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People-Led Digitalization :
Lessons learned from two concrete shell research projects

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Abstract

The shell and spatial structures engineering community has long-since been at the forefront of computational design development. Yet, as we look at the vast number of new buildings being constructed in cities around the world, examples of such efficient structural engineering solutions are hard to spot. It is as though these innovative computational designs are being ignored in favor of the inefficient status-quo. This paper uses two recent research projects to highlight the issue, and introduces new people-focused research to suggest a solution. The ACORN project developed an automated off-site construction system for thin-shell fiber-reinforced concrete floors capable of reducing embodied carbon by 40% compared to their solid-slab equivalents. The Aerial-ABM project developed autonomous drones capable of 3D printing buildings in concrete. Both projects developed novel methods of efficiently constructing buildings using cutting-edge technology, but neither have [yet] led to a step-change in current practice.

The hypothesis of this paper is that the missing link is People; and that without placing people at the heart of technology-based solutions, important opportunities for innovation will be missed. The "Made Smarter Innovation: Centre for People-Led Digitalisation", hosted by the University of Bath, UK, creates needs-driven processes to support industry in realizing the potential of a people-led approach to digitalization. The shell and spatial structures engineering community should therefore adopt a people-led approach to its computational design development, in order to fully realize the benefits of its innovation.

Keywords: technology, adoption, stakeholder involvement, design, construction, people-led digitalization

1. Introduction

This paper begins with the ubiquitous warning that its readers have no doubt heard many times before - the Construction Industry must change. It is a major contributor to global carbon emissions, the main cause of climate change, and with building energy demand far outstripping building energy reduction measures, the situation is getting worse and the sector is not on-track to decarbonize by 2050 (UNEP [1]). Yet the Construction Industry continually refuses to change, despite the world changing around it. There has been a wealth of new technologies, both hardware (robotics, virtual reality, IoT, Additive Manufacturing) and software (BIM, Parametric Modelling, Optimization, Machine Learning, AI) that other sectors have adopted with great success. Yet a 2015 briefing paper by McKinsey [2] identified Construction as the second worst sector for digitalization in the US, and there is little evidence to suggest things have improved since (e.g. Tuckwell [3]).

Lots of excellent research is carried out, both in academia and in practice, that results in new hardware and software specifically targeted at improving the productivity and sustainability of the sector. In particular, over the 65 years of the IASS's existence, the complexity, both geometrically and structurally, of shell and spatial structures, has necessitated the creation of innovative digital tools to support their design and construction. Nevertheless, there is certainly no plethora of new shell and spatial structures being constructed around the globe to combat climate change. Most building sites still pour carbon-intensive concrete into disposable timber molds, or bolt together standard steel sections in regular non-optimized grids of beams and columns, just as they did when the IASS was founded.

During a coffee break at a previous IASS Symposium, the lead author was explaining to a contractor how his new research could save significant amounts of concrete in buildings by putting material only where it was needed. The contractor replied along the lines that he wasn't interested in saving concrete, since his fee for a job was calculated as a proportion of the concrete poured, and therefore the more concrete a building used the more money he made. Speechless, and exasperated, the lead author refrained from banging his head against the wall, and instead joined the Made Smarter Centre for People-Led Digitalisation (PLD) based at the University of Bath. PLD recognizes that digital technologies have the potential to transform manufacturing, which includes construction, by increasing productivity and opening up new business. And whilst this may seem like a purely technical challenge, many of the barriers are due to human factors, be they a skills gap, employee resistance or a lack of senior management's support or vision.

It is therefore the hypothesis of this paper, that the barriers the construction industry faces in achieving the required change are human not technical. The authors make the case that we must place our most valuable asset – people – at the core of all our solutions, otherwise innovation risks being overlooked and the sector will continue its race to the bottom of the digitalization index.

The paper starts with an overview of two technically challenging research projects that highlight the conservatism inherent in the construction industry. It then introduces new research, using stakeholder interviews and thematic analysis to identify barriers to adoption of new technology within the sector, and finishes with some suggestions of how these barriers can be mitigated.

2. Case Study Projects as Motivation

The lead author was involved in two recently completed research projects involving the integration of innovative software and hardware, resulting in two very different new approaches to building construction. The technical details of these projects has been published elsewhere. What follows here focuses on the public's subsequent reaction to the innovations, to highlight the construction industry's contentment with its conservatism, as a motivation for the stakeholder study reported in Section 3.

2.1. A very sensible idea that met with lots of opposition

The Automated Concrete Construction (ACORN) project developed a digital workflow from design to fabrication, form-finding segmented concrete shells for building floors, analyzing them to determine minimum concrete thicknesses, and then fabricating them using an adaptable computer-controlled 'pin-bed' mold (Figure 1). Academic papers have been published by Costa et al. [4] in terms of software, and Oval et al. [5] in terms of hardware, amongst others. Since the resulting floors contained only a quarter of the concrete of the equivalent flat-slab, the prototype gathered a significant amount of interest in the more mainstream construction press (Sabina Aouf [6]), making it one of the RIBA Journal's Top 5 Product Stories of 2022 (Kucharek [7]).

Along with the congratulations and encouragements, the project garnered a non-trivial amount of (often constructive) criticism from industry professionals on social media, in email correspondence and at seminars. The criticisms can be roughly divided into two categories, those that are due to the early-stage research not being fully developed (not least thanks to the pandemic lab closures), and those due to the radical change in current practice needed for such an innovation to be adopted by the industry.

Figure 1: The ACORN concrete shell full-scale prototype
[Photo credit : ACORN team at University of Bath, University of Cambridge & University of Dundee]

Technical barriers identified by the researchers, and echoed by the public, include the need for robust connections between segments, worries about acoustic performance and dynamic response, not to mention the performance in fire. However, whilst the researchers took these barriers as a challenge to innovate, and bid for follow-on research funding to answer them, construction industry professionals tended to use them as an excuse to maintain the conservative status-quo and do nothing. For example, the question of fire performance was often addressed along lines of "we need a slab X-hundred mm thick to provide enough cover to the reinforcement to comply with the design codes". However, the ACORN slab embedded short FRP fibers throughout the mix, rather than having a traditional layer of mesh, and its thickness varied between 30-60mm, since it was designed for strength and optimized to save material. Rather than starting from the new building form and then working out how to ensure it is safe in fire (intumescent protection?, sprinklers?), industry practitioners started from current practice and stopped at the first barrier (design codes).

An example of a non-technical challenge, along the lines of my IASS contractor friend who was paid per ton of concrete, is the issue of floor-to-floor height for the ACORN Shell. Many developers commented that the relatively large (60cm) mid-span rise of the curved shell would add significantly to the floor-to-floor height of a building, meaning that either the building would need to be taller, thereby requiring a more costly façade, or that fewer floors could be constructed within the same planning permission envelope, thereby reducing the rentable floor area. Rather than embracing the architectural delight of a curved ceiling (which had been designed to accept building services under the flat false-floor), they instead started from current practice of costing buildings based on flat floor area and stopped at the first barrier. What does the term floor-to-floor height really mean for a curved ceiling, and which building user would care if the ceiling came down a bit lower in the corner of the room anyway?

2.2. A less sensible idea that met with little opposition

The Aerial Additive Building Manufacturing (Aerial ABM) project developed the world's first untethered concrete 3D printer (see Figure 2), alongside a scalable multi-robot path-planning framework that enabled drone tasks and population size to be adapted in response to variations in geometry, battery charge and material reserves. The project's aim was to harness the benefits of 3D printing, not least the freedom to construct complex yet efficient shell geometries, work in congested urban contexts or in post-disaster scenarios, whilst at the same time removing the fixed build-volume constraints of ground-based 3D printers. Thanks to its publication in the journal Nature (Zhang et al. [8]), this project also gained a lot of attention from construction industry professionals. Surprisingly however, most of the criticism was not focused on the lack of structural integrity of the printed prototype, but instead addressed logistic challenges of recharging batteries and material cartridges, and societal issues around machines making human jobs redundant.

Figure 2: The Aerial-ABM concrete tower prototype
[Photo credit : Aerial-ABM team at Imperial College London, University College London & University of Bath]

Again, rather than embracing the technological advancement and exploring ways to make it work for the construction industry, people tried to understand the radical new technology within current methods of working, and were quick to dismiss it when it failed to fit.

3. Stakeholder View

With humans proposed as the main barriers to technology adoption in the construction industry, the authors carried out an interpretive qualitative study (Myers [9]), to identify ways in which these barriers might be addressed. Data was collected through semi-structured interviews of 23 digital technologies adoption stakeholders, with some interviews held face-to-face but most conducted online using MS Teams, each taking approximately 30mins. Transcripts of the interviews were created, which then underwent multiple iterations of a thematic analysis using both qualitative analysis software (NVivo) and manual thematic analysis. Activity theory's extended ActAD framework (Engestrom [10]) was used as a conceptual lens to uncover preliminary themes, which were then refined and grouped, leading to the identification of the following 6 principal considerations:

- Motivation for behavior change and digital technology adoption
- Stakeholder communication framework
- Stakeholder landscape planning and management
- Organizational digitalization approach
- Organizational digitalization limitations
- Intrinsic determinants of adoption

Since a full exploration of all these considerations is not possible within the page limit, this paper focuses on the first two as being most relevant in the context of computational design of shell and spatial structures.

3.1. Motivation for Technology Adoption

Anecdotally one might expect Engineers, who are problem-solvers used to working with technology, are more likely to be early-adopters and jump at the chance to try something new. However, a construction project inevitably involves a broad team of stakeholders, not least architects and contractors. Of course, different project involve different people, with varying attitudes to risk and experimentation with new methods. Furthermore, it is often the case that a particular technology cannot simply be adopted by one stakeholder group in isolation. Even if it can, the benefits it brings may often only be fully realized if adopted across the wider project team. For example, a decade ago, Hudson et al. [11] showed the benefits of adopting a parametric model (what was back then a new technology) across both architecture and engineering teams, in terms of allowing design changes to quickly progress down the design workflow. Even outside of the design team, external constraints, such as the client's fee-structure – paying a contractor per ton of concrete as mentioned above – or the insurance / legal framework within which the project team must work, can all introduce obstacles that must be overcome if new technology is to be tested. This means that there has to be a very strong motivation put in place to make people change the way they work and overcome the (perceived or real) pain barrier involved in adopting new technology. As one participant put it in their interview:

> "I think technology relevance [is important], if people don't see it as relevant to what they're doing, then why should they change or why should they do something new? The functionality: If it's replacing something that is already there but doesn't do the same bits. it's like, well, why should I use it?" Participant #4

Of course, external factors can also help with motivation rather than hinder it. For decades, structural fire engineers have (sometimes) had fee structures which pay them in proportion to how much fire projection they (safely) engineer-out of a design. Government targets for achieving net-zero have been passed down to clients who construct and then operate new buildings, who in turn pass them on to the design team. There has perhaps never been a better time to experiment with the adoption of new technology in the design process. But we must motivate the individuals who will actually have to implement the technology.

> "What we're very good at within the construction industry is focusing on the output, focusing on that final product… we don't think about the people element."
> Participant #2

3.2. Stakeholder Communication

The decision to implement new technology can come from the top-down, or the bottom-up. Readers may well have first-hand experience of a corporate decision to implement a new digital system or software, only to have it ignored, or worse sabotaged, by those responsible for using it on the ground. There are perhaps fewer examples of where a team have identified an opportunity to adopt new digital tools to help automate repetitive tasks, only for the more senior decision-makers to say either say no, or perhaps worse, to request a detailed business case that would involve more work to prepare than the tool would save, at least in the short term.

For the successful implementation of new technology, relevant stakeholders need to be identified, and then a clear communication plan put in place to ensure everyone involved understands why the change is being introduced and makes clear what the benefits are expected to be. Communication is a two-way process, and therefore in parallel there needs to be a mechanism by which stakeholders can raise concerns and see that their concerns are considered.

> "I think when any kind of digitalization has worked well, it has been when there has been the right group of stakeholders with real clarity on their role… They've been involved early, there's has been clarity of responsibility, accountability. When people are being consulted and being informed early in the process, it being a priority to engage stakeholders." Participant #1

Technology changes rapidly, and any implementation of new technology should be seen as a first iteration. It is unlikely to work perfectly first time, but that does not mean that a team should give up at the first hurdle. By creating a motivated team of informed stakeholders with clear two-way channels of communication, lessons can be learned and fed back to make improvements and further leverage the benefits whilst mitigating the barriers.

> "My view on changing transformation is always that if people feel part of the process and they feel their involvement in that end product or that end service then they're more likely to be accepting of that change or that transformation." Participant #2

4. Discussion and Conclusions

The two case studies above show how technology that perhaps should be adopted more widely is often not adopted, and how technology that perhaps should not be adopted more widely might nevertheless be adopted. The key factor in both cases is the attitude of the people involved in the implementation, rather than the individual merits of the technology itself.

Engineers, architects, contractors, and wider stakeholders in the IASS community, have for a long time been at the forefront of technology development, in order to solve the challenges of complex geometry, non-linear structural behavior and construction of a wide range of shell and spatial structures across a wide range of geotechnical, climatic, economic and social contexts. Perhaps understandably however, the human-aspects of technology implementation are often overlooked. The lead author would be the first to admit to having put a significant amount of time and effort into developing software to "help" streamline the design process in practice, without first carefully engaging with stakeholders to help co-create the brief, nor once considering what support should be provided immediately after release, both to improve adoption and to gather feedback on potential improvements.

The world is entering an age of incredibly rapid technology development. AI is an obvious example, with the UK's deputy prime minister saying in a speech to the UN that it is developing too fast for regulators to keep up with (Stacey and Milmo [12]). Yet that has not stopped a number of sectors from adopting AI technology. The construction industry on the other hand is littered with examples of technology adoption being hindered. Unless stakeholders can be sufficiently motivated to change the way they work, this is likely to continue. BIM was not properly adopted across the industry, in the UK at least, until legislation was put in place to force people to adopt it. Additionally, effective strategies for communication must be put in place alongside technology adoption, to ensure stakeholders understand why changes are being made, what the expected benefits are, and how they can be engaged in and influence the process.

The first step is for us all to stop dismissing attempts to change by saying that the construction industry is conservative. An industry cannot be conservative, it is the people that work within it that can be conservative. We must include *people* in the heart of all our solutions, and develop technology that people will want to adopt, if we are to make our industry truly ready to tackle the global challenges we know it must address.

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