium to longer term.

5. DISCUSSION

Compared to manufacturing, which is a huge success story, construction has stayed pretty flat since 1947 and is a poor environment for growth and tends to be low-margin. For example, big listed construction firms make 4% profit with really tight margins. Besides, construction companies are interchangeable and there is little to differentiate between them, thus they should invest in delivering a productivity shift. Modularity can be part of this shift.

As discussed, modularity has both dowsides and benefits. So far, "construction has been producing vast continuous things", but somehow this big scale infrastructure starts becoming an assembly of objects, the purpose of which is more explicit and they become easier to handle.

One of the most important benefits that modularity can bring to construction is that companies making modules can apply *just in time manufactirung*, in a manner that they can pre-commision to a point, by bringing the offsite fabricated modules on-site. Taking

[4] As mentioned by one of the interviewees.

[5] https://www.arch.ethz.ch/en/forschung/nationale-und-internationale-forschungsschwerpunkte/digitale-fabrikation--nfs-.html

people and boxes of comonents out of the construction site environment and into a clean factory environment contributes to the *health and safety and efficiency* as well. Moreover, in terms of better planning, construction vehicles are off the road, so there is only one vehicle delivering the module, rather than many suppliers.

All this implies a *change in the way supply chain behaves*, but, at the same time, one of the aims is to keep it fairly consistent. There is therefore a *massive cultural shift in the way to deliver modular buildings*. Bringing *modularity into construction is an innovation by itself* and needs an investment into the R&D departments, as well as proper innovation management inside a construction project.

6. CONCLUSION

The paper's objective was to identifying the issues that underlie complexity in the delivery of modular infrastructure projects and thus offer preliminary evidence and lay the theoretical, as well as the practical, foundation for a Systems Engineering framework to address them.

So far, construction industry uses checklists, spreadsheets (e.g. Excel) or drawings (e.g. Visio) to communicate information regarding interfaces. However, to articulate the impact of interfaces and interactions, "we need a process that is strongly founded on systems thinking". This is mainly due to the nature of modular construction, which is different to traditional construction.

What is distinctive in modular construction is that companies are trying to design a system that captures all residential projects aspects. So, *they are not designing one building in one place in time; they are designing a system that can go anywhere*. Therefore, companies do not design for a specific modular contruction project, but for a system. "It is a system that projects have to fit into, rather than designing a system that fits into a project".

"Systems Engineering can keep complex a bit simple", by offering scalable tools to monitor asset health through life. Furthermore, it can deal with discontinuity and incompatibility of tools used by designers and engineers, reduce the number of tools, standardise the systems approach and propose a uniform culture. Diferent scientific disciplines, which study systems, offer a plethora of tools, spanning from functional and interconnectivity analysis to modelling languages and mathematics.

Simply put, we need systems tools to partition and recombine the whole picture. Such tools should help us design and interpret what is happening physically with and within the system. The step after that would be the sensitivity of human interaction.

7. REFERENCES

[1] H. Simon *“The Architecture of Complexity*”, in Managing in the Modular Age, R. Garud, A. Kumaraswamy and R.N. Langlois, Eds. 2003 [1962], Blackwell: Malden, MA. pp. 15-37.

[2] HM Government, *Industrial Strategy Building a Britain fit for the future*, London, 2017.

[3] A. M. Shaik, V. K. Rao and C. S. Rao “Development of modular manufacturing systems—a review.” *The International Journal of Advanced Manufacturing Technology*, 76(5-8), pp. 789–802, 2015.

[4] D. M. Gann “Construction as a manufacturing process? Similarities and differences between industrialised housing and car production in Japan.” *Construction Management and Economics*, 14(5), pp. 437–450, 1996.

[5] S. D. Green, S. Fernie and S. Weller “Making sense of supply chain management: a comparative study of aerospace and construction.” *Construction Management and Economics*, 23(6), pp. 579–593, 2005.

[6] W. Pan, A. G. Gibb and A. R. Dainty “Strategies for Integrating the Use of Off-Site Production Technologies in House Building.” *Journal of Construction Engineering and Management*, 138(11), pp. 1331 –1340, 2012.

[7] E.M. Generalova, V. P. Generalov and A. A. Kuznetsova “Modular buildings in modern construction.” *Procedia engineering*, 153, pp.167–172, 2016.

[8] J. T. O’Connor, W. J. O’Brien and J. O. Choi “Standardization strategy for modular industrial plants.” *Journal of Construction Engineering and Management*, 141(9), p.04015026, 2015.

[9] W. R. Ashby “Requisite variety and its implications for the control of complex systems.” In *Facets of Systems Science* (pp. 405-417). Springer, Boston, MA, 1991.

[10] Z. Verwater-Lukszo and I. Bouwmans “Intelligent complexity in networked infrastructures.” In *Systems, Man and Cybernetics, 2005 IEEE International Conference*, 3, pp. 2378–2383), 2005.

[11] P. M. Herder, I. Bouwmans, G. P. Dijkema, R. M Stikkelman and M. P. Weijnen “Designing infrastructures using a complex systems perspective.” *Journal of design research*, *7*(1), pp.17–34, 2008.

[12] M. P. C. Weijnen, P. M. Herder and I. Bouwmans “Designing complex systems: A contradiction in terms.” In M. M. Eekhout, R. Visser and T. Tomiyama, *Delft Science in Design, A Congress on Interdisciplinary Design*, 3, pp. 235-254, 2008.

[13] M. Batty “*Cities and complexity: understanding cities with cellular automata, agent-based models, and fractals.*” The MIT press, 2007.

[14] D. D. Siljak “*Decentralized control of complex systems*.” Courier Corporation, 2011.

[15] J. Whyte The future of systems integration within civil infrastructure: A review and directions for research. In *INCOSE International Symposium*, 26(1), pp. 1541-1555, 2016.

[16] E. W. Aslaksen, M. deLamare, K. Fehon, R. Godau, A. Knott, A. Kouassi and J. de Liefde *Guide for the Application of Systems Engineering in Large Infrastructure Project*s. San Diego: INCOSE Infrastructure Working Group, 2012.

[17] F. Salvador, M. Rungtusanatham and C. Forza “Supply-chain configurations for mass customization.”, *Production Planning & Control*, 15(4), pp.381-397, 2004.

[18] J. P. Womack, D. T. Jones, and D. Roos. *The machine that changed the world.* Simon and Schuster, 1990.
[19] R. Levitt "Swimming Across Lanes:Addressing Barriers to Modular & Systemic Innovation in the Construction Industry", *Distinguished Lecture* at the Centre for Systems Engineering and Innovation, 2017.
[20] D. Hall and T. Lehtinen "Agile Cost Shifting as a Mechanism for Systemic Innovations", in Engineering Project Organization Conference. The University of Edinburgh, Scotland, UK, 2015.
[21] J. Taylor and R. Levitt "Understanding and managing systemic innovation in project-based industries" Innovations: Project management research, 83-99, 2004. [working version].
[22] R. Tees, A. Davies, J. Whyte and S. MacAulay "Modular Components, Integrated Practices: Managing Complex Collaboration in Temporary Organization", *Academy of Management Conference*, Atlanta, Georgia, 4-8 August, 2007.
[23] P-Y Hsu, M. Aurisicchio and P. Angeloudis P, Supply chain design for modular construction projects, 25th Annual Conference of the International Group for Lean Construction (IGLC), Crete, 7-12 July, 2017.
[24] F. Salvador, C. Forza and M. Rungtusanatham "Modularity, product variety, production volume, and component sourcing: theorizing beyond generic prescriptions.", *Journal of Operations Management*, 20(5), pp.549-575, 2002.
[25] B. M. Zunk, M. Marchner, I. Uitz, C. Lerch and H. Schiele "The role of E-procurement in the Austrian construction industry: Adoption rate, benefits and barriers.", *International Journal of Industrial Engineering and Management*, 5(1), pp.13-21, 2014.
[26] A. W. Hubler "Understanding complex systems: Networks." *Complexity*, 10(3), pp.17-17, 2005.
[27] S. Sheard, S. Cook , E. Honour, D. Hybertson, J. Krupa, J. McEver, D. McKinney, P. Ondrus, A. Ryan, R. Scheurer and J. Singer "A complexity primer for systems engineers." *INCOSE Complex Systems Working Group White Paper*, 2015.

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