CONCRETE PREFABRICATED HOUSING VIA ADVANCES IN SYSTEMS TECHNOLOGIES – DEVELOPMENT OF A TECHNOLOGY ROADMAP

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The concrete and housing industries of Australia collaboratively engaged in a project to develop a Technology and Innovation Roadmap that will advance the Concrete Industry’s supply chain capabilities by identifying and mapping innovation necessary for prefabricated concrete house construction. The roadmap lays out what is necessary for an off-site systems-based approach to housing construction in Australia. The systems-based approach to prefabricated concrete products is a relatively new and developing extension of the concrete industry supply chain in Australia. New manufacturing technologies and innovations, which are emerging locally and from overseas, make these potential extensions possible. For the long term sustainability of the concrete industry it is critical that it better understands how to adopt cooperative innovations in prefabrication to realise these benefits in the housing industry and advance Australia's competitiveness. The first phase of the mapping involved the development of an industry-maturity model that determined the current state of the industry, and plotted this against the desired route for the future. Numerous industry-based workshops and interviews gathered the views of the industry towards existing concrete housing systems, and where their main difficulties were in relation to adoption. Using this data a Technology Roadmap was developed, together with three options on how these might be realised using the Roadmap. The options offered through the roadmapping process form the basis for ongoing experimental trials of concrete houses in the major cities of Australia. This paper discusses the roadmapping methodology and its application to concrete prefabricated housing in Australia.

Keywords: concrete, housing, prefabricated, technology roadmap.

INTRODUCTION

Residential building in Australia is a substantial market, accounting for 50% of all building activity with more than $32 billion worth of work done during 2007 (ABS 2007a). In 2006-07 there were 151,717 dwelling commencements in Australia, with new houses accounting for more than 100,000 of these commencements (ABS 2007b). The underlying demand for this housing is driven mainly by population growth, together with the rate of household formation and the number of demolitions. Market research by the peak industry body for concrete (Cement, Concrete & Aggregates Australia or CCAA) during 2008, indicated that the Australian Building Industry experienced a period of ‘under-building’. The wide gap between housing

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starts and underlying requirement was widely acknowledged as being due to deteriorating housing affordability in most capital cities. By June 2008 the Housing Industry Association estimated the housing shortage to be 85,000 dwellings and projected the gap to grow significantly to 203,000 by 2013 (HIA 2009). Until the end of 2008 this had created significant unfulfilled demand that was forecast to fuel a housing boom in 2010-11. Although these forecasts are likely to be delayed by 12-24 months due to the economic downturn of late 2008 and 2009 (CCAA forecasts 2008), indications are that underlying requirement has not abated.

New housing construction is however highly cyclical. The typical cyclical nature of the industry has resulted in a building approach that has grown to be flexible and responsive to dramatic shifts in demand. This results in redundancies and inefficiencies with a heavy reliance on a subcontracted labour force that can be expanded or reduced to meet changing demand. Another result of the industry’s cyclical nature is that large inventories and buffers are held in the materials supply chain to compensate for uncertainty in demand.

Added to these pressures, the heavy reliance of construction on labour has given further concern as the age and shortage of the skilled work force continues to rise. An industry report in 2007, (HIA 2007) revealed that all thirteen residential construction trades surveyed were in short supply, and that some trades had experienced annual price increases of over 12%. These trade shortages have further added upward price pressures on the construction of new homes in Australia over this period.

This unfulfilled housing demand, together with a sub-optimal supply-chain, has created opportunities for investigating alternative delivery systems for the housing market in Australia. Unfortunately there are many barriers to innovation in the housing industry. These include high levels of fragmentation; low levels of industrialisation; a complex and inefficient supply chain; very poor capitalisation; a heavy reliance on subcontractors; a declining skills base; and a flagging training effort. These barriers also present opportunities for innovation. The concrete industry, recognising this opportunity, undertook to investigate the possibilities of filling this gap through a paradigm shift in housing delivery.

**Concrete in housing**

Although the market presents these opportunities, the concrete industry faces several industry-specific barriers. Concrete systems and elements are underused in the detached residential and home improvements markets, relative to other markets (CCAA 2004). The building market is aware of the various possibilities of concrete panelised systems. Despite their appeal in some respects, the market appears unconvinced of their overall advantages. Recent market analysis and strategic planning by CCAA, in collaboration with the industry, identified the residential detached housing sector as less ready to adopt the use of prefabricated concrete product than other sectors of the construction industry. For example, concrete market share for walling in new detached residential housing was at 12% (including concrete block, brick, lightweight block and fibre cement) in 2007 (BIS Shrapnel 2007). By stark contrast, concrete market share in multi-residential construction was registered at 62%, and in non-residential construction at 54%.
The concrete industries in the USA, Europe, the UK and parts of Asia appear to have made greater advances in developing prefabricated concrete housing systems, relative to Australia. In the case of the UK it could be argued however that these advances have been limited (using findings of Goodier & Gibb 2004b) even though they have been attended with coordinated industry-level strategies (e.g. Egan 1998, Housing Forum 2002, BRE 2004, Buildoffsite 2006). An understanding of how the industry could adopt cooperative innovations in prefabrication was seen as critical to the concrete industry’s long term sustainability in Australia. The industry also sees the possibility of moving beyond the advances made in other countries and leading innovation in the area.

It is evident that there will be no substantial market share increase for concrete, and very little economic benefit achieved, by implementing a new concrete housing system that simply substitutes other materials with concrete, and continues to use the current construction process. Detached domestic housing provides an ideal market for a product that can embrace the potential offered by manufacturing principles. PATH (2002) in the United States recognised these advantages and called for increasing industrialisation of house building. The concrete industry identified the need to develop a whole-of-life, whole-of-process approach based on manufacturing principles if it is to advance.

**Manufacturing approach**

Manufacturing provides several ideas for developing a concrete housing system that will deliver superior quality products to customers and greater economic benefit to the supply chain. The manufacturing approach generally offers many advantages over the current construction approach (Housing Forum 2002, PATH 2002, Gibb & Isack 2003, Goodier & Gibb 2004a, Blismas & Wakefield 2009), although these can be broadly summarised into two categories.

First, manufacturing technology and processes seek to produce increasingly different products using a single systematised approach – ‘product flexibility’. To enable this flexibility, certain characteristics are required of the parts and the product, such as standardised and accurate dimensions. Hence product control for quality is vital. An aspect of this that may not be prominent in manufacture, but which is relevant to construction, is open systems thinking. ‘Open systems thinking’ goes further than the simple production of a customised product – it is open to future changes within a flexible system (as represented by Eichart & Kazi 2007, for instance). It suggests that the product is flexible into its useful life. This concept translates into the design and building of a house that can accommodate future changes in use, configuration, appearance or size. Applying open systems thinking has significant potential for addressing and improving the sustainability of housing stock.

Second, manufacturing offers substantial process efficiency, achieved through disciplines such as ‘factory physics’ (Hopp & Spearman 2000). Manufacturing has increasingly developed production, resource control and management systems, enabled by information technologies. The ‘production’ rather than ‘project’ approach of manufacturing permits the analysis and design of each part of the production process so that efficiency is maximised. Applying process efficiency to aspects of the residential housing construction may go some way to addressing affordability concerns in housing.
The PATH project (2002) summarised some examples of industrialisation of manufacturing concepts that have been successful in other industries and that may have application in housing construction. Briefly these include (but are not limited to):

- Just-in-time (JIT) manufacturing that includes effective supply chain management;
- Flexible, agile, lean production systems;
- Concurrent engineering and design for manufacturers that use various techniques and processes to enhance the manufacturability of the product;
- Manufacturing requirements planning (MRP), manufacturing resource planning (MRP II), and enterprise resource planning systems (ERP), which are processes enabled by information technology;
- Concurrent design, where communication among designers and the producers (construction foremen, site supervisors, trade contractors) can significantly improve the efficiency of production;
- Time- and space-based scheduling that facilitates keeping track of who is where, doing what, and when. This type of scheduling is especially appropriate for construction activities, as crews move between sites.

The challenge that faced the concrete and housing industries in Australia was determining how to strategically and cohesively move the industry towards a new advanced housing delivery system. Engagement between the concrete and housing industries has previously been inadequate, presenting two notable hindrances to development. First, there has been a persistent lack of suitable product and supply capability that can satisfy the particular needs of the housing industry. Second, the opportunity to unlock innovation in both industries has not been realised.

A substantial investigative research project was undertaken to overcome these hindrances and map a way forward for the concrete industry. It developed a Technology and Innovation Roadmap (TIR) for the concrete industry to chart the research and development route required to stimulate a substantial shift within concrete housing delivery. The TIR needed to demonstrate how the industry could move towards delivering a new, detached residential house to the market that had a lower total build cost, was faster and easier to build, would have enhanced selling ability, and be offered to the market at a reasonable price. Although a TIR has been previously developed in the US housing context (PATH 2002, 2004), this is a first for Australian housing and particularly concrete prefabricated housing systems.

The project was jointly funded by the Australian Government and a consortium of six leading companies, broadly representing the concrete industry. The project ran from January 2007 through June 2008. RMIT University was a member of the consortium providing research expertise. The remainder of this paper briefly explains the development of the TIR before describing three options or routes through the roadmap that were chosen by the industry for further development.

DEVELOPMENT OF A TECHNOLOGY ROADMAP

The methodology used for the development of the TIR was adapted from that of Garcia and Bray (1997). Technology roadmapping is a needs-driven technology planning process to help identify, select, and develop technology alternatives that satisfy a set of product needs. It brings together a team of experts to develop a
framework for organising and presenting information critical to making appropriate
technology investment decisions and for leveraging those investments. It is a way of
developing, organising, and presenting information about the critical system
requirements and performance targets that must be satisfied in specified timeframes to
meet a given a set of needs.

A TIR identifies alternative technology ‘roads’ that can be taken to meet certain
performance objectives. A single path may be selected and a plan developed. If there
is high uncertainty or risk, then multiple paths may be selected and pursued
concurrently. The Roadmap identifies precise objectives and helps focus resources on
the critical technologies needed to meet them. This focusing is important because it
allows increasingly limited R&D investments to be used more effectively.

The roadmapping process often consists of three phases as outlined in table 1 (Garcia
and Bray, 1997). As the steps in Phase I preceded the project, this paper only focuses
on Phases II and III.

Table 1: Phases in the technology roadmapping process (from Garcia and Bray, 1997)

<table>
<thead>
<tr>
<th>Phase I</th>
<th>Preliminary activity</th>
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<tbody>
<tr>
<td></td>
<td>Satisfy essential conditions.</td>
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<td></td>
<td>Provide leadership/sponsorship.</td>
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<td>Define the scope and boundaries for the Technology Roadmap.</td>
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<th>Phase II</th>
<th>Development of the Technology Roadmap</th>
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<tr>
<td></td>
<td>Identify the ‘product’ that will be the focus of the Roadmap.</td>
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<tr>
<td></td>
<td>Identify the critical system requirements and their targets.</td>
</tr>
<tr>
<td></td>
<td>Specify the major technology areas.</td>
</tr>
<tr>
<td></td>
<td>Specify the technology drivers and their targets.</td>
</tr>
<tr>
<td></td>
<td>Identify technology alternatives and their time lines.</td>
</tr>
<tr>
<td></td>
<td>Recommend the technology alternatives that should be pursued.</td>
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<td></td>
<td>Create the technology roadmap report.</td>
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<th>Phase III</th>
<th>Follow-up activity</th>
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<tr>
<td></td>
<td>Critique and validate the roadmap.</td>
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<td></td>
<td>Develop an implementation plan.</td>
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<td></td>
<td>Review and update.</td>
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The steps in Phases II and III were achieved through a series of national roadmapping
workshops that relied on significant industry participation. The workshops identified
innovations necessary to facilitate the use of prefabricated concrete systems in
Australian housing. The workshops also identified barriers to implementation and
application of the innovations. To ensure national coverage, and to account for any
regional differences, workshops were held in Sydney (New South Wales), Perth
(Western Australia), Melbourne (Victoria), Brisbane (Queensland), and two in
Adelaide (South Australia). The workshops were held over a period of approximately
6 weeks from early May 2007 to mid-June 2007. The workshops attracted 85
delegates from across the supply-chain and were considered adequately representative
of industry views (as illustrated in Table 2).

Three distinct data collection exercises were undertaken during the workshops in
groups ranging from 2-10, depending on room configuration and number in
attendance. In the first exercise, delegates were asked to identify critical system
performance requirements for all elements of a house. The group discussions were recorded onto preprinted sheets. The second exercise was a group evaluation of current concrete housing products and why they were not being widely used. The barriers identified were also captured on preprinted sheets. The final exercise allowed delegates to freely document an ‘ideal’ system that would overcome the barriers identified while still satisfying all the critical system requirements. These were recorded on blank pages, most often as annotated diagrams. The workshops closed with a summary of the outcomes.

Table 2: Attendance information of the roadmapping workshops

<table>
<thead>
<tr>
<th>Attendance in each state</th>
<th>Number</th>
<th>% of national attendance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vic (May 2007)</td>
<td>16</td>
<td>18.82%</td>
</tr>
<tr>
<td>NSW (May 2007)</td>
<td>14</td>
<td>16.47%</td>
</tr>
<tr>
<td>Qld (May 2007)</td>
<td>22</td>
<td>25.88%</td>
</tr>
<tr>
<td>SA (May/June 2007)</td>
<td>21</td>
<td>24.71%</td>
</tr>
<tr>
<td>WA (June 2007)</td>
<td>12</td>
<td>14.12%</td>
</tr>
<tr>
<td>Number of delegates invited</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>Number of delegates in attendance</td>
<td>85</td>
<td>70.83% acceptance rate</td>
</tr>
</tbody>
</table>

Categories of Delegates in attendance (mainly senior managers)

<table>
<thead>
<tr>
<th>Delegates in attendance</th>
<th>Number</th>
<th>% of attendance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Builders</td>
<td>46</td>
<td>54.12%</td>
</tr>
<tr>
<td>Suppliers</td>
<td>26</td>
<td>30.59%</td>
</tr>
<tr>
<td>Architects</td>
<td>5</td>
<td>5.88%</td>
</tr>
<tr>
<td>Other</td>
<td>8</td>
<td>9.41%</td>
</tr>
<tr>
<td>Number of companies represented</td>
<td>52</td>
<td></td>
</tr>
<tr>
<td>Number of HIA Housing 100 companies represented</td>
<td>13</td>
<td>25.00%</td>
</tr>
</tbody>
</table>

The data collected from the workshops was summarised into a series of tables for ease of analysis. These tables formed the basis for mapping the barriers and opportunities for concrete housing and creating the Technology and Innovation Roadmap. After the workshops the data was collated and a draft Roadmap produced for verification. The Roadmap was discussed with a number of key industry persons representing high volume house builders or precasters. Their comments were incorporated into the final Roadmap.

The methodology produced a comprehensive list of Critical System Requirements (CSR) that served to focus attention on the essential requirements of each system within a house. This is particularly helpful for discerning what precisely a system is required to perform, allowing the possibility for new technologies to be investigated against the required performance. When critical system requirements are not highlighted, existing technologies are generally reinforced: in the belief that performance requirements are already adequately addressed, the mind is closed and the opportunity to explore different solutions is not taken up. Further it evaluated current concrete solutions against the CSRs, highlighting their advantages, and noting why they had not been adopted more widely. Barriers and opportunities were
identified and tabulated against a typical brick veneer project house in Australia. The main barriers that needed to be overcome for concrete housing products to be more widely adopted centred on adaptability, cost, logistics, system interfaces and services distribution.

TECHNOLOGY AND INNOVATION ROADMAP

Using the workshop data, a TIR (example in figure 1) was constructed in the form of a matrix that captured the vital elements of the entire house building environment across two dimensions. The first dimension was time, so that all aspects necessary for development of future concrete systems were captured. The dimension of time was easily captured using the accepted concept of project phases. The TIR used a modified six-phase format that includes a distinction between offsite and onsite works as illustrated in figure 1.

The second dimension, against which these phases were arrayed, captured the three vital elements of any building system used in house construction. The first element relates to the Product, in this case a detached dwelling, over its life. Within each phase the evolution of the product is described, from its design to the manufacture and construction of its components, and then to its maintenance and adaptability. Within each of the cells (the intersection of phase and element) a spectrum of possible options is provided, typically from most basic to most advanced. Behind each option within each cell is a detailed typology with a set of barriers and opportunities (not illustrated).

The second element relates to the Processes needed to produce the Product. Within this element the possible process routes for each phase are detailed so that current and future systems can be mapped. Traditions in house building processes mean that particular sub-processes are favoured and entrenched, making it difficult for the industry to adopt a new process paradigm.

The final element is the Platforms required to support both the Product and Processes. These are typically tools, IT, knowledge, and management systems that surround all industries to varying degrees. Again this element allows current systems to be identified and compared against advanced, state-of-the-art systems available in other industries. Any attempt to innovate in housing will require very careful mapping of the support systems required to facilitate change in industry processes.

The matrix format emphasises the importance of the vertical and horizontal integration that is necessary for a system to function effectively. As a project progresses, it is expected that the product, processes and platforms would naturally integrate across the whole life of the project. However, in most cases current systems are fragmented across phases so that systems are often not related. The elements highlight the necessity for horizontal integration.

The matrix also stresses the necessity for vertical integration across products, processes and platforms within project phases. The three elements are supportive of each other, and cannot function effectively or efficiently without full synchronisation between these elements. For instance, conventional 3D CAD platforms cannot capture or model construction information, resulting in the manufacture and installation design being developed independently of the architectural design. This ‘cellular’ approach, where product, process or platform innovations are developed in isolation
from each other, exacerbates both fragmentation and the resulting inefficiencies. This Roadmap is designed to provide the overview necessary to overcome the limited view prevalent in the construction industry, and arguably in research.

The TIR was used in the following typical manner:

- The precise product being investigated was described and established to avoid diffusion of issues within the roadmap. Unless this step is taken, the issues identified within the cells of the TIR can be diluted;
- The current type of house delivery was then mapped onto the roadmap indicating the state or maturity of the industry (cells at the base of the arrows in figure 1);
- The objectives of the product development initiative were identified and documented so that any targeted moves on the roadmap could be justified;
- Following steps 1-3, all sub-systems able to deliver the objectives were identified. These sub-systems were then scrutinised to determine how such moves on the roadmap would add benefit to the industry;
- A new desired house delivery system, based on step 4, was mapped (cells at the point of the arrows in figure 1);
- The barriers and mitigation strategies of the new route were identified;
- Following the preceding steps preliminary cost and risk analyses were undertaken to help formulate a development and implementation strategy.

The project concluded with a suggested strategy for development. The strategy was presented to the industry consortium for scrutiny and approval. The final section below briefly outlines three development options identified by the roadmap.
A NEW APPROACH

Three concepts from the roadmapping exercise are proposed as a way forward for the residential building and concrete industries to deliver flexible, affordable and high performance concrete houses. Concrete can provide high strength structural frames, large open spans and movable interior partitions. The concepts move towards delivering an open system which can deliver flexibility and performance. The three concepts are:

- standard grid
- simple ‘kit-of-parts’
- advanced ‘kit-of-parts’/Open Building.

These three concepts have been articulated as milestones for development, each with associated investment requirements and risks (figure 2). Rather than being distinct from each other, the milestones generally represent a progressive development. The grid-based system could be implemented on its own. However, a grid-based system must be developed with either the simple kit-of-parts or the advanced kit-of-parts.
The first concept is ‘grid-based design’ for concrete housing. A grid-based system allows any parts to be designed to a predetermined, and agreed, grid. The grid would determine standards for panels, windows, doors and other items, and is a vital first step in assisting the concrete products manufacturers and designers to work to a common framework. Although standard sizes are commonly used, many are based on a traditional system suited to timber or brick sizes. A new common grid-system is needed. The apparent advantage of a grid-based design system is that it does not require intervention in existing processes and practices; it merely provides a standard template for designers and manufacturers to produce concrete houses. It is, therefore, a considerable benefit to designers and encourages them to attempt more concrete design. However, on its own a grid-based design system would only deliver marginal benefits to others in the supply or value chains.

The second concept builds on the simple ‘grid-based design’. Essentially the simple kit-of-parts encourages the supply of parts to a standard grid-based system. This allows buildings to be designed using sets of parts (mainly panels) from any number of suppliers that offer products compliant with the grid. The grid would determine standards for panels, windows, doors and other items, and would detail a common interface technology so that the parts could fit together. Effective implementation requires changes to industry products, processes and platforms. The simple kit-of-parts approach is attractive because, through changing processes, significant value gains are made within the supply chain. Standardisation permits the use of a high proportion of offsite components with the associated benefits of industrialisation. It is particularly important to note that if significant investment is made to encourage differentiation, the simple kit-of-parts will support design variety. Implementation of a simple kit-of-parts requires a more significant financial outlay than grid-based design. Implementation also carries more risk because process changes in the industry are difficult to effect and will require a broad and sustained implementation strategy.

The third or ‘Open Building’ concept extends this to a more flexible design and erection process that incorporates supplies more broadly from the construction industry. It is an extension of the simple kit-of-parts to incorporate a more integrated
and sophisticated open system which has a concrete skeletal system or frame that allows large open spaces. The frame can be clad with any variety of panel – concrete, glass or timber – as long as it complies with the grid. Further, the connections would be well-engineered and detailed to ensure maximum performance. Services and internal partitions would typically have a modular system that allows movement within and between spaces. Wet areas would probably be modularised as completed pods. The greatest challenge to the advanced kit-of-parts is the change required in the supply chain. Most trades would move into the factory environment where manufacturing principles would be implemented to optimise process efficiency. The advanced kit-of-parts ensures that the design incorporates all the necessary information from the outset so that control of production is maximised.

CONCLUSION

The housing under-supply and fragmented nature of the Australian housing construction industry has provided an opportunity for the development of a concrete prefabricated housing system. An industry consortium initiated this process by developing a Technology and Innovation Roadmap. The significant industry input resulted in a roadmap that allowed the housing industry to evaluate its current level of maturity, and also look forward to cutting-edge technologies and delivery systems to plot an R&D path for the future. Through the workshop process the concrete industry envisaged a paradigm shift to housing delivery using concrete technology and formulated a development and implementation strategy that progressed from the current state to an advanced ‘kit-of-parts’ system. This technology roadmapping process is one of the first in the Australian concrete and housing industries, and offers an exciting prospect for moving the industry into a new model of delivery.

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