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Implications of Flat-Pack Plumbing Systems For High-Rise Construction Efficiency

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Abstract

The concept of design for manufacturing and assembly (DfMA) is gathering momentum in the high-rise construction industry. The construction of tall buildings is well-suited for the adoption of processes that optimize the off-site fabrication of sub-systems. This paper analyzes the reception of DfMA principles in the Australian construction industry and illustrates the specific case of wall-integrated plumbing as an exemplar of the emerging philosophy of "flat-pack" prefabrication in residential high-rise construction. In contrast to the radical off-site manufacturing emphasis that is proposed by prefabricated prefinished volumetric construction (PPVC), flat-pack prefabrication implies off-site manufacturing, combined with the ability to improve, but not discard entirely, processes of erection on-site. These systems can provide the most tangible benefits of productivity and are poised to cause a cultural shift in the way high-rise projects are procured today.

Keywords: DfMA, Flat-Pack, Prefabrication, Modular, Construction

Introduction

Design for Manufacturing and Assembly (DfMA) is a concept developed to improve the efficiency and optimization of industrial processes and products. It has roots in research work started in the late 1970s by merging the two ideas of Design for Manufacture (DfM) and Design for Assembly (DfA) into one framework. Since the 1990s, the concept of DfMA and some of its derived models of application have gathered acceptance in industrial design as a well-established technique for accomplishing significant improvements in productivity (Boothroyd et al. 1994).

At the core of DfMA's philosophy, there are strategies of labor optimization favoring design solutions that facilitate ease of manufacturing. Common examples of such strategies are the minimizing of part count, the shortening of reticulation and cabling for services, and the avoidance, whenever possible, of unique or non-standard components and products. The application of DfMA principles also pursues processes that facilitate part handling and ease of assembly, such as minimizing actions of re-orientation, selecting self-locating or self-fastening parts, avoiding diversity of fasteners and connections, and avoiding the need for adjustments after assembly. Above all, DfMA is a *modus operandi* that often feeds into industrial production processes that support modular design or semi-modular assembly.

The adoption of DfMA in the disciplines of the built environment has been considered and widely tested, but its principles and applications are not as well established as in the field of industrial design. There is, in fact, abundant academic work concerned with the adoption of DfMA in construction management. Recent studies in this area have highlighted the presence of barriers to its implementation in specific regions (Gao et al. 2018) and considered risks and benefits for particular sub-sectors of the industry (Trinder 2018). A growing area of interest for DfMA applications pertains to high-rise construction, where its value has been manifested in enhanced building productivity (Banks et al. 2018).

Tall DfMA: Modular Trends in Construction

The appeal of DfMA concepts in the high-rise construction industry derives from the likelihood of repetition, which is often an inherent characteristic of tall buildings, and by the high stakes of economic risk and public safety, which are associated with the timely completion of speculative commercial projects. The idea of applying DfMA strategies in the conception and erection of tall buildings is, therefore, a theme of debate that has gathered interest in the CTBUH community.

Designs conceived with ease of manufacture and assembly in mind can contribute to more efficient tall building construction. This argument is often presented as the justification for high-rise experiments in modular construction. Case studies have been shown where strategies of "partial modularization" have brought tangible benefits of productivity for contractors. One study claimed up to 60% reduction in on-site labor and 30% reduction of program time (McFarlane and Stehle 2014). Moreover, the transfer of DfMA principles from the industrial manufacturing realm to that of construction has an even stronger appeal when applied to three-dimensional modular construction systems, also known as prefabricated prefinished volumetric construction (PPVC). The affinity between the manufacturing of products and the assembly of PPVC modules is almost self-apparent and suggests that there are abundant opportunities for direct transfer of technologies and processes of production from vehicle manufacturing to building construction. Notwithstanding that PPVC may remain as a vital component of the high-rise innovation agenda for years to come, the construction of high-rise buildings with three-dimensional modularization also has significant limitations (Mills et al. 2015; Krulak 2017). It is often suggested that three-dimensional vertical modularization will continue to grow in the future (Wallance et al. 2015), but it is doubtful that PPVC design will be the primary conduit through which DfMA concepts can more effectively penetrate the construction industry.

This paper analyzes the prospects of growth of DfMA in the built environment, by arguing that processes of innovation with flat-pack systems, rather than three-dimensional modularization, can act as an effective catalyst for innovation in tall building projects. The validity and possible repercussions of DfMA for tall buildings are discussed by using the case study of a wall-integrated plumbing system that was developed for the bathrooms of a high-rise apartment tower in Australia. The innovative capacity of flat-pack systems in high-rise projects is considerable, as evidenced by an experimental research project that was carried out by the University of Melbourne in collaboration with Richstone Group, a plumbing contractor based in Melbourne.

Vices and Virtues of the "Pod" Phenomenon

Concepts of DfMA have been already applied successfully, such as in the case of mechanical, electrical and plumbing (MEP) services using prefabricated construction. In modular projects, the components of the buildings are first manufactured in factories and then delivered to the field, where they are hoisted or erected as pre-assembled units that integrate the work of several trades. The benefits of this approach include cost reduction, faster installation and improved quality. Some of the highest environmental and safety hazards associated with construction sites are also significantly mitigated.

A typical application of this kind of prefabrication, which has gathered significant interest in Australia and elsewhere, is the adoption of prefabricated units for bathrooms, also known as "pods" (See Figure 1).

Figure 1. Prefabricated Prefinished Volumetric Construction (PPVC) of bathroom pods in an Australian tall building (left) installed on the floor during construction, with pre-finished interior (right). © G. Marfella

Figure 2. The in-situ approach to the plumbing of high-rise buildings assembles a multitude of standard components (top) in stud construction installed on-site by others (bottom). © Richstone Group and G. Marfella

Bathroom pods usually consist of self-contained and almost entirely pre-finished three-dimensional modules that are inclusive of partition walls, reticulation of cold and hot water, wall and ceiling linings, floor finishes, joinery and pre-installed plumbing fixtures and fittings. In a typical high-rise job, a batch of bathroom pods is transported on site "just-in-time" by motorized transport. Pods are then hoisted one-by-one on the receiving floors by the tower crane. Once located on the floor in the right position, the pods are "plugged" into main service runs. The primary motivation behind the construction of three-dimensional modular wet areas is the desire to minimize, or preferably eliminate, any labor-intensive trade from the site construction sequence. As a result, the core of "wet" trades, like plumbing and tiling, is relocated to a factory environment.

The impetus behind the use of "pods" in Australian construction sites can be easily understood by considering the cost difference between the labor rates of manufacturing workers in factories against the rates of licensed plumbers qualified to conduct work on-site. Off-site plumbing labor can be 35% to 65% less costly than an equivalent task carried out on-site. Notwithstanding the immediate savings produced by this wage differential, the decision to modularize large portions of a building floor plan may encounter significant limitations in high-rise projects in dense urban areas. Restrictions of access and transport, combined with the limited availability of tower crane time, can quickly negate the practical or economic feasibility of these radical off-site solutions.

Nonetheless, in a high-wage industrial context like Australia, the traditional approach of in-situ construction of wet areas is a solution that, in the long term, seems untenable in terms of productivity. The limitations of traditional installation methods of the plumbing services - i.e. with the delivery of a multitude of small parts and components for individual site assembly (see Figure 2) - can be explained by analyzing step-by-step the implications of such methods in the construction sequence of a typical residential high-rise scenario.

"More than half of the working time of a plumbing company that operates with the traditional model is likely to be spent on coordination with supervisors and other trades, waiting, or shifting equipment, material or personnel between floors."

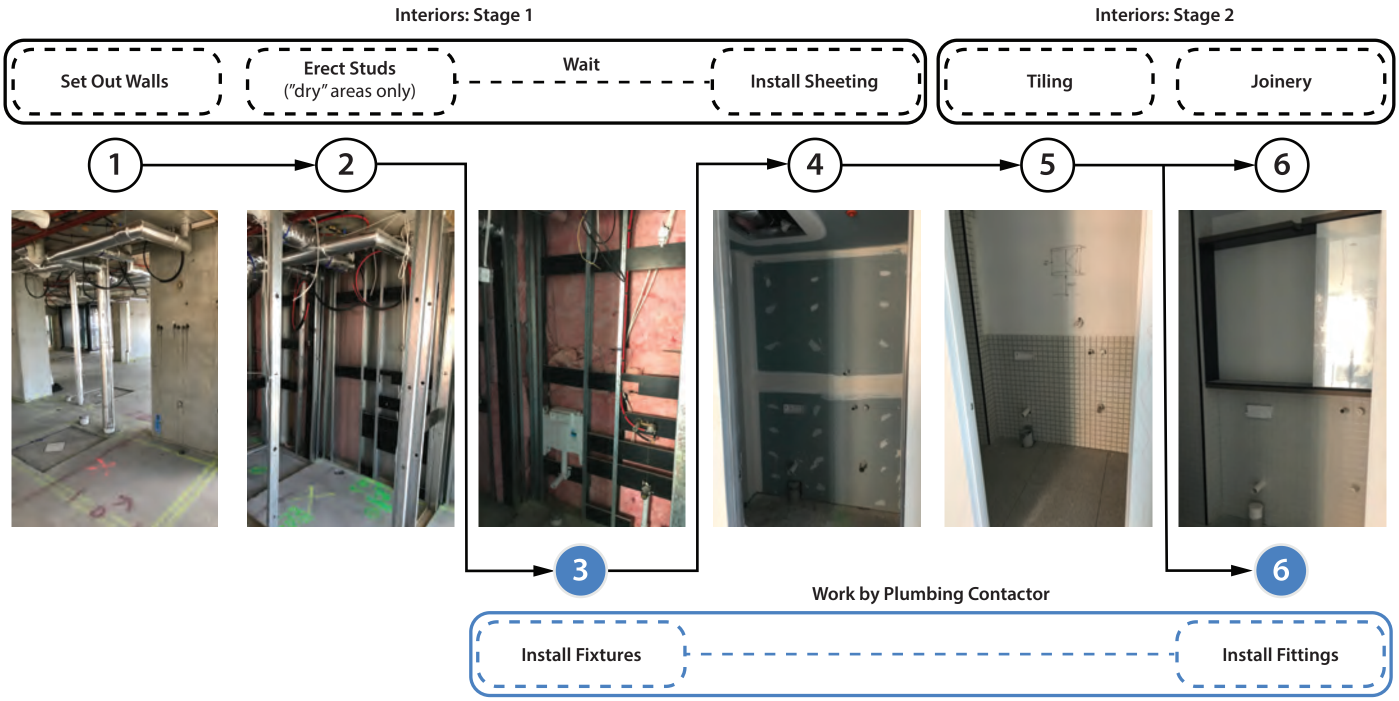

Figure 3. Traditional construction trade sequence of interior finishes in wet areas.

Plumbing and Process Engineering

The construction sequence indicated by a typical traditional scenario involves at least three separate sub-contractors (see Figure 3). While the initial work of the chain can be handled in relative autonomy by the wall contractor (steps 1 to 2), the completion of the wet area partition walls (step 4) cannot proceed until the plumbing contractor has completed the installation of plumbing fixtures on studs (step 3). This small interruption of the workflow of the wall contractor creates significant limitations on the capacity to accelerate the completion of works in the case of unforeseen delays or program pressures. This traditional construction sequence, therefore, puts the on-site work of the plumbing contractor on the critical path for the completion of partitions, and ultimately for the handover stage. It also generates a significant amount of risk and time pressure that can only be offset by coordination between the two sub-contractors, or by allowing, as a contingency plan, the addition of on-site workers in response to unforeseen circumstances.

The researchers were able to carry out an internal assessment of traditional work that the company delivered as a sub-contractor of several residential and commercial buildings of more than 10 stories. The cross-project evaluation found that the time spent for the actual completion of plumbing works on site accounted for only 40% to 45% of the time effectively allocated to personnel on projects. In other words, over half of the working time of a plumbing company that operates with the traditional model is likely to be spent on coordination with supervisors and other trades, waiting, or shifting equipment, material or personnel between floors.

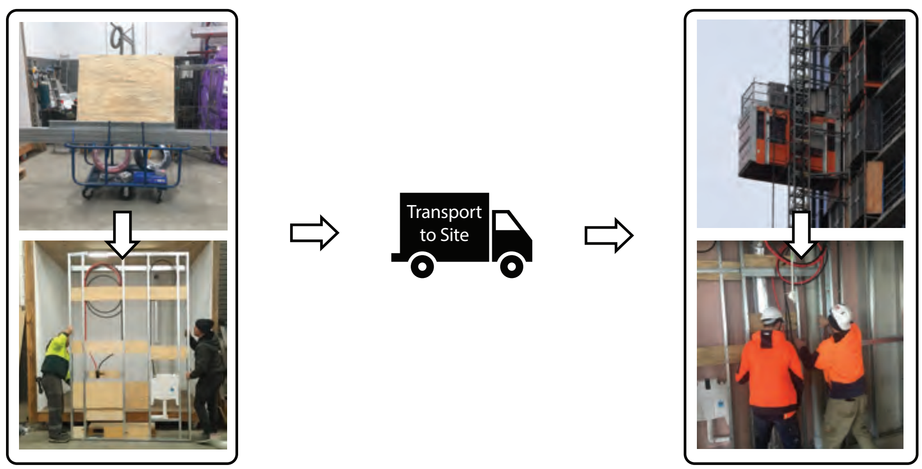

Figure 4. The flat-pack approach to plumbing pre-fabrication: walls and plumbing fixtures are pre-assembled off-site (left), delivered to site by truck (center), lifted by hoists and assembled on-site in less than 10 minutes (right).

In the wake of such considerations about time lost on-site, the present trends of off-site prefabrication with modules, parts and components of MEP services are shaping up as a most reasonable strategy to increase productivity. In the context of this shift, there is an opportunity for plumbing sub-contractors to turn such challenges into opportunities for innovation and adopt the mentality of a "process engineer" (Kieran and Timberlake 2004). However, it is essential to understand that processes of innovation in construction, rather than occurring as radical shifts, may be more likely to spread widely when they occur incrementally, and when they involve existing skills and trades already available in a market. An example of this incremental process of re-engineering sub-contractor work is the flat-pack approach to a wall-integrated plumbing module described hereafter, a solution that, in the process of its development, was also able to test, demonstrate and benefit from the application of principles of DfMA (see Figure 4).

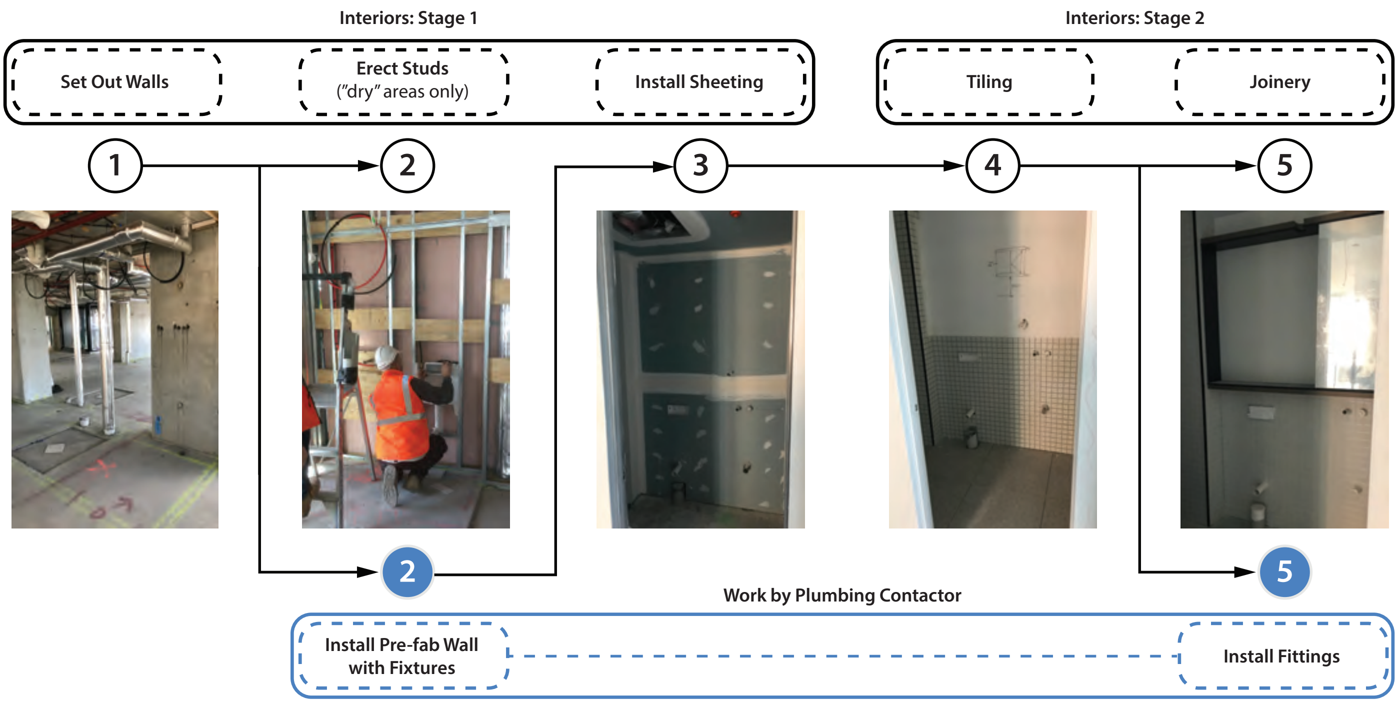

Figure 5. Construction trade sequence of interior finishes in wet areas with "flat-pack" wall-integrated plumbing.

A Flat-Pack Model for High-Rise Plumbing

By applying DfMA concepts and through a series of productivity studies, the authors' team has developed an innovative approach for the design and installation of plumbing services in high-rise projects. The innovation consists of a partially prefabricated wall element that integrates the reticulation of water supply and wastewater into its construction. The element can be manufactured and prefabricated off-site and assembled with ease directly by the plumbing contractor. Its primary implication is the elimination of a critical area of risk and delay, usually associated with the traditional in-situ construction sequence of wet areas in large multistory projects (see Figure 5).

Through the activities of the research project, it was observed that the transfer of assembly activities from a high-rise construction site to a factory environment increased productivity and improved quality without the need of specialized or additional labor skills, while providing a reduction of cost. The project involved the preparation of a prototype and a subsequent assessment of productivity in the context of a high-rise project under construction in Melbourne. The research team also engaged with the implementation of management systems and quality control, which used agile methodologies and quantitative monitoring of the production time.

In summary, the critical activities of the research project included:

1. The design of a prefabricated structural flat-pack modular wall system with integrated plumbing suitable for high-rise apartment bathrooms;
2. The application of DfMA strategies in the development of the system to improve productivity both off-site and on-site;
3. A manufacturing phase, which included the procurement of materials, laboratory testing and a trial assembly with a full mock-up of the system;
4. An assembly phase, during which the research team analyzed productivity by comparing the performance of the DfMA-inspired flat-pack system against conventional site-built methods.
5. The application of the system in a real project scenario, specifically for the typical interiors of bathrooms in a 71-story residential tower in Melbourne with more than 1,000 apartments (see Figure 6).

The design of the prototype for the prefabricated bathroom walls was conceived to fulfill brief design criteria derived from a real project. While based on project-specific inputs, the system was developed to be replicable with minor variations for future project applications.

During the development of the system, the research team experimented with the application of DfMA concepts in order to simplify the general manufacturing and assembly process of the wall, as well as of its integrated plumbing elements (see Figure 7).

Several design concepts for ease of manufacturing were adopted in the development of the prefabricated wall system. These DfMA-led improvements


Figure 6. The flat-pack wall-integrated plumbing solution was tested in a real project scenario, Swanston Central, Melbourne. © G. Marfella

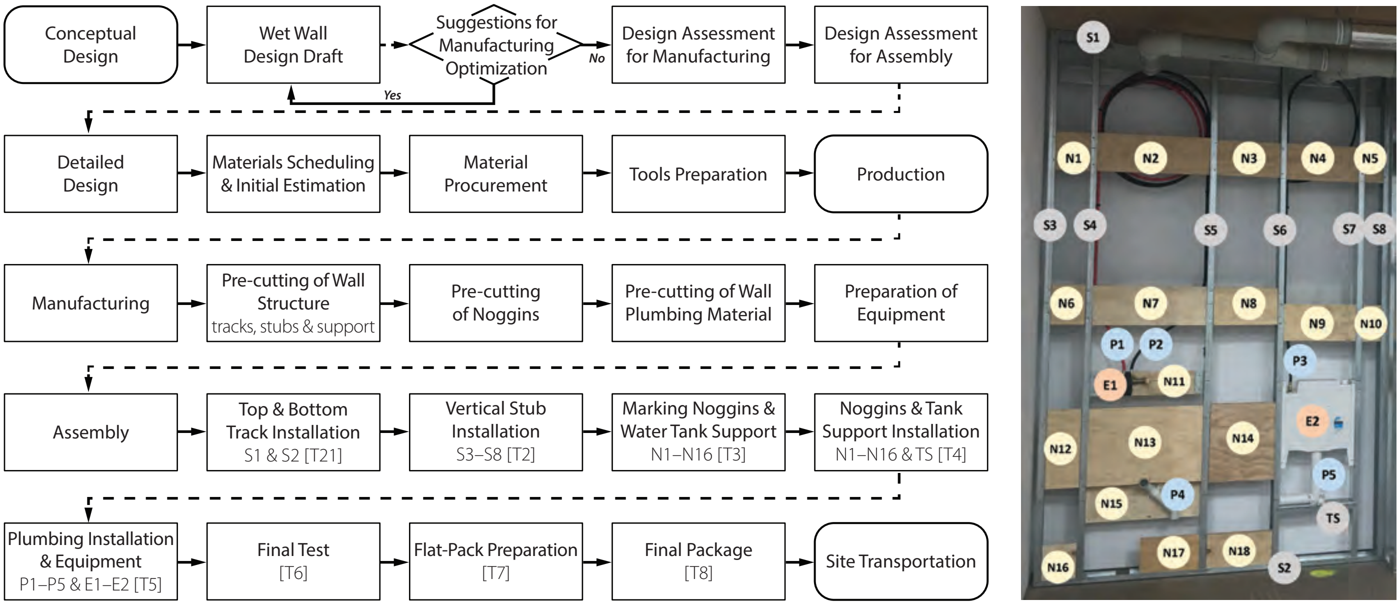

Figure 7. Flow chart of DfMA process applied to wall-integrated plumbing elements and prototype with parts identification.

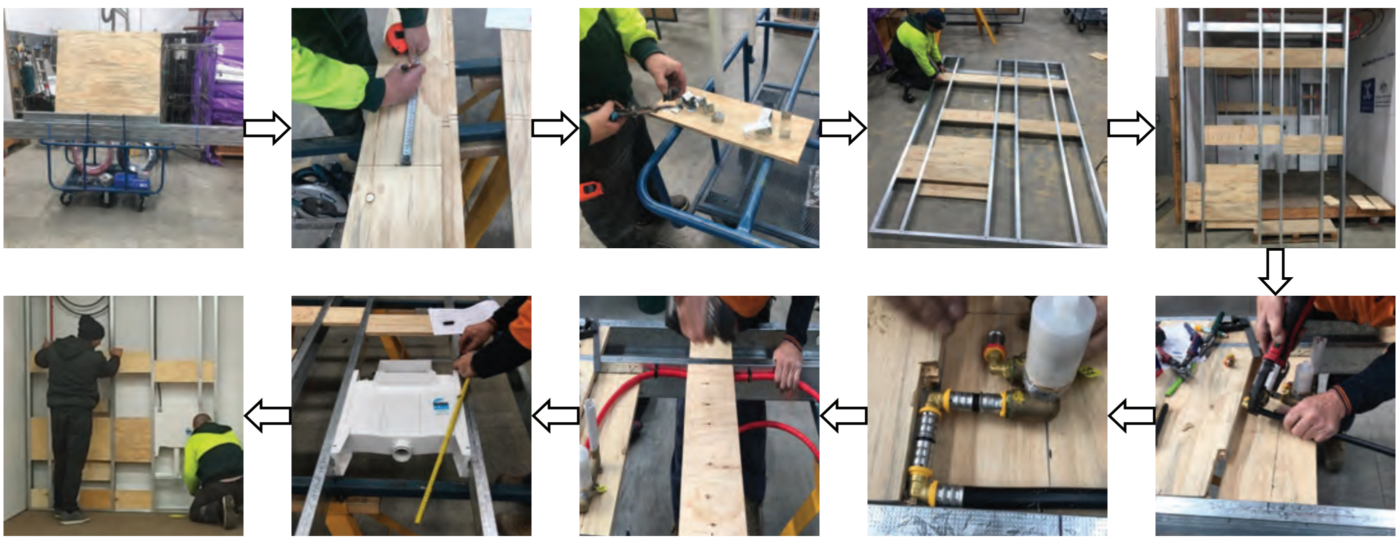

Figure 8. DfMA-optimized sequence of manufacturing and assembly activities associated with the integration of plumbing in wall partitions.

included strategies such as the minimizing of the number of parts (by combining two existing parts into one) and the re-design of some parts for ease of handling, insertion and fastening. Whenever possible, the project sought to use standardized parts that can be easily obtained. The application of DfMA principles generated minimum variations to the assembly process, a reduced inventory of parts, and the reduction of planning and scheduling tasks. In summary, it resulted in a higher probability of "getting it right the first time": reducing error and unnecessary complications.

Other DfMA-driven decisions derived from the assessment of off-site production capabilities that were already available in-house. These decisions generally constrain design solutions that "make do" without significant new capital investments into equipment or employment of additional human resources. Nonetheless, through such constraints, the design team was induced to discover alternative processes or methods that the team was able to implement or plan for future developments, even when the in-house capabilities were not ideal.

The application of the DfMA guidelines led to a solution that could be assembled with simplified tasks of manufacturing, thus allowing the plumbing contractor to improve off-site procedures, as well as gain additional productivity by reducing assembly time in the factory (see Figure 8).

In the context of the high-rise project where the experiment was tested, the traditional sequence required for the construction of bathroom walls was found to require at least 11 steps. After the application of DfMA concepts, the sequence of site installation was reduced to six steps (see Table 1). The process reduced the number of activities by more than half, including waiting times associated with the need to inform supervisors.

Finally, it was possible to adopt a "just-in-time" approach for the supply and installation of the prefabricated wall elements, thus not interfering with the minimum on-site storage available in the project. A critical design aspect of the flat-pack wall-integrated plumbing system was its ability to be installed

Step	Traditional Assembly Sequence	DfMA Sequence
1	Drywall marking and installation of metal tracks (top, bottom and vertical)	Drywall marking and installation of metal tracks (top, bottom and vertical)
2	Inform the supervisor	Inform the supervisor
3	Plumbing trade to arrive on-site and mark noggins	Plumbing trade installs the flat wall
4	Inform the supervisor	Inform the supervisor
5	Drywall trade to install noggins	Drywall trade to finish the wall installation with plasterboard, tiling and painting
6	Inform the supervisor	Plumbing trade to install final fittings on the wall
7	Plumbing trade to install pipes and support for fittings	
8	Inform the supervisor	
9	Drywall trade to finish the wall with plasterboard, tiling and painting	
10	Inform the supervisor	
11	Plumbing trade to install final fittings on the wall	

Table 1. Comparison of traditional and DfMA sequences for assembly of bathroom pods.

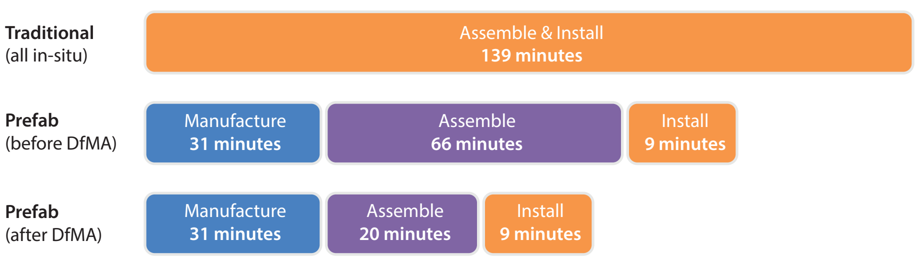

Figure 9. Comparison of time requirements between traditional, prefabricated and DfMA-improved methods of construction of plumbing in high-rise wet areas.

without the need of a tower crane. The walls were explicitly designed to fit inside the hoists provided by the contractor for the general circulation of trades on-site.

Wall-Integrated Plumbing: Implications

At the end of the experiment, the site installation time for the prefabricated wall took approximately 9 minutes, of which 6 minutes were required for the erection of the wall, and another 3 minutes to connect the system to hot and cold water lines. By comparison, the on-site work for a similar wall would have required more than 1.5 hours for it to be measured, cut, erected and plumbed. Furthermore, the sub-contractor was able to benefit from up to 19% in cost savings, due to reduced site labor and time spent in non-productive activities (see Figure 9).

The shift to off-site manufacturing also brought other benefits, which were perhaps not immediately tangible in economic terms, but certainly not less important. Better quality assurance, a smaller workforce and fewer materials stored on-site led to less demand on the tower crane and hoists, while waste and risks associated with occupational health and safety were also diminished.

In the context of the high-rise project where it was tested, the flat-pack approach of wall-integrated plumbing also had positive repercussions for the head contractor. Semi-prefabricated walls allowed condensing into 9 minutes a sequence of work that would otherwise take up days. This time savings brought significant benefits for the overall construction sequence of the floors by anticipating the end of the first stage of the finishing works. Furthermore, the experiment indicated that there is a possibility to extend similar approaches of partial prefabrication for other trades. In the future, flat-pack systems optimized with DfMA principles could give similar abilities to wall contractors. Similar concepts could be used to accelerate internal partition works, by setting up wet areas as a kind of "in-situ pod" to be assembled on-site with partially prefabricated wall elements.

The most significant side effect that ensued from the experiment relates to the ability of head contractors to feel sufficiently invested in a process of innovation that is ultimately led by subcontractors. Flat-pack, semi-fabricated methods like the one described here suggest the need to reconsider the role of specialist trades as the potential drivers of innovation in high-rise buildings. In this form of innovation, change occurs through a bottom-up process that is led by companies that can control the highest level of specialist skill. Of equal importance to the process is the ability of specialist subcontractors to influence the design by pushing their expectations for ease of manufacturing and assembly upstream, hopefully reaching out early enough to inform the work of architects and engineers at the initial stages of design. In this process, contracting firms with lesser technological specialization and design skills may be the ones that risk losing competitive advantage or move a step down in the supply chain and assume the role of subordinate subcontractors.

Conclusions

The flat-pack semi-prefabricated construction system is a process-oriented innovation that is inevitably dependent on cultural change in a determined industrial context. The benefits of DfMA principles may appear to offer only a limited opportunity of improvement to some, but upon at a closer inspection, these trends of change in the Australian construction industry suggest that the long-term implications could change the landscape of an entire industry. The subcontracting market may take a decisive turn in the future, moving towards scenarios in which the actors most able to integrate different disciplines in the production of technological systems may emerge as the new market leaders. The case of prefabrication with integrated plumbing is, in fact, a global phenomenon on the rise, of which very sophisticated examples can be witnessed in prominent recent buildings under construction worldwide, such as at 100 Bishopsgate in London (see Figure 10).

Such developments may have seemed unthinkable in the context of traditional schemes of procurement only a few years ago. However, processes of innovation that depend on the concentration of know-how have occurred long before in other subsectors of the high-rise industry, such as unitized curtain walls.

In other words, the future of subcontracting in high-rise projects may leave little room for fragmented, micro-specialized and labor-intensive trades. By contrast, the firms that are keen to integrate a diversity of skills, bring a higher level of technological sophistication and nurture a culture of research and development may be the ones that will benefit the most from these present trends, particularly in countries where high labor costs are likely to endure, as in Australia. The construction companies that are most likely to succeed may not be necessarily the ones that dive into costly large-scale off-site manufacturing endeavors. The quest for breaking the new height record of volumetric modular construction is likely to continue. However, more importantly, the upper hand in modular and semi-modular innovation may be with the contractors that take the highest stake in the design, and not only in the quick delivery, of large, complex projects. In such a dynamic context, it is not difficult to imagine a future role for DfMA in tall buildings outside the intersection of efficient off-site manufacturing and practical on-site assembly.

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Figure 10. Large scale pre-fabrication of bathrooms units (left) developed by Modular Interiors for the construction of 100 Bishopsgate, London (right). © Allies & Morrison and Arney Fender Katsalidis

"There is a need to reconsider the role of specialist trades as the potential drivers of innovation in high-rise buildings. In this form of innovation, change occurs through a bottom-up process that is led by companies that can control the highest level of specialist skill."