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Review

Plug n Play: Future Prefab for Smart Green Schools

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Abstract: While relocatable, prefabricated learning environments have formed an important component of school infrastructure in Australia, prefabrication for permanent school buildings is a new and emerging field. This review of prefabrication for schools is timely. In 2017, Australia's two largest state education departments committed to prefabrication programs for permanent school infrastructure. In this paper we examine the recent history of prefabrication for Australian school buildings in the context of prefabrication internationally. We explore the range of prefabrication methods used locally and internationally and introduce evaluation indicators for school infrastructure. Traditional post-occupancy evaluation (POE) tools measure indicators such as indoor environment quality (IEQ), cost benefit, life cycle performance, and speed of delivery. In response to a shift towards more student-centred learning in a digitally rich environment, recently developed POE tools now investigate the ability of new generation learning environments (NGLEs) to support optimum pedagogical encounters. We conclude with an argument for departments of education to consider how prefabrication provides opportunities for step changes in the delivery, life-cycle management and occupation of smart green schools rather than a program of simply building new schools quicker, better, and cheaper.

Keywords: permanent prefabrication for schools; school design; school post-occupancy evaluation; construction innovation; mass customisation

1. Introduction

Between 2016 and 2026, Australia's school student population is expected to grow by 650,000 [1]. This equates to 26,000 new classrooms or around seven new classrooms every day for the next decade. In 2017 the NSW Audit Office noted a 'chronic under-investment in NSW government school infrastructure' stating 'the condition of classrooms has been declining due to insufficient maintenance, and many are not configured to support contemporary and desired future learning and teaching methods' [2] (n.p.). The NSW Department of Education School Assets Strategic Plan noted 'for three decades, the NSW government school population has been stable catering for between 750,000 and 800,000 students. This has begun to change in the last five years, with student numbers increasing by around 30,000 [3] (n.p.). In response to increasing student numbers, Australia's two largest education departments initiated permanent modular school programs in 2017. In November 2017, the NSW Education Minister announced a call for innovative classroom designs that are permanent and responsive to growth in student numbers. An industry briefing was held in the same month with a commitment to invest $4.2 billion to deliver 120 new and upgraded schools or 1500 classrooms over a four-year period. This is the biggest investment in public education infrastructure in the history of NSW [4]. Concurrently in Victoria, a state-wide audit of 1712 government school buildings found high risk asbestos in nearly 500 schools. By March 2016 all high-risk asbestos had been removed. The Victorian School Building Authority (VSBA) is now addressing medium-risk schools. By 2020, the VSBA will replace 100 school buildings containing medium risk asbestos with permanent prefabricated buildings [5] (n.p.). This is part of the State Government's $155 million investment into the Victorian School Asbestos Removal Program.

It is useful to consider this unprecedented shift to prefabricated permanent school infrastructure in the context of recent developments within Australia and internationally, as well as the long history of prefabrication for Australian relocatable classrooms, referred to as relocatables. In this paper we draw on prefabrication research undertaken as part of an Australian Research Council (ARC) Linkage Project called Future Proofing Schools and subsequent post-occupancy evaluation undertaken by the authors and funded by the Department of Education in Victoria.

In this review of research related to prefabrication for schools, we are particularly focused on developments over the past decade as Australia's prefabrication industry has matured. Catalysts for this maturation include establishment of Australia's first peak body for off-site construction called PrefabAUS. Additionally, some high-profile national and international construction companies were seeking to improve their triple bottom line [6], and concurrently there has been a convergence of building information modelling (BIM) and emergent manufacturing technologies.

An innovation in our research approach is the inclusion of multiple discipline perspectives as represented in Figure 1. Focus 1 clusters research concerned with how the design performs for users and how users experience the learning spaces in terms of pedagogy, wellbeing, and design quality. The second cluster considers the design and prefabrication processes. This research considers opportunities for mass customisation and life cycle analysis (LCA) and costing (LCC) using building information modelling (BIM). We argue that holistic perspectives can highlight blind spots and missed opportunities.

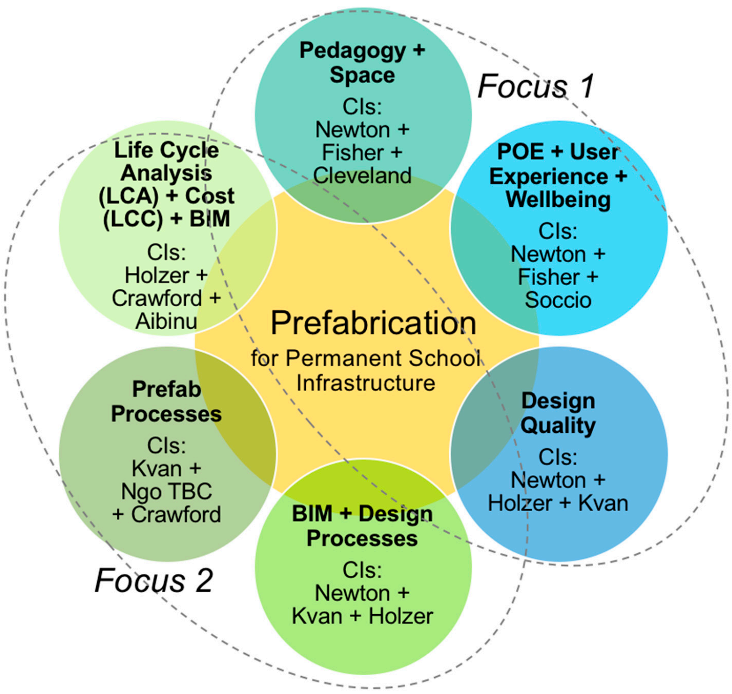

Figure 1. Taking a multi-disciplinary perspective to prefabricated schools. Image: Authors.

The paper begins with a review of prefabrication past and present, and then examines prefabrication for learning environments. We follow with an important parallel review of how innovative learning environments (ILEs), also referred to as new generation learning environments

(NGLEs), are changing to accommodate emerging pedagogies. It is necessary to understand the innovations taking place within education, and how new learning spaces need to be holistically evaluated in terms of their alignment between space and pedagogy. In conclusion we argue for step changes to be considered so that the intersections between pedagogy, space, and emergent construction and manufacturing technologies create optimal contexts in which school students can flourish.

2. Prefabrication in Australia and Internationally

2.1. Prefabrication as Architecture's Oldest New Idea

Prefabrication is often described as architecture's oldest new idea for good reasons. For decades prefabrication has been viewed as being at the cusp of redefining design and construction and yet the potential has often not been realised beyond prototype stage. Prefabrication has a long history. Nonsuch House, the earliest documented prefabricated building, was constructed in Holland and assembled in London in 1579. In 1851, prefabrication enabled the Crystal Palace to be completed in under six months. At that same time, elegant cast iron houses were prefabricated in British cities such as Glasgow and shipped to Australia, of which Corio Villa in Geelong is a notable example. During the First World War Nissen Huts provided relocatable housing for the army with each hut taking approximately four hours and six men to construct. In the 1920s, the German architect Walter Gropius had conceived a modular system of volumetric components. A decade later the American architect Rudolph Schindler developed a housing system using a kit of parts approach as an early form of mass customisation. From 1945, prefabrication helped to address skilled trade labour shortfalls in post war Europe, whilst also addressing the population growth due to the baby boom. By the 1960s, designers were fascinated with modular experimentation which led to projects such as Moshe Safide's Habitat 67 built for that year's Expo in Montreal [7]. Likewise, prefabrication for school infrastructure is not new. Thousands of schools were prefabricated in Western European countries after the Second World War and in the 1960s. These mass-produced and low-cost buildings were in response to an urgent demand for schools [8]. Despite this history of innovation, prefabricated construction technology has not yet achieved its full potential.

2.2. Prefabrication: Many Names for a Family of Approaches

Prefabrication is an overarching term that refers to any part of a building that has been fabricated in a location other than its final location. Prefabrication is also referred to as off-site construction (OSC), modern methods of construction (MMC), and industrialised construction depending on location and context. It is the process of taking a component of the building and re-engineering it so that it can be constructed away from the construction site and then incorporated into the works at a later date. Off-site construction can be as simple as a wooden door unit assembled in the factory instead of on site, or as complex as a building module that incorporates structural, facade, and finishes and is craned into site as one unit. Prefabrication encompasses two main families of systems—2D systems which are generally component or panel-based kits of parts, and 3D systems such as an entire small modular building, or modules that are combined in a range of ways to create a larger building. These 2D and 3D systems can be used on their own, used as hybrids with each other, or used in conjunction with traditional construction approaches.

Different systems have different advantages. Modular buildings can be constructed in the factory in parallel to site preparation activities, then arrive on site largely complete, leading to time savings and less disruption on site. Flat pack systems can be easier to transport, and although the assembly may take longer than modular systems, explicit assembly guidelines enable the use of less skilled labour in local communities. Factory controlled processes can ensure improved quality control and safety, and tightly managed material flow and construction waste has both resource and sustainability benefits.

Despite advantages described in documents such as Sir John Egan's influential 1998 report Rethinking Construction for a UK context [9], the 2009 publication Advancing the Competitiveness and Efficiency of the U.S. Construction Industry [10], and the 2004 report Construction 2020 A Vision for Australia's Property and Construction Industry [11], Australia has been slow to adopt prefabrication broadly. The authors' ARC research Future Proofing Schools identified a stigma associated with the prefabrication as a contributing factor. The Australian market had largely perceived prefabricated construction to be lower quality than in situ construction as it was so often employed for building typologies of a temporary nature and therefore given less design attention. Often temporary school buildings became permanent infrastructure.

2.3. Australian Tipping Points in Prefabricaton

Skills shortages and associated labour costs are the key drivers for the use of off-site construction in Australia [12]. However, during the authors' previous research, it became apparent that a catalyst was required to nurture the local prefabrication industry and overcome the associated stigma. Industry bodies can play a vital role in supporting nascent industries, with PrefabNZ in New Zealand and Buildoffsite in the UK as guiding examples. In 2012, at the end of the ARC research into relocatables, an industry workshop brought together educators, designers, and manufacturers. The aim was to encourage the participants to work towards establishing a peak body for Australia's prefabrication industry. Not only did PrefabAUS emerge from that workshop, but new partnerships between education departments, architects, and prefabricated building manufacturers were forged. The key to unlocking an industry's potential requires the creation of links across and between disciplines in which conversations and innovations occur at the interstices, and the opportunities for those conversations were just beginning [13].

The stigma associated with Australian prefabrication is changing. Concurrently tipping points are gradually impacting the construction industry. These include the convergence of Building Information Modelling (BIM) technologies, manufacturing automation and robotics, innovative construction materials; sustainability pressures, renewed interest from the design community, a broader desire to improve productivity, significant government and university investment in research through the CAMP.H program [14] and a construction industry that is rapidly becoming globalised.

2.4. BIM and Life-Cycle Costing

BIM is the 3D representation of buildings and their components that can be used at the design and construction stages but also for building management throughout the life of the building. When the building developer is also the owner, as in the case for many education developments, there are considerable facilities management benefits in using BIM. For the past ten years BIM has been the accepted acronym across the construction industry for object-based virtual modelling of buildings and their components to encompass the entire building life cycle. Design and construction industries are gradually moving towards coordinated BIM models to achieve system integration and process automation but hurdles remain. A shift in mindset, as well as skillset, is required for designers, consultants, contractors, and subcontractors to adopt BIM strategies particularly as the construction industry is historically rooted in craft-based skills rather than manufacturing. Protocols for interoperability and integrated data-sharing are still maturing as is software linking BIM directly to Product Lifecycle Management (PLM) and Enterprise Resource Planning (ERP).

Globally, countries are at different stages of awareness, education, and uptake of BIM [15]. While BIM is not yet mandated for government projects within Australia, elsewhere there are numerous precedents for mandated BIM (Table 1). For example, the UK now requires a full 3D collaborative BIM model for all government projects [16].

Life cycle costing (LCC) considers the total cost of building ownership during its lifespan [17]. It can be used to quantify those costs across a range of physical and temporal scales, for example capital costs of whole buildings and their components, and operational running costs. LCC is therefore core in evaluating the cost-effectiveness of a building's design [18]. For Australian education departments who are often both building owner and user, the combined management and evaluation framework provided by BIM and LCC plays an important role in project review, refinement and planning based on lessons learned.

The potential interface between BIM, LCA, LCC, architecture, construction, and manufacturing might seed a step change for Australia's prefabrication industry. Plug n play elements can also have a place in this interface. BIM tools can facilitate design-to-fabrication workflows whereby building components represented in digital formats are converted to file formats that can be read by manufacturing equipment.

Table 1. BIM uptake by government jurisdictions internationally (15, 16].

Country	BIM Uptake [1]	Comment
China	Low	Not mandatory, HK exception [1]
Denmark	High	BIM required since 2007
Finland	High	BIM required since 2007
France	Emerging	Investing in BIM infrastructure
Germany	Emerging	Investing in BIM infrastructure
Norway	High	BIM required since 2010
Singapore	Emerging	BIM since 2015 for >5000 m
South Korea	Emerging	BIM required since 2016
Sweden	High	BIM required since 2016
UK	Emerging	BIM required since 2016
USA	High	BIM required since 2003 [2]

[1] Hong Kong Housing Authority required BIM since 2014. [2] 72% of US construction firms believed to be using BIM.

2.5. New Horizons for Open Building Implementation

The idea of plug n play elements within the built environment context is not new. Long advocated for Open Building Implementation [19] approaches recognise that change is a reality of the contemporary built environment. Such change and adaptation can be supported by a modular approach to building components, with obsolete building elements being replaced by new elements of the same size yet different quality or nature [20]. For example, a wall panel in a school could feature a drop-down desk as a touch-down spot for a laptop. In later years, as technologies change that wall panel could be upgraded or replaced with a smart interactive wall display.

Such modularity and interoperability require industry agreement on standards related to data, electronics, software, and physical component connections [21] and are challenging to achieve at scale and across a range of industry sectors. Yet for large client groups such as education departments, there is the opportunity to consider such modular and interchangeable componentry as fundamental criteria within their performance specifications for projects. The convergence between digital design, BIM, prefabrication technologies, and 3D printing also offers potential as replacement componentry could be printed to suit [22]. While the democratic nature of these approaches would disrupt a conservative construction industry, early adopters could achieve a competitive advantage. This plug n play approach can also help address many of the environmental pressures associated with the construction and use of educational buildings.

2.6. Holistic Environmental Design

Our awareness of environmental issues is growing rapidly. The construction and use of our buildings results in a considerable proportion of the natural resources we use, as well as the greenhouse gas (GHG) emissions, pollution and waste that we produce. This is leading to rapid depletion of many non-renewable resources, reduced air quality, pollution of waterways, destruction of land and natural ecosystems, climate change, and human health consequences. Current design and construction approaches have barely addressed these critical environmental concerns. While energy efficiency and IEQ have been of considerable focus, especially in schools, a more holistic environmental design approach offers an opportunity to properly address many of the other, equally important issues.

This approach must consider buildings from a life cycle perspective, including their effect not only on ecological systems from 'cradle to grave' but also on human health and wellbeing. This would involve the use of life cycle assessment (LCA) to inform the selection of low impact building materials and components [23], as well as POE, ongoing monitoring during occupancy, and environmentally focussed facilities management.

The plug n play approach aligns perfectly with environmental design approaches, such as design for reuse (DfR), deign for disassembly (DfD), and design for adaptability (DfA). These approaches, in particular, focus on minimising the demand for resources and maximising the embedded value in existing building materials and components. By using modular components, mechanical fixings and careful selection of materials to match specific physical durability or other performance requirements, buildings can be easily modified as needs change. The design of educational buildings using an approach that has the environment and human health and wellbeing at its core also provides a chance to use the physical nature of the building, such as its materiality, design, building systems and technologies, as well as results of post-occupancy evaluation (POE) to educate future generations on environmental and human-centred design, and sustainable living practices. These will be essential elements of the buildings and lifestyles of the future. In addition, by integrating the life cycle environmental design approach with BIM, LCC, and prefabricated manufacturing techniques it will be possible to further enhance the whole of life performance of educational buildings.

3. Australian Prefabrication for Schools and the International Context

3.1. Australian Prefabrication as the 'New Kid on the Block'

When undertaking ARC research into Australian prefabrication earlier this decade, our focus was on transforming relocatables (also referred to as portables). Australian relocatables have been an important part of government education infrastructure, efficiently accommodating changing demographics, supporting remote communities, and as a rapid response after disaster. Unfortunately, these classrooms are not always included within a resolved master plan so if many relocatables are in use, schools lose access to important outdoor spaces such as ovals. Their prosaic design response highlighted their temporary nature while the permanent infrastructure was usually of a superior design quality.

The three-year ARC research program included an ideas competition based on international best practices in the fields of prefabrication, 21st century pedagogies, sustainability, and context-specific design. Our question in the ARC research was to ask how relocatables could be designed as exemplar spaces that supported teaching and learning excellence, rather than temporary classrooms hidden at the back of schools.

International precedents provided valuable insights, and visits to Germany, Scandinavia, and Japan demonstrated the higher construction quality, superior design approaches, and the benefits of a true manufacturing mindset. Industry focused publications and events presented these international case studies to Australian industry, followed by prefabrication study tours in Japan, Germany, and Austria. The ARC research converged with industry and market appetite for change. An array of new products and designs has been introduced onto the market, particularly design-led prefabrication for housing. Many of these projects are modular in nature, meaning that the modules can be factory built in parallel to site preparation, allowing for fast installation times.

3.2. Modular Schools in Australia

Five Australian state education departments had been partners to the Future Proofing Schools' research, so they observed the growth of local expertise and capacity. One such project was Duffy Primary School in the Australian Capital Territory, elaborating on NBRS Architecture's prize-winning entry for the ideas competition, in collaboration with manufacturer Hickory, as shown in Figure 2. In the five years since completion of the ARC project, the Australian prefabricated building market has continued to mature. Numerous permanent modular schools have been completed through collaborations between manufacturers and experienced education architects, paving the way of what is to come. A specific benefit of modular construction in relation to schools is the reduced disturbance in existing schools where new spaces are needed. The factory environment is not impacted by inclement weather, meaning construction programs can be precise. With careful planning, the most disruptive activities in site preparation and installation can take place during school holidays.

(**a**) (**b**)

Figure 2. Duffy Primary School 2013 (**a**) under construction; (**b**) detail of modules. Images: S.B.

In 2017, two Australian state education departments announced programs for delivering permanent school infrastructure using modular construction. When the NSW state minister for education composed a media-release announcing the strategy, the word prefabrication was not included within the statement. Rather the media release described 'creative designs for delivering new types of sustainable and permanent classrooms' [3] (n.p.).

3.3. A tale of Two Cities

In 2010, as part of the ARC research, the authors visited numerous manufacturers and projects across Europe and the UK. The Het 4e Gymnasium School in the Houthaven district of Amsterdam became an exemplar for the research. A district undergoing rapid transformation, five-year permits had been granted for a temporary school and student housing, with these two elements intended to spark regeneration of the area. Architects HDVN (now Studio Nine Dots) conceived a modular school that was temporary yet of permanent quality (Figure 3).

Figure 3. Temporary Het 4e Gymnasium School. Image: Future Proofing Schools.

The modules were pre-planned to be dismantled for a new life in a different location, and alternative future configuration for these modules had been considered and agreed to by local authorities. The prosaic modules and the joins between them were cleverly concealed by an elegant rainscreen cladding. A core lesson from the relocatables is that modules can be moved and redeployed if this is considered from the outset. However, with no future location identified, the temporary permit period fast approaching, and relocation costs looking to be considerable, the local council took the decision to demolish rather than reuse. Whole school relocation is expensive.

The authors also visited manufacturers and designers of prefabricated schools in the USA. The visit to California coincided with increased sustainable design requirements, resulting in new prefabrication products and systems. Many of the projects were modular in nature. In contrast the San Francisco-based company Project Frog took at kit of parts approach linked to the American LEED rating system (Figure 4). Project Frog designs, develops and delivers software and prefabricated building components with configurable kits of building parts designed for 2-dimensional, flat-packed shipping [24]. Taking a product design approach, their concept is to standardise and streamline data flow between architectural designers, factories where prefabricated components are built, and the building site through use of cloud software. Working with the company's component inventory, customisation of a Frog is straightforward, and component inventories can then generate the associated costings. Investors include General Electric and, most recently, Autodesk Forge [25]

(a) (b) (c)

Figure 4. Project Frog's Crissy Field project, San Francisco (**a**,**b**) exterior view; (**c**) interior. Images: Future Proofing Schools.

There is potential here relating to approaches to customisation and the interface between client, designer and manufacturer. There are also opportunities for rural and remote communities where there can be limited access to skills and materials. Schools and their buildings are frequently positioned at the heart of communities. In addition to design and construction efficiencies, this component approach creates opportunities for sophisticated design that can then be manufactured within reasonable distance and then assembled with local communities. Assembly of a school could therefore play an important role in community building.

3.4. Lessons from Catalonia

Concurrent with the Future Proofing Schools project, researchers in Catalonia were investigating the roll-out of more than 200 school centres using industrialised or prefabricated construction since the year 2000 [8,26,27]. The building process required architects, builders, and component manufacturers to work collaboratively to achieve quality outcomes. Components used in the construction of the schools were mostly (a) prefabricated or precast concrete technologies or (b) prefabricated light steel structures and facades. Temporary modular school buildings installed in the 1990s had led to negative perceptions of modular construction, as was the Australian experience [8]. The research included critical reflections on the nature of the construction technologies, the speed of on-site assembly, and the opportunity to reduce environmental impact [26,28].

Interestingly, there was a significant research focus on the pedagogical possibilities of the construction technologies, and whether they could have a positive impact on learning activities within school communities [8]. This positive impact was considered through two primary lenses, the intrinsic and the extrinsic. The intrinsic lens examined the nature of the school environments such as construction methods, architectural design and harmony, indoor environment quality (IEQ), or various furniture arrangements for different modes of learnings, and how these would impact learning. The extrinsic lens examined the pedagogical opportunities for using the above as active learning tools [8]. For our research, this suggests opportunities to embed these pedagogical principles into Victoria and NSW's permanent prefabricated school programs, for example how examining IEQ or prefabricated construction can play a role in a science, technical, engineering, arts, and maths (STEAM) curriculum.

4. Prefabricated Learning Environments, Pros and Cons

4.1. The Pros of Prefabricated Learning Environments

New prefabricated learning environments are unlike older Australian relocatables. They have been designed to accommodate new modes of learning and are able to be configured in a range of ways. It is argued that they are a more environmentally conscious building solution as factory construction can reduce building waste by up to 40 per cent in comparison to in situ construction [27]. Prefabrication has potential to improve building quality and reduce life cycle costs with greater attention to detail. Instead of one-off designs, designs across schools can be coordinated with mass-customisation techniques. Improved worker safety and reduction in lost days due to inclement weather are additional advantages of prefabrication. Figure 5 shows one of the first permanent learning environments built under the Victorian program. The allocated time for delivery of the learning spaces is 37 weeks with 20 weeks for design and 17 weeks for construction broken into ten weeks for the manufacturing stage, one week for delivery, five weeks onsite, and one week for handover [27].

Figure 5. Altona South Primary School Library by Arkit. Images: Alessandro Cerutti.

The Victorian School Building Authority has selected 15 companies to manufacture the prefabricated buildings. Given up to 90 per cent of each building can be manufactured, on site works are minimal thereby reducing school disruption. Manufactured buildings can be conceived through a cradle-to-cradle lens so that components or modules can be replaced or relocated if an upgrade is required or they can be deployed elsewhere. With high quality construction, smart technologies might be embedded into the building fabric for optimising economic performance and comfort levels. The construction process might be followed virtually by students as part of their STEAM curriculum. Integrating design for manufacture and assembly (DfMA) can improve the delivery but does require extra time to be spent at the planning and design stage. Integration through cross-sector shared knowledge of systems protocol could reduce construction costs and time.

4.2. The Cons of Prefabricated Learning Environments

A challenge is to retain a focus on the role of learning spaces for users and the community. There is a risk that educators are removed from the design process as standardised designs evolve to meet the needs of manufacturers through a top-down process [29]. The authors are interested in how BIM and other representational media can be used as part of the briefing and design conversations, providing the means for customisation of a standardised design, and allowing educators to reflect on the evolving needs of students in a digitally rich world.

More broadly, there is a challenge in building an awareness and knowledge of prefabrication. Research highlights that there is a significant disconnect between what is being practiced in the industry versus what is being taught and researched in schools of architecture and construction. So that the construction industry can innovate and adopt more productive, less wasteful building approaches, schools of architecture, and construction need to assume the role of knowledge generators and disseminators [30].

5. New Generation Learning Environments

The Evolution of NGLEs

Early moves towards student-centred constructivist approaches have roots in 20th century educational theorists such as Friere [31], Vygotsky [32], and Gardner [33]. Friere argued that children's learning should be linked to their experiences rather than guided by a dominant culture. Vygotsky understood learning as a language-based collaboration, while Gardner recognised that different students have different learning styles. Taking multi-disciplinary approaches enables learners to consider larger societal issues which cannot be addressed within one discipline alone. In the last two decades, the digital revolution has transformed teaching and, in the process, transformed the types of spaces where learning might occur.

Space supports students and teachers formally and informally as they work in a range of modes from explicit teaching and online learning to group project work and collaboration. Spaces and time for teachers to collaborate and build trust are important for successful team-teaching. The teacher to class relationship is being challenged as students tackle problem-based learning that requires a range of discipline perspectives. In the process they may consult several teachers to draw together the required expertise. Figure 6 shows the range of stakeholders involved in the design, delivery and occupation of NGLEs.

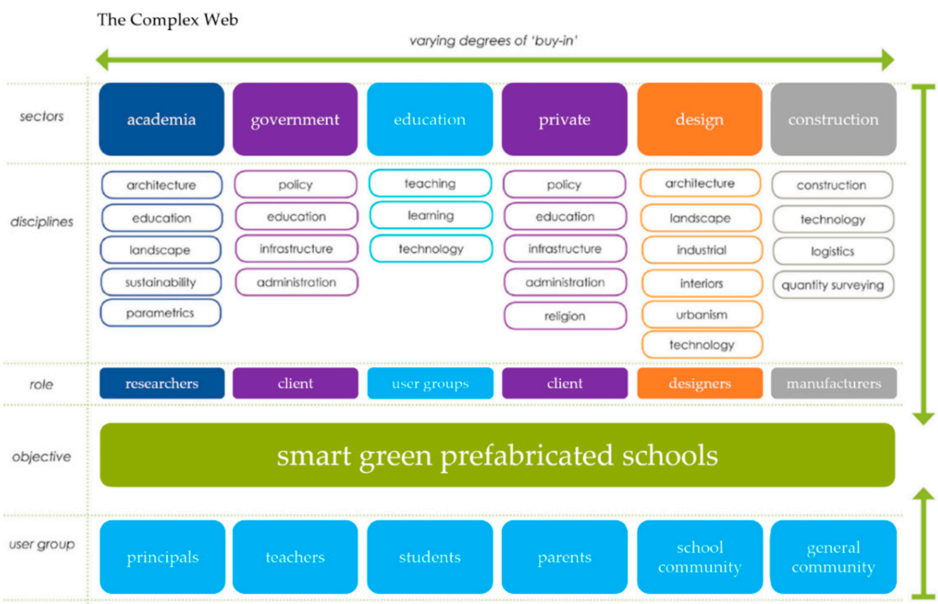

Figure 6. The Complex Web Image adapted by S.B from [13].

6. Evaluation Methods for Schools

This section introduces a framework for evaluating learning spaces in terms of pedagogy. The authors particularly draw on two case study evaluations. The first was undertaken by a government appointed taskforce to review a major infrastructure program for education [34]. The second was undertaken by the authors of a prefabricated learning environment designed to reduce operational energy by 90 per cent and life cycle CO_2 emissions by 50 per cent.

6.1. Traditional POE Lenses of Cost, Timing, Building to Brief and IEQ

In 2010 the Australian federal government appointed an evaluation taskforce to review a major Australian investment into schools. The Building the Education Revolution (BER) investment into schools was in response to the global financial crisis and the BER Implementation Taskforce was appointed to investigate complaints regarding the operation and implementation of the investment program. One of their evaluation criteria was value for money (VFM). This in turn was divided into quality (30%), time (20%), and cost (50%). The taskforce considered whether the buildings were fit for purpose, whether the buildings were delivered in accordance with agreed timeframes and whether the projects were on budget and relative to historical costs benchmarks [35]. Projects that are on time, on budget, and meeting a specific brief may not, in themselves, deliver the best value for money. Higher quality and same cost but longer time may be a better built outcome over the life of a building than a building which adequately meets all three criteria. What was missing from this evaluation was a whole of life costing. This evaluation taskforce particularly focused on construction quality rather than how the spaces might accommodate 21st century pedagogies. How evaluation is undertaken often reflects the expertise of the evaluation team. A better evaluation process could have been to evaluate construction quality separately from an evaluation of design quality [35].

The Learning Environments Applied Research Network (LEaRN) undertook of literature review of learning space evaluation [36]. Evaluation instruments for schools had been developed across several countries however most were found to focus primarily on the physical environment rather than whether the learning spaces supported desired educational practices and behaviours. The review noted that a difficulty of POE strategies is that they tend to be conceived from disciplinary rather than interdisciplinary perspectives.

Over the past two decades much research, particularly within the United States, has focused on evaluating the physical features of the learning spaces and correlating the findings with student outcomes. One such consideration is indoor environment quality (IEQ) which is concerned with how the human sensory system experiences the combined impacts of lighting, air quality, thermal comfort, and acoustics [37]. Existing evaluation instruments for assessing the IEQ performance of learning spaces generally use subjective methods, such as questionnaires and building walkthroughs despite the growing availability of IEQ sensors and methodology [38]. Learning spaces with poor IEQ can reduce the pedagogical effectiveness of teachers and the curriculum. Specifically, the studies found that students' ability to concentrate was affected by localised discomfort from lack of ventilation (and a build-up of carbon dioxide), temperature fluctuation, glare and noisy or reverberant spaces. There were also more extreme examples of poor IEQ resulting in school absenteeism as toxins and particulate matter in the air triggered or exacerbated asthma and other respiratory problems [39].

In 2014 the Victorian Department of Education undertook an evaluation of new prefabricated learning spaces in terms of the alignment between space and pedagogy. This evaluation was commissioned to complement two earlier studies on the environmental performance and IEQ of 'N' series relocatable learning spaces. The first study was a comparison of the environmentally sustainable design (ESD) features of the N2 design, compared with the original N1 design. The outcome was the ESD specification for the new prefabricated learning spaces, specifically additional wall and subfloor insulation, double glazing, ceiling fans, motion activated lighting, and automatic systems to control natural ventilation and the building HVAC [40]. The second study was a POE with the occupants of the new prefabricated learning space, which used mixed methods to assess the occupants lived experience of the building's IEQ features.

6.2. New POE Overlay of Alignment between Space and Pedagogy

As part of the Future Proofing Schools ARC Linkage Project research we asked the school users what they would like for their learning spaces and then this became part of the evaluation framework. Students, teachers, and principals had different responses. As shown in Figure 7, the student' responses were primarily linked to comfort while the teachers focused on facilities. The principals highlighted issues to do with logistics and costs.

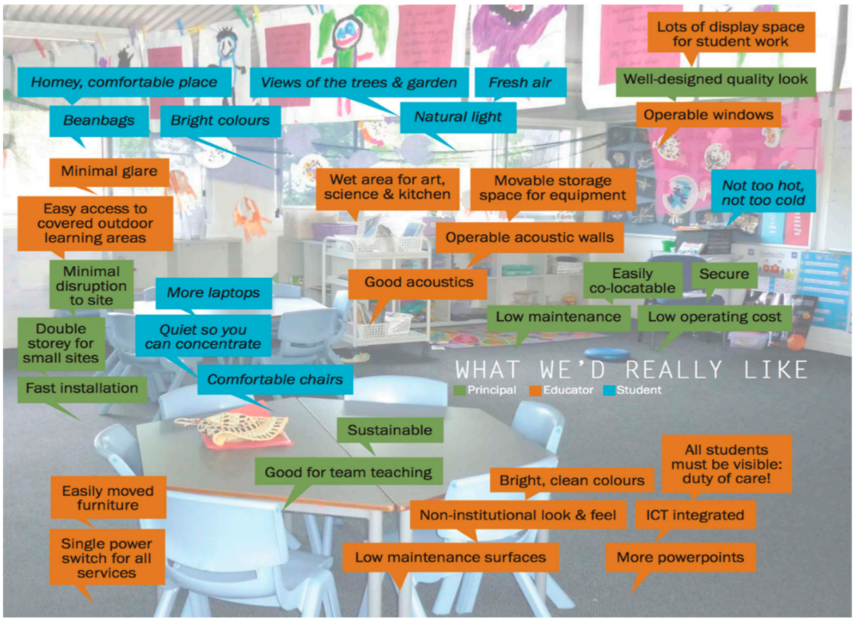

Figure 7. Priorities for users of prefabricated learning spaces. Image: *Future Proofing Schools.*

For evaluating a new prefabricated learning space we applied LEaRN's mixed methods tool called the School Spaces Evaluation Instrument (SSEI)—Alignment of Pedagogy and Learning Environments [41] to help evaluate the links between space and pedagogy. The spaces we evaluated largely duplicated the common Victorian 'Mod 5' plans which consist of five modules connected into two classrooms linked partly by an operable wall and small retreat room. The SSEI research methodology includes consideration of the school's context, culture, educational philosophy and vision for learning. Data is collected via interview, structured observations, expert walkthroughs, surveys, and reflective presentations. In addition, photographs of the spaces in use were taken. The expert 'walkthrough' is a variation on an architectural observation method where spaces are reviewed and critiqued. For our research the expert team included education and design researchers along with the principal, a teacher, and a representative of the infrastructure section of the education department. These informed participants were able to develop more nuanced observations of how the space was operating as a balance between pedagogy and space.

In addition to the walkthrough, results from interviews with key stakeholders and a survey of students and teachers were analysed and summarised for reporting back. The quantitative data from the survey were analysed using a thematic narrative analysis [42]. The data revealed a high level of satisfaction with the prefabricated learning spaces with some suggestions for improvements. The layout and size prevented flexibility for team teaching and collaboration beyond the dual classrooms and connections to outdoor learning spaces were limited. In contrast the permanent facilities had more flexibility to accommodate larger teams. Staff particularly appreciated the lightweight chairs and tables that could be easily reconfigured to suit a range of learning modes. While staff and students agreed the indoor environment quality with automatically operating louvres was comfortable in terms of air quality, students commented on the noise of the system indicating less tolerance of incidental noise in comparison with the teachers.

Indeed, similar issues arose for both research projects. The SSEI research indicated an opportunity to further review the design and furnishing of modular buildings to allow schools to have more input into how the spaces are configured to suit their learning vision and methods. At this school, the principal and staff were keen to work across entire year levels to coordinate between the explicit teaching needs of students and opportunities for collaborative work. While the prefabricated learning space suited traditional teaching it was less suited to project based learning given the lack of wet areas, project space and display space.

The strength of the SSEI tool is that it helps teachers and school leadership teams better align space with pedagogy through a detailed review system, which takes into account the school's own educational vision. The same strategies can be used at briefing stage to help schools determine the types of spaces required. A key issue when considering the design of spaces is that they need the agility to adapt over time to different types of users and pedagogies. The mix of quantitative and qualitative data is a strength of the model. This method has been used by the LEaRN team across 60 schools in Australia bringing together survey data from approximately 4500 students.

7. Conclusions: Next Generation Prefabricated Learning Environments

As this article has indicated, Australian prefabricated learning environments have been transformed in recent years, leveraging a maturing industry, growing interest for large client groups, and a convergence of technology, new materials, and new pedagogical approaches. Yet our research highlights that there remains both an opportunity and need for step change. Within a complex web of stakeholders (Figure 5), emergent technologies could still place learning communities at the heart of the process.

Researching the design, delivery, and occupation of learning spaces is concurrently an opportunity and complexity given the number of disciplines involved. Rather than focusing on just the logistics, costs, environmental impacts, and efficiencies of prefabrication, we argue for more nuanced and holistic evaluation processes. A systems-thinking approach allows us to think beyond standardised designs and look towards mass customisation. A component-based approach for construction also allows for adaptation over time, so we can imagine a suite of plug n play elements such as smart wall panels, extension of indoor space or adding outdoor decks, or other elements that allow for transformation over time.

Product design approaches such as that of Project Frog also let us imagine how apps might be developed, be the design solution 2D or 3D in its prefabrication approach. Such apps could allow designers to mass-customise designs from a pre-defined menu of components. Co-design approaches could be facilitated between users, designers, and manufacturers. As the three-dimensional model is developed to meet the user needs, costs and environmental impacts could be generated on the fly.

While these approaches require significant investment to support cross-sector step changes in how buildings are designed and delivered, the investment could achieve efficiencies in design, construction, and whole of life operation. In addition, these new spaces might have better agility to accommodate new ways of learning over the coming decades as technologies impact pedagogy. Quicker, better, cheaper is good but might this be a unique opportunity for step change innovation and industry transformation?

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