J. W. Gottstein Memorial Trust Fund

The National Educational Trust of the Australian Forest Products Industries

DESIGNING TIMBER CONSTRUCTION FOR MANUFACTURE AND ASSEMBLY

By

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2016 GOTTSTEIN FELLOWSHIP REPORT

SYDNEY

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Joseph William Gottstein Memorial Trust Fund

The Joseph William Gottstein Memorial Trust Fund was established in 1971 as a **national educational Trust** for the benefit of Australia's forest products industries. The purpose of the fund is "to create opportunities for selected persons to acquire knowledge which will promote the interests of Australian industries which use forest products for the production of sawn timber, plywood, composite wood, pulp and paper and similar derived products."

Bill Gottstein was an outstanding forest products research scientist working with the Division of Forest Products of the Commonwealth Scientific Industrial Research Organization (CSIRO) when tragically he was killed in 1971 photographing a tree-felling operation in New Guinea. He was held in such high esteem by the industry that he had assisted for many years that substantial financial support to establish an Educational Trust Fund to perpetuate his name was promptly forthcoming.

The Trust's major forms of activity are:

1. Fellowships and Awards - each year applications are invited from eligible candidates to submit a study programme in an area considered of benefit to the Australian forestry and forest industries.

2. Seminars - the information gained by Fellows is often best disseminated by seminars as well as through the written reports.

3. Wood Science Courses - at approximately two yearly intervals the Trust organises a week-long intensive course in wood science for executives and consultants in the Australian forest industries.

4. Study Tours - industry

Further information may be obtained by writing to,
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About the Author

Perry has a strong mix of research, teaching, academic, managerial and practical experience obtained in the construction industry over a 38 year period. His experience stems from initiation at trade level followed by senior management positions in design, construction, estimating, project management and professional consultancy organisations. He successfully melded his industry experience with a broad spanning career in academia which has culminated in his current role as Professor of Construction Project Management, as followed by his previous role as Head of School (School of the Built Environment) at the University of Technology Sydney (UTS). In research and project sponsorship terms, Perry has won in excess of $1.0 million worth of work at UTS.

His core research areas track industry needs and include: construction productivity, process improvement, modern methods of construction, supply chain integration, quality management, customer satisfaction, waste management, uptake of digital technologies and sustainability issues. Much of this has occurred in around the advancement of prefabricated systems, especially around timber construction. In making use of the above, Perry has advised many leading companies and government bodies both within Australia and overseas.

Coupled with the above, Perry has received a number of industry and academic awards. He has published widely including over 70 articles in academic, educational and industry publications.

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Abbreviations

BIM – Building Information Modelling

CLT – Cross Laminated Timber

CNC – Computer Numerical Control

DFMA – Design for Manufacture and Assembly Approcah

GLT – Glue Laminated Timber

NLT – Nail Laminated Timber

1 Introduction

This report describes research undertaken as part of a Gottstein Fellowship study concerning the advancement of prefabricated timber construction with a view to improving its presence in the multi-unit residential and commercial building markets.

The study aimed to learn lessons from the application of advanced prefabricated timber construction settings in Sweden, Austria, Switzerland, Germany and Canada. The focus was on a progressive vision of timber construction as a highly efficient and adaptable process that smoothly integrates the continuum from design to production to construction onsite. Attention was given to digitally driven methods of fabrication, automation and efficient work methods onsite.

This report covers the investigative processes used, the organisations visited, the research findings and finally, the conclusions and recommendations made.

2 Context of the Study

Timber is becoming increasingly sought after as a construction solution for larger building forms (beyond its current dominance in detached housing). Engineering advancements and sustainability features have made it an inviting option that designers and customers now seek out.

An important aspect is the cost and a reliable means of delivering timber buildings in order to make it competitive in relative market terms. A point of difference for timber is its intrinsic linkage and suitability to prefabricated construction. With this in mind, timber must focus upon how this linkage can be optimised in order to open up new markets relating to larger buildings. For instance, there must be efficiency not just in the individual phases of design, production and construction, but a continuous and synergistic flow from one stage to the next. Work flow and integration are important in order to make timber cost competitive with the likes of traditional in-situ concrete construction.

There is an arising need to better understand the conversion process from design to production to construction. For instance, as onsite work reduces there is a corresponding need to reduce site costs because at least some of these costs will be deployed to off-site production (prefabrication) processes. Further, digital technology lends itself to creating a design file that can be exported as "file to factory" and then potentially “file to site” and this can improve the continuity, efficiency and automation of processes. There is the need for a smoother transformation across these stages in order to improve the value proposition that prefabricated timber construction offers.

Consequently, this report looks at state-of-the-art practices surrounding prefabricated timber construction in other countries. In aiming to shift the debate forward, attention is placed on the efficiency of transformation from design to production to construction takes place. Attention is given to designing timber construction (including products and processes) with a smoother flow from manufacturing to on-site assembly in mind.

3 Organisations Visited and Investigative processes

As mentioned previously, the study focused upon practices in Sweden, Austria, Switzerland, Germany and Canada. Data was obtained via a mix of meetings, recorded interviews, factory visits, onsite site visits, provided documents, provided images and first-hand observations. The table below provides a summarised view of the organisations and sources involved.

Table. 1. Sources used for data gathering and information

Country	**Organisation**	**Context**	**Comments on investigation and data gathering techniques**
Sweden	Randek http://www.randek.com/en/	Leading worldwide producer of timber prefabrication equipment; host company whilst in Sweden.	Interaction included factory visits, extended meetings and interviews with senior management; exposure to prefab supply chain and detailed overview of prefabrication in Sweden.
	A-Hus http://www.a-hus.se/	Manufacturer of prefabricated residential construction - mainly panelized construction	Design office and factory visits.
	Västkuststugan http:/www.vastkuststugan.se	Small to medium prefabricator of panelised housing and apartment construction	As above
	Anebyhus http://www.anebyhusgruppen.se/	Medium to large scale producer of both panelised and volumetric housing	Visit and detailed briefing of design office, sales office, multiple factory visits; meeting with CEO.
	Bo Klok https://www.boklok.com	Large-scale housing developer of low-cost apartment housing; manufacturer of housing modules; joint venture between Skanska and IKEA	Detailed interview with senior project manager; visits to completed projects; photographs of site processes and publications.

	Site visits	Various apartment buildings under construction (3-4 storeys); Observation of a number of reference buildings and housing developments.	Observation of onsite techniques and face-to-face discussion with site managers and workers.
Austria	Stora Enso http://www.storaenso.com	Large-scale diversified manufacturer of various massive timber products	Site visit, factory tour, presentations, publications and discussion concerning state-of-the-art CLT manufacturing (including digitally driven CNC cutting of CLT panels).
	Binderholz http://www.binderholz.com/en/	Large-scale diversified manufacturer of various massive timber products including production of both standard and customised panel lines	As above
	Weihag http://www.wiehag.com/en	Large project driven fabricator including diversified services spanning timber engineering, timber series products, commercial and industrial construction and house construction. They undertake design, fabrication and installation of many large and complex timber structures and have state-of-the-art CNC production facility	Design office tour, site tour, factory tour, logistics tour, presentations, publications and discussion concerning state-of-the-art CLT manufacturing.
	Site visits and completed reference buildings	Various multi story apartment buildings, institutional buildings, industrial buildings, geodesic domes and complex three-dimensionally curved specialty buildings	Observations and discussions with site staff; site practices; fabrication techniques; site safety practices; materials handling and cranage practices; use of massive timber construction,

	University of Vienna	Centre for timber engineering research and development	Meetings with various academics and industry practitioners; attendance at World Timber engineering conference
Switzerla-nd	Blumer Lehman http://www.blumer-lehmann.ch/en/the-company/	Large scale and diversified project driven fabricator of complex timber structures. They undertake design, fabrication and installation including advanced usage of parametric design and parametric estimating	Site tour, factory tour, design office tour, presentations, publications and discussion concerning state-of-the-art CLT manufacturing (including digitally driven CNC cutting of CLT panels).
	Haring https://www.haring.ch/de/	Diversified and progressive fabricator and contractor involved in both prefabricated volumetric and complex building forms	Factory tour, presentations, publications and discussion concerning state-of-the-art timber construction.
	Erne http://erne.net	Large scale and technically advanced producer and contractor of prefabricated and volumetric multi-storey building including particularly advanced robotics in production.	Site tour, factory tour, presentations, publications and discussion concerning state-of-the-art timber construction.
	ETH Zurich http://www.ita.arch.ethz.ch	Technically advanced university including high-level research covering timber engineering, robotics and automation	Site tour, debriefing and discussion with University personnel; exposure to advanced fire testing, composite timber elements and advance structural forms
Germany	Webberhaus	Large-scale producer of panelized custom homes and apartment buildings including export to various countries within Europe and Great Britain	Factory, design office, sales, logistics and site visits. Detailed debriefing on internal processes and first-hand observations.
	Site observations		Observed low to medium rise timber buildings under construction and reference buildings.

Canada	University of Alberta	Leading university in the study of modular off-site construction	Meetings with senior academics and attendance at modular off-site construction conference
	Landmark homes http://landmarkgroup.ca	Advanced timber prefabricator of housing in Alberta; high levels of production; high levels of penalisation and semi-modular roof and stair sections	Factory visit, presentation, discussions with senior management.
	Western Archrib http://westernarchrib.com	Leading producer of GLT in Canada; produce value added beam, column, panel elements for erection by others	Factory visit, meeting with Director and senior management, site visits, and reference building visits.
	StructureLam http://www.structurlam.com	Leading producer of CLT, GLT and other massive timber products.	Factory visit, meeting with Director and senior management, site visits, reference building visits.
	Wood-works http://wood-works.ca	Key advocacy and development arm for large-scale timber construction in Canada especially concerning the uptake of massive timber construction. Host organisation whilst in Canada.	Day long workshop concerning Brock Commons building, detailed briefing on timber construction in Canada, attended meetings with selected personnel, site visits in multiple locations (Edmonton, Vancouver, Penticton).
	University of British Columbia	Leading university in Canada; strong research and industry linkages in timber construction; campus contains a number of benchmark timber buildings	site visits (see below), meeting professorial counterpart and postgraduate students working in the area of timber construction productivity.
	Site visits		Mix of projects under construction including Brock Commons, a number of typical 4 to 5-storey

			apartment buildings, health centre, pool complex, hotel complex; many reference buildings observed.
	Seagate Structures https://seagatestructures.ca	One of the main contractors undertaking large scale timber construction, were the erection contractor on the well-known 17 story Brock Commons building	Site observations; detailed interview; insights into site processes and overview of practices in British Columbia.
	Fast and Epp http://www.fastepp.com/index.php/en/	Key structural engineering company in the timber design field	Detailed interview with the main engineer on Brock Commons and other buildings
	FP innovations https://fpinnovations.ca/Pages/index.aspx	Federal Government based technical timber research and development arm; involved in the development of timber building systems, standards and materials testing	Interviews and meetings with senior managers; tour of materials testing lab and discussions with related technology managers
	Lubor Trubka	Well known timber architect in British Columbia http://www.lubortrubka.com	Site visit, interview, detailed briefing on projects.
	Cadmakers http://cadmakers.com	Leading exponents of virtual design and construction who aim to convert manufacturing principles to solving construction problems	Interview, meetings and presentations of virtual design and construction methods

4 Findings

The nature of prefabrication varies considerably according to the market context, prevailing functional requirements and regulatory requirements. The culture and mindset of the supply chain are particularly important. Details on each country are provided separately under dedicated subheadings below.

4.1 Timber Construction in Canada

Canada has large forestry deposits across the country, and there is subsequently an inclination to take advantage of this resource as a preferred construction material. For instance, the "wood first act" places an onus on provincially-funded projects to use wood as the primary construction material[1].

Usage of timber is already common in apartment construction especially buildings in the order of 4 to 6 storey range. In recent years there have also been strong moves to champion the implementation of massive timber construction as part of the apartment sector as well as non-residential construction applications.

Despite the apparent linkage between larger timber building construction and prefabrication, there are still relatively limited examples of high level prefabrication in the market place despite the extremely cold weather that prevails in the winter months. For instance, timber framed projects in the order of 4 to 6 storeys typically involve joisted floors and wall frames being “stick built” on-site. Some sites setup a dedicated prefabrication bay but this typically only caters for semi-closed wall panels (mainly exterior sheathing rather than finished cladding) and rarely extends to the likes of cassette floor elements (refer Figure. 1). Dedicated framing plants are few compared to Australia. Exceptions obviously apply, but the above represents the main trends. One example of an exception is BC Passive House who adopts higher levels of prefabrication in the low density housing market around sustainability themes[2]. Another is Landmark homes in Edmonton who have impressive levels of factory automation and usage of digital technology and provide large economies of scale.

[1] See for instance: http://wood-works.ca/bc/featured-topics/wood-first-act/
[2] http://www.bcpassivehouse.com

Figure. 1. "Stick built" framed apartment construction in Vancouver

Despite this, there are still significant moves towards high levels of prefabrication and higher levels of associated technologies away from conventional framed construction. Arguably, the main area of movement concerns massive timber products and the usage of 'file to factory' technology to facilitate improved production off-site. For instance, companies such as Structurelam[3] manufacture CLT and GLT out of Penticton and are the only CLT producer on the western side of the country; Western archrib[4] manufacture GLT out of Edmonton. Both commonly convert architectural CAD drawings into machine files using the likes of CADworks software, which drives CNC cutting technology to produce value-added elements such as pre-cut or pre-machined panels, columns and beams. Their services are commonly paired with separate site erection contractors who tender separately or potentially as part of a joint bid.

Combined, the likes of StructureLam and Western Archrib form the main base suppliers of massive timber products in British Columbia and Alberta. Somewhat surprisingly, Nail Laminated Timber (NLT) is also common in these areas, and this is to some extent because it provides a cost competitive and diversified choice in the market place. NLT can be made into prefabricated floor plate panels (and other elements) using relatively basic plant and equipment, thus making it within reach of a broader number of timber framing prefabricators. A strong advocate of this approach is Structurecraft[5] who take on a variety of large and complex projects in both Canada and the United States. The company's founder, Gerry Epp,

[3] http://www.structurlam.com
[4] http://westernarchrib.com
[5] https://structurecraft.com

is a well known timber engineer and the company has the ability to provide structural design, off-site production and on-site installation packaging which occupies a useful position in the marketplace. It is also evident that interest and expertise in massive timber (in all its forms) is helping to fill in other parts of the supply chain. In engineering, companies such as Fast and Epp[6] and Equilibrium consulting[7] both have well developed expertise and work in an integrated way with other supply chain participants to generate the best value for timber as a coordinated construction system. Timber oriented architects are also on the rise and importantly, their advocacy create projects which act as exemplars of what is achievable with timber in larger scale buildings including the likes of the Wood Innovation Design Centre (architect, Michael Green, http://mg-architecture.ca), the Earth Sciences Building at University of British Columbia (architect, Perkins and Wills, http://perkinswill.com), a number of First Nations buildings (architect, Lubor Trubka, http://www.lubortrubka.com) and Brock Commons also on the University of British Columbia campus (architect, Acton Ostrey http://www.actonostry.ca, assisted by Hermann Kaufmann)

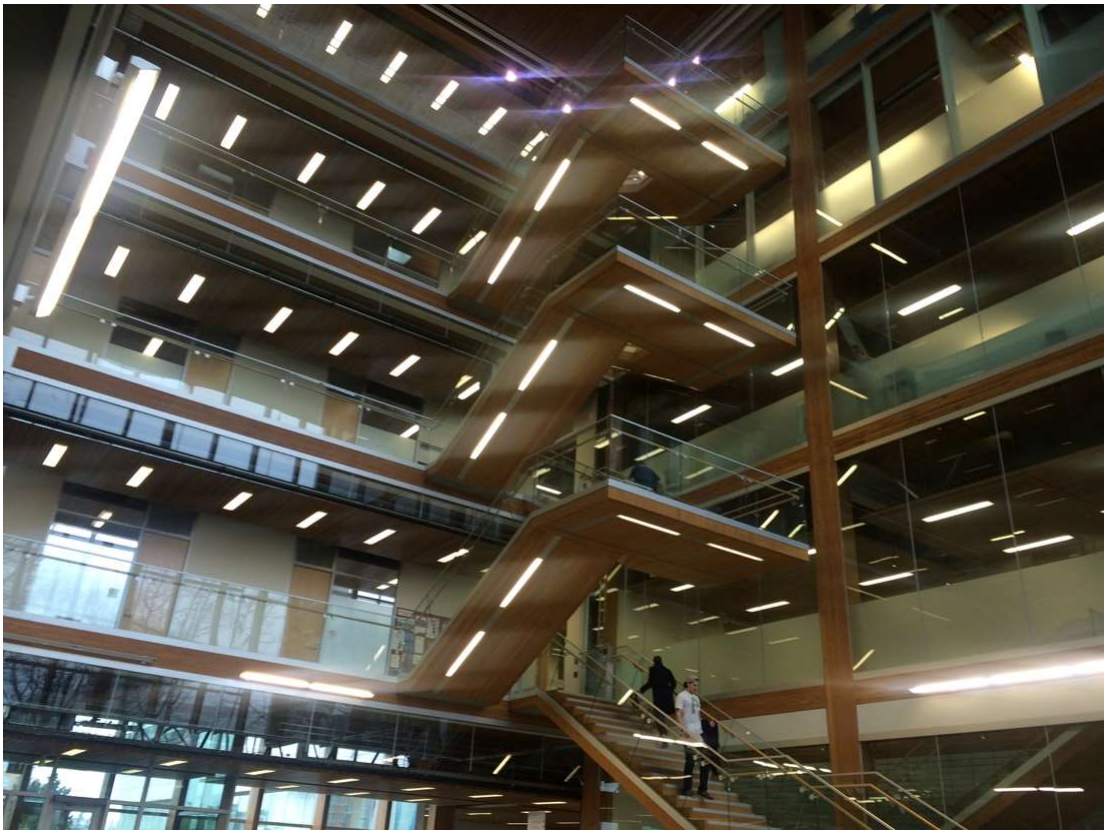

Figure. 2. Earth Sciences Building, University of British Columbia (showing cantilevered stairway)

[6] http://www.fastepp.com/index.php/en/
[7] http://www.eqcanada.com

Figure. 3. Earth Sciences Building, University of British Columbia (showing post and beam structure)

Among these, and as consistent with the need for timber to emulate a coordinated building system, the WIDC building is notable for its attention to a systematic and limited kit of parts and includes access floor style construction on each alternate floor panel to provide a standardised void for the installation of services.

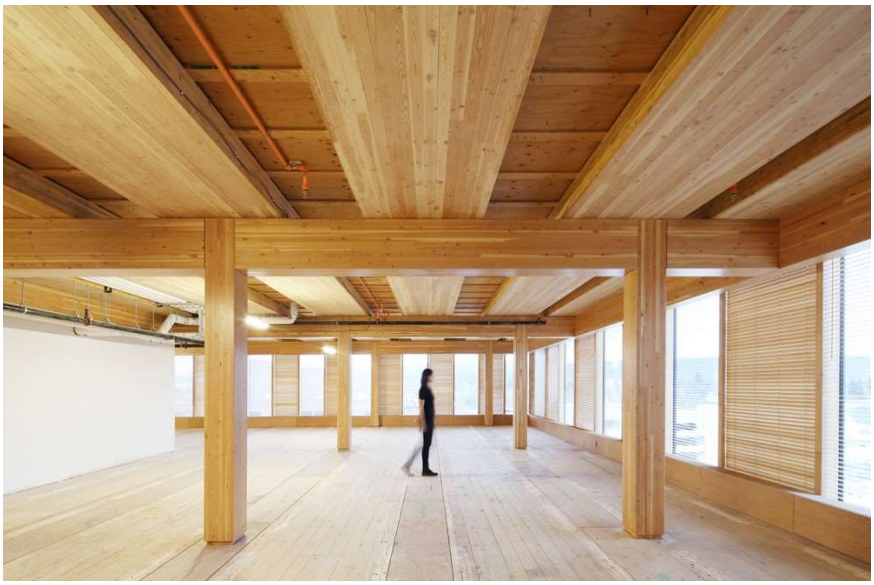

Figure. 4. Provision for ceiling services in WIDC building (Source: Michael Green, http://mg-architecture.ca/work/wood-innovation-design-center/)

Figure. 5. Architect's impression of structure and services in the WIDC building (Source: Michael Green, http://mg-architecture.ca/work/wood-innovation-design-center/

Arguably, the most notable in terms of design for manufacture and assembly approach, is the recently completed Brock Commons building. This 18 storey building is the tallest timber building in the world at present. Attention to planning and execution is particularly apparent in the two-day floor cycle that was achieved during execution of the work.

Figure. 6. Brock Commons building after completion of the facade

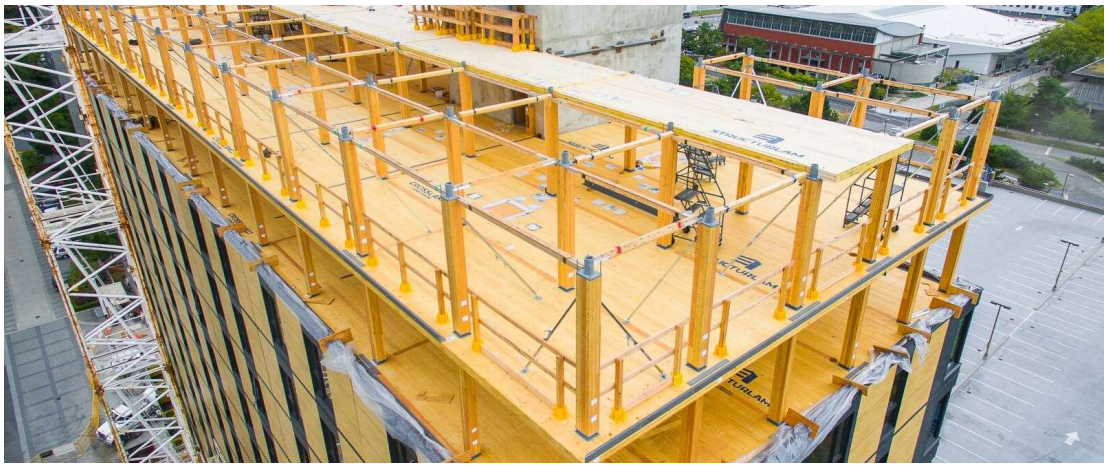

Figure. 7. View of typical floor plate erection on Brock Commons building (Source: http://www.naturallywood.com/emerging-trends/tall-wood/ubc-brock-commons)

Being a student housing project there was a relatively small column grid which enabled flat plate construction of the floors and avoided the need for dedicated primary beams. This facilitated very simple and fast construction processes on-site. Further, the use of virtual design and construction by all members of the team made it possible for complicated planning of site processes, to be simplified via the distribution of simple video files to designers, site managers and trade workers alike. This enabled simple feedback and collaboration without requiring high level knowledge in BIM or strong computer capability. Detailing and systematisation of work processes were clearly important to the speed of execution onsite. As an example, metal connectors at the bottom/top of columns provided simple and well thought out site processes that allowed loads to pass down through the floor levels without compressing wood fibre in the floor plates and fast placement of columns. For an entire floor plate, columns could be placed within a couple of hours by a small crew of 3 to 4 men, and without crane assistance.

The benefits observed in such projects are now spawning further projects for these and other companies. For instance, Shigeru ban's design for a 19 story hybrid timber building for developer Portliving[8] , located in the downtown area of Vancouver, will likely replace Brock Commons as the tallest in the world once constructed. Already, a number of the Brock Commons participants have had preconstruction stage involvement and it is apparent that such projects allow supply chains to develop further, which will advantage timber construction significantly in the mid to long term.

[8] http://portliving.com/residential/terrace-house/

Figure. 8. Shigeru Ban designed 19 storey timber hybrid terrace house, currently in preconstruction stage (source: http://portliving.com/residential/terrace-house/)

4.2 Timber Construction in Sweden

Sweden is arguably the most assimilated country when it comes to the uptake of prefabricated construction methods. The majority of this involves panelised systems, but there is a quickly growing trend towards volumetric construction. Here, the former involves closed panel wall and floor elements (including provision for services) where very little additional work is required onsite. The latter volumetric approach simply means that panel manufacturers capable of advancing further, simply add an additional production line to convert panels into volumetric modules. It is also notable that for volumetric modules, trucking logistics and site access are not particularly problematic in most housing development areas as large parts of Sweden mainly consist of low to medium density urban development. There is also an excellent road network around the country.

Sweden is subsequently an advanced market with a strong manufacturing mindset and where design is manufacturing lead. The end user market appears to readily accept such products especially where well targeted to suit specific market segments. At times, certain instances of prefabricated housing appears to some extent utilitarian, relative to Australia housing, but this appears to be accepted by customers who generally appear less concerned with customised architecture and viewing housing as a measure of status. What's more, the Swedish Supply chain has a mindset of working smarter rather than harder. Making profit is built around working synergistically with others and less around the small business, low capital investment, speculative and risk divestment strategies that tend to dominate the Australian construction sector. They invest with the mid to long-term in mind. The manufacturing mindset also means that in the order of 80% of the work takes place off site and this significantly changes market behaviour whereby site based contracting become less relevant

in construction procurement behaviour and this significantly changes the cost economics and risk divestment profile normally associated with construction projects.

The vast majority of timber construction is framed construction but with the proviso that such methods have been adapted for manufacture and subsequently remove the likes of unnecessary noggings and instead optimise OSB sheathing for bracing and rigidity in panels. There is also the need for significant width in walls to accommodate insulation and condensation management. The overall approach has been adapted to suit production line processes whereby digital files drive automated fabrication equipment, and factory workers are furnished with tablets that display detailed 2 dimensional drawings to assist the fabrication process as each stage in the production line. Here, studs and subassemblies are loaded up onto the production line and then plates and nailing are all undertaken using automated means. Automatically cut insulation feeds into the line, followed by sheathing, vapour barriers, and so on. In contrast to some other countries studied, there is relatively little use of massive timber construction and whilst this may be due to the lack of insulation thickness that can be cost effectively afforded by such construction, a simpler reason may be that massive construction has yet to take root in Sweden.

Figure. 9. Typical mixed townhouse and apartment development in regional Sweden

Figure. 10. Panelised construction on 4 storey apartment building

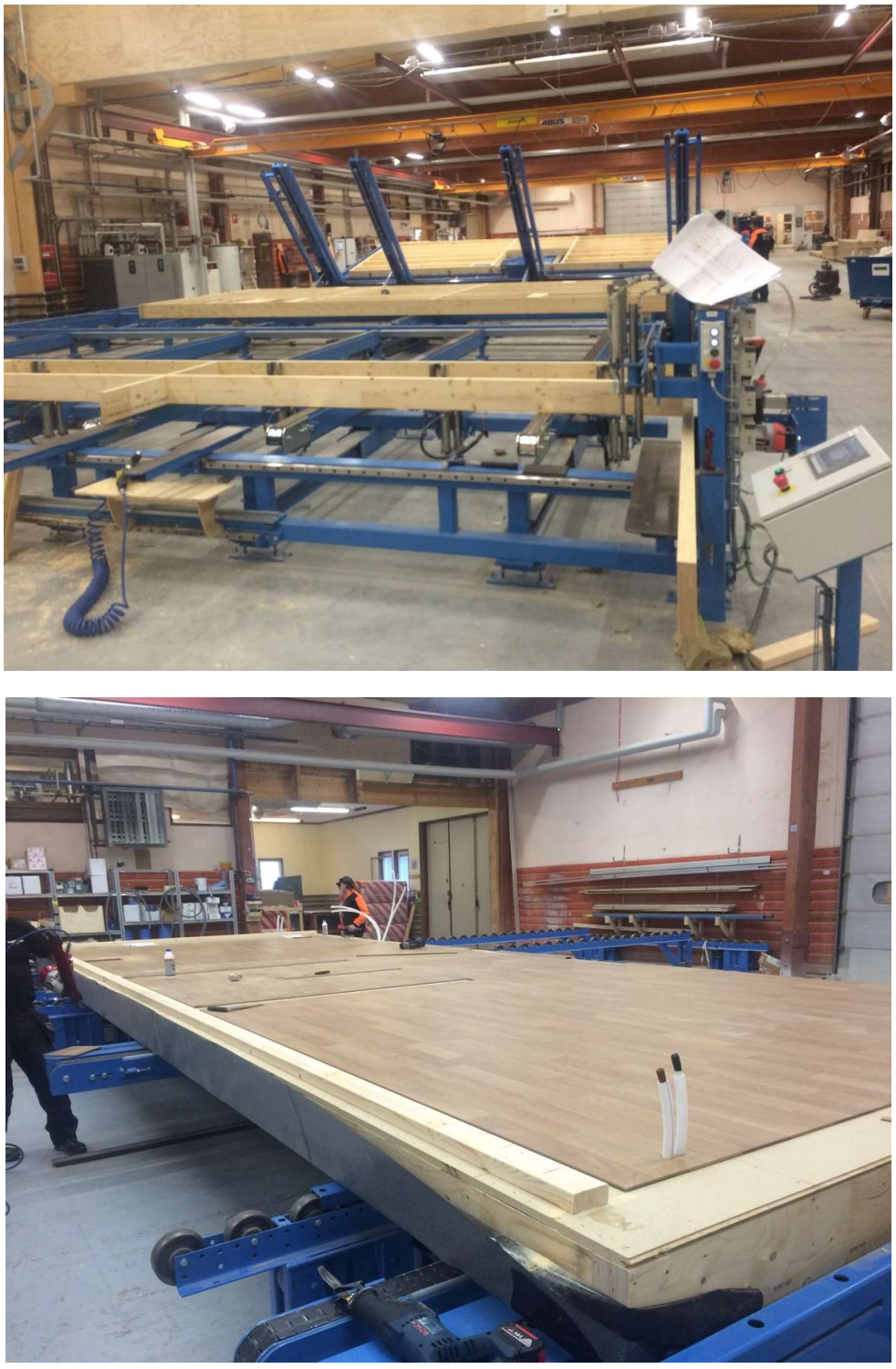

Figure. 11. Randek floor cassette production line

Figure. 12. Panelised roof elements ready to go to site

Figure. 13. Typical module production line

Housing developers in Sweden seem able to save money, deliver housing more quickly and provide high performance standards by virtue of utilising relatively standardised prefabricated and modularised housing designs. This is applied to detached housing, low rise and to some extent medium rise multi-unit residential housing. For instance, developers such as Bo Klok treat prefabrication and land development in a highly integrated way where centralised production of housing modules is a key aspect of their overall operating strategy. Having a controlled and stable system from developer through to construction execution has allowed Bo Klok to become a highly successful business.

4.3 Timber construction in Central Europe (Austria, Switzerland, Germany)

Central Europe represents a huge and multi-generational depth of expertise in timber construction. Large and internationally recognised manufacturers of massive timber and advanced engineered timber products exist in this part of the world. There is a well developed supply chain whereby manufacturers, fabricators, engineers, universities and

installation contractors work well together and have high degrees of vertical integration. Design file, to factory file, to site file form a commonly used underlying tool throughout the supply chain. Advanced automation and robotics are apparent, especially in Switzerland. There is strong attention to working intelligently and synergistically at both business and technical levels, rather than the fragmented and adversarial approach common in many other construction industries. Advanced parametric design and parametric estimating, coupled with CNC cutting technology, suggest that this is the direction of the future. As one example, companies such as Blumer Lehmann regularly undertake fabrication of high complex designs for world-famous architects such as Shigeru ban and Norman Foster. Many of the companies mentioned in Section 3 export product and services to different parts of Europe, the United Kingdom, North America and Australia.

It would therefore seem that in the central Europe area, technology adoption of massive timber construction has moved well beyond the "first movers" stage. It would also seem that this is attributable to a well-developed and well integrated supply chain which occurs in an enclave like network that involves resource availability, technical services, engineering expertise, prefabrication expertise and relatively centralised logistic capabilities.

Figure. 14. Closed panels being installed on housing in Germany

Figure. 15. Long span timber construction, Wels exhibition centre, Austria

Whilst all of the countries in studied central Europe are quite advanced, it is clear that Austria has considerable forest resource and many wood manufacturers have set up in or around this area. Germany has very precise and well controlled packaging of entire prefab building systems especially in housing and especially in their ability to deliver such housing whilst still maintaining relatively high degrees of customisation. Switzerland is particularly interesting as there appears to be greater interest and greater investment in advanced timber construction systems that aim to synergistically and elegantly deal with improving timber as a building solution. They are adventurous in their approach to engineering and as an example of this, Universities such as ETH work closely with industry to develop concepts that optimise digital fabrication by virtue of using additive layers of simple elements to form complex geometric structured such as the long span truss roof of the ETH Arch Tec Lab shown in Figure. 16[9].

[9] refer https://www.youtube.com/watch?v=OCQvEDhKMfw and https://www.youtube.com/watch?v=xtr1YtcmGoE for details

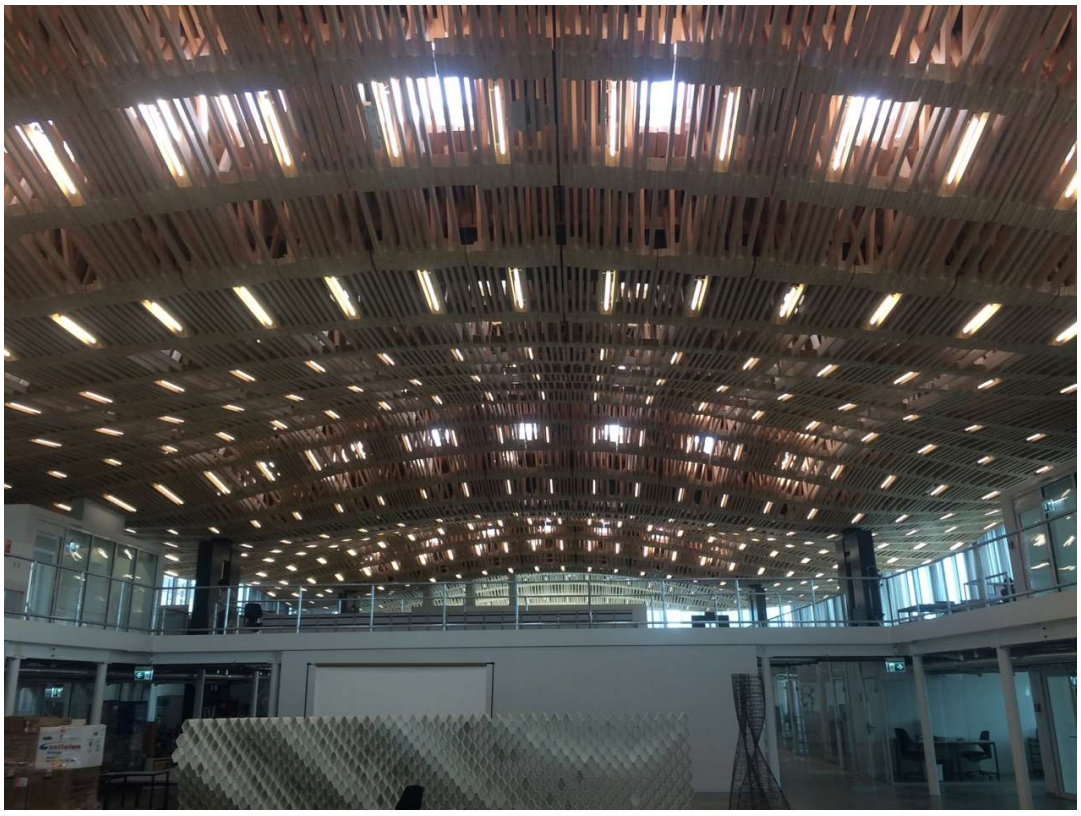

Figure. 16. ETH Zurich, Arch Tech Lab, Trussed roof showing complex geometry

Along a similar line, creative structural design is apparent in Timbatec's (http://ts3.biz/de/aktuelles/meldungen/2015-09-25_KTI-Forschungsprojekt-genehmigt.php) structural system for multi-storey open span buildings which uses a flat plate and column approach. Of note, use of CLT flat floor plates is coupled with an in-line hardwood column head. The two pieces are edge glued together which can be seen in Figure. 17. This potentially provides an open and unimpeded clear span beneath, and possibly a simplified construction process as well. The glue driven approach is quite an adventurous aspect of the engineered solution. It is still undergoing further development and places quite high importance on quality control. Another aspect is through housing of the circular column to prevent fibre crushing in the floor plates.

Figure. 17. Model of Timbatec's adventurous TS3 structural column and floor plate concept for multi-storey buildings (Note: palletes beneath the floor plate are for exhibiting purposes only)

Both in Switzerland and Austria significant thought is paid to site processes. Cranage and load lifting efficiency are central to this as they directly effect achievement of efficiency in prefabrication processes onsite. One example of the methods used concerns adaptation of rock climbing technology applied to fast release load lifting/release onsite using the reusable Sihga "pick" load lifting devices https://www.sihga.com/holzbau-wasserbau/systemverbinder-lastaufnahmemittel/pick.html. These make it easy to transport panels without unnecessary protrusions. The device can be quickly fitted on-site into pre-machined holes, and once the panel has been placed, the fitment can be very quickly released and then reused on other panels (which avoids the cost of metal lifting fitments being placed in each and every panel). One of the advantages of this approach is simply that timber cutting work is done in the factory, but there is no additional hardware that needs to be physically fitted in the factory.

Another example concerns their use of relatively inexpensive lightweight and fast erection cranes. These are well suited to tight sites and have sufficient carrying ability for the lightweight nature of prefabricated timber panels (as applied in low to mid rise buildings). There are also specialist tools to assist on-site processes such as the use a very light telescopic prop adjusters with release triggers that allow fast and simple propping and bracing during on-site installation processes.

Figure. 18. Leibherr 32H lightweight, fast erection crane (source: https://www.liebherr.com/en/deu/products/construction-machines/tower-cranes/fast-erecting-cranes/h-cranes/details/71141.html)

5 Discussion about a Design for Manufacture and Assembly Approach (DFMA)

Given the previous discussion, it is thought that a progressive way forward for prefabricated timber construction is to think of it in terms of a "design for manufacturing and assembly" approach. Boothroyd *et al.*[10] were pioneers in this area and applied the DFMA approach in three main activity areas including:

- in concurrent engineering to help the design teams simplify the product structure to reduce costs in manufacturing and assembly
- as a benchmarking tool against competing products
- as a cost estimating tool to control costs and negotiate supply contracts

The development of DFMA started with a systematic method to quantify designs for the ease of automated assembly. Basic principles include reducing the number of assembly operations by reducing the number of parts; and making the assembly operations easier to perform. Of note, reducing the number of separate component parts also reduces the cost of assembly as well as reducing the cost of the parts.

Logically, this holds true for timber construction components as well. For instance, parametric design can work towards standardised assemblies to promote simplicity and economies of scale. Conditional application of this should also consider the benefits of digital fabrication whereby additive layering – as seen in the ETH Arch Tech Lab roof – still potentially allows the achievement of complex shapes using a relatively standardised kit of parts.

Whilst the DFMA provides a reasoned approach for introducing automation in factory based assembly, the context for prefabricated construction must also consider onsite assembly and competitive benchmarking against traditional methods of construction, as this represents the lowest common denominator in terms of benchmarking production costs.

Boothroyd *et al*[10] argue in favour of spending more time making slightly more complex parts in order to simplify assembly processes, and it would seem this is also a good idea for the eventual installation of prefabricated assemblies onsite. Even so, adopting such an approach requires a different mindset in the construction supply chain. Here, construction contractors are used to setting up the site for labour intensive construction on-site whilst prefabrication requires rethinking this whereby site setup is kept to an absolute minimum.

Consequently, the transfer process must aim to supplant on-site labour and temporary site establishment costs, with offsite production. Clearly, different combinations concerning the tidemark between offsite production and onsite construction must be considered to work out the best approach.

[10] Boothroyd, G. Dewhurst, P, Knight, W (2010) Product Design for Manufacture and Assembly, CRC Press, Third Edition

6 Conclusions and recommendations

Timber construction is well placed in terms of becoming the primary material suited to prefabricated construction and this can offer better value than traditional site-based construction methods. Indeed, it's future in moving towards large-scale buildings (beyond detached housing) is intimately linked to being a leader in prefabrication. To a large extent, this is a function of the inherent ability of timber to be easily machined as driven by digital fabrication and quickly progressing levels of automation. The key opportunity is in making current interest in BIM go beyond a simple means for designers to work more efficiently and collaboratively together, and to make it a meaningful way of transitioning design information into digital fabrication and then leveraging this further in transitioning to more efficient onsite installation. This creates the perfect scenario for better flow from design to production to construction onsite.

This high degree of work flow and efficiency is still developing in Australia but there are clear signs of rapid advancement, and to some extent, this has been assisted by the adoption of primarily European technologies. Further, recent projects in Canada provide examples that have direct and obvious similarities to the Australian market and champion the advancement of timber construction and the process applied to it.

If there is a single message coming out of the study, it is simply that the system must change towards "construction as production" built around “the rise of timber and its coupling with the rise of the machine” as the main vehicle for assisting delivering. The previously discussed “design for manufacture and assembly” can be coupled with this approach. The supply chain, in particular, must be developed further in providing a vertically integrated process, and this is the case because timber supply chains are not as well developed (for larger buildings) as traditional construction systems such as in-situ concrete construction. Participants in the supply chain must work more collaboratively to provide a degree of integration that provides value for money in competitive terms. There is potential for digital technology to be an underpinning thread from one link in the supply chain to the next. The same vehicle, can clearly be the main feeder for driving machine logic and production processes and can then go on to provide the appropriate information to site personnel, to make their life easier and more efficient in erecting buildings.