Sustainable
Built Environment
National Research Centre

USING BUILDING INFORMATION MODELLING (BIM) FOR SMARTER AND SAFER SCAFFOLDING CONSTRUCTION

The aim of this research is to develop BIM-based tools that integrate construction and safety constraints directly into the design, analysis, assembly, inspection and disassembly of scaffolding.

SBEnrc Project 3.27

Built Environment
National Research Centre

Acknowledgement

This research has been developed with funding and support provided by Australia's Sustainable Built Environment National Research Centre (SBEnrc) and its partners.

Core Members of SBEnrc include Aurecon, John Holland, NSW Roads and Maritime Services, Queensland Government, Government of Western Australia, Curtin University, Queensland University of Technology and Swinburne University of Technology.

Core Members

aurecon

John Holland

NSW Government Transport Roads & Maritime Services

Queensland Government

GOVERNMENT OF WESTERN AUSTRALIA

Curtin University

QUT Queensland University of Technology

SWINBURNE

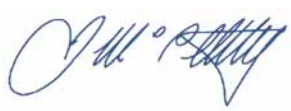
Project Affiliates

construc CONSTRUCTION CONSULTING ENGINEERS

Preface

The Sustainable Built Environment National Research Centre and its predecessor, the Cooperative Research Centre for Construction Innovation, has been committed to leading the Australian property, design, construction and facility management industry in collaboration and innovation. We have been dedicated to disseminating practical research outcomes to our industry — to improve business practice and enhance the competitiveness of our industry. Developing applied technology and management solutions, and delivering relevant industry information is what our Centre is all about.

We look forward to your converting the results of this applied research project into tangible outcomes and working together in leading the transformation of our industry to a new era of enhanced business practices, safety and innovation.



John V McCarthy AO

Chair

Sustainable Built Environment National Research Centre

Dr Keith Hampson

CEO

Sustainable Built Environment National Research Centre

Executive Summary

Temporary structures like scaffolding have a significant impact on the quality, safety and profitability of construction projects. Given that Workplace Health and Safety (WHS) Authorities in Australia have found that 40% of all scaffolding projects do not comply with national safety and design standards, this impact can often be negative. The purpose of this research is to deliver tools and knowledge that reduce the likelihood of onsite accidents resulting from non-compliant structures, and streamline scaffolding design and construction processes to improve productivity.

This research will facilitate the design and construction of smarter and safer scaffolding through the use of rule-based modelling systems that link with existing Building Information Modelling (BIM) software and technology. It will develop digital modelling tools and processes that integrate construction and safety constraints directly into the design, analysis, assembly, inspection and disassembly of these temporary structures. Building on a QUT funded pilot study, this project will identify opportunities for improved safety practices and more efficient design and construction processes, both in Australia and Korea, and seek to extend the results to other parts of Australasia.

Deliverables include: (i) a comprehensive understanding of practices related to the design and construction of temporary scaffolding structures; (ii) digital modelling tools and processes that aid scaffolding design and construction to improve the safety, productivity and profitability of construction projects and prototype 3D modelling tool; (iii) education and training requirements to facilitate the uptake of these digital modelling technologies and thus reduce workplace accidents while maximising social and business benefits for construction workers and organisations.

Presently, direct outputs of the prototype include 3D scaffolding models and quantity take-offs for any extruded building form with an orthogonal footprint, and to a limited degree, simple forms extruded from a curved footprint; 2D documentation is also easily derived from the 3D model. As well as these deliverables, the prototype captures practical knowledge related to scaffolding construction and safety by encoding information dependencies that govern its structural configuration. The 3D modelling prototype provides decision-support by presenting user choices as explicitly-defined input parameters that allow the design intent and assumptions behind a particular scaffolding solution to be communicated amongst different project stakeholders, establishing a shared understanding of project-specific requirements and constraints. These parameters can be manipulated to generate different design options rapidly for evaluation without the need for any manual remodelling, which helps to avoid any loss of data or duplication in its handling. Combined, the functionality of the prototype demonstrates how digital modelling tools and processes can facilitate smarter and safer scaffolding practices that maximise social and business benefits for construction workers and organisations by improving integration across various aspects of project delivery.

1.0 Introduction

A considerable number of accidents that occur on construction sites in Australia can be attributed to temporary structures which are non-compliant and unsafe. According to Safe Work Australia (2010), there were a total of 445 serious scaffolding-related workers' compensation claims issued in the Australian construction industry in 2008-09. This represents a 330% increase from the 135 claims made in 2000-01. In response to this increase, Workplace Health and Safety Authorities conducted a campaign that focused on industry compliance with applicable standards and codes. In 2009-10, Heads of Workplace Safety Authorities in Australia assessed 1,264 scaffolding sites nationwide for compliance and found that 40% did not adhere to the legislated scaffolding standards (AS/NZS 1576) and/or jurisdictional regulations (HWSA 2010) . Such non-compliance is a contributing factor to productivity stagnation in the construction industry, with statistics revealing a productivity growth rate less than half that of the remaining non-farm market sector over the last two decades (Independent Economics 2012; Australian Bureau of Statistics 2008). These statistics, along with those concerning workplace accidents, indicate a need for scaffolding design and evaluation tools and processes that are informed more directly by safety and construction considerations. This is critical to mitigate safety risks onsite and improve productivity.

There is significant opportunity to improve construction safety for temporary works via Building Information Modelling (BIM). Recent research has revealed BIM to have benefits for safety practices, planning and management, through the application of clash detection to construction sequencing, and risk analysis to site planning. Links to structural analysis also serve both as a design aid and to support onsite compliance checking. Yet despite such advances, more work is still needed to develop tools and knowledge that help to reduce the likelihood of accidents arising from non-compliant scaffolding structures. BIM objects that have been developed previously to represent scaffolding structures cannot be readily combined with other BIM components and models while actively addressing practical safety and construction considerations. Furthermore, BIM-based applications for temporary works are typically standalone and targeted at one specific phase or task in the overall process lifecycle.

Given that BIM representations encapsulate information concerning non-geometric attributes as well as building geometry, this project aims to build on existing research to aid compliance with construction and safety regulations from early design onwards. It proposes a more holistic approach to BIM-based support for these temporary structures through the development of a series of modular and interconnected tools that link flexibly with each other and existing design and construction practices.

1.1 Project aim

The purpose of this research is to establish how construction and safety constraints might directly inform the design and evaluation of scaffolding structures. The output from the pilot study is a prototype rule-based modelling system for scaffolding design that supports the integration of safety and construction constraints early on in the design process. This project looks to expand on the pilot study by providing further support for tasks that arise later in the process lifecycle, through the provision of: (i) automated model and drawing outputs; (ii) quantity takeoffs for competitive tendering; (iii) visualisations for 4D scheduling and onsite assembly, inspection and disassembly; (iv) direct links to structural analysis for performance compliance; (v) onsite safety checks and real-time tracking of construction works. The ability of the proposed digital modelling applications to aid in these activities will rely not only on the technologies that they employ, but also on how accurately they capture the tacit practical knowledge possessed by contractors who have extensive onsite experience in working with these structures.

1.2 Definitions

Scaffold

A temporary structure specifically erected to support access platforms or working platforms, used for the purpose of conducting work activities.

Scaffolding

Refers to the plant components and materials that, when assembled, form a scaffold.

Scaffolding work

Scaffolding work means erecting, altering or dismantling a temporary structure erected to support a platform and from which a person or object could fall more than 4 metres from the platform or the structure.

The Occupational Health & Safety Act of Australia requires that any person who acts as a scaffolder must have been properly trained in the erection and dismantling processes of the type of scaffolding being used. It is also important that building industry workers, especially scaffolders and riggers, are able to work safely at heights.

Building Information Modelling

Building Information Modelling (BIM) is a data-rich, object-oriented, intelligent and parametric digital representation of the facility. A building information model concludes the geometry, spatial relationships, geographic information, quantities and properties of building elements, cost estimates, material inventories and project schedule. For this characterises, BIM is a demonstration of the entire construction lifecycle that allow to redefine the work scope, generate high quality three-dimensional (3D) design schemes, support four-dimensional (4D) scheduling and five-dimensional (5D) cost estimation, and optimise facility management and maintenance.

2.0 Risk Management/Assessment Process

Codes of Practice (How to Manage work health and safety risks - safe work Australia) provide step-by-step guidance on how to manage the risks associated with scaffolding, through the use of existing BIM software and technology that link with safety rules, there is a two phases' risk management/assessment following a systematic process which involves:

Phase 1: Hazard profile

Step 1

Identify hazards - find out what could cause harm

Step 2

Identify factors that may be contributing to the risk

Step 3

Review the health and safety related rules in codes of practice of Australia Occupational Safety and Health, which is relevant to the particular hazard;

Phase 2: Work method statement - BIM

Step 4

Identify the BIM actions necessary to eliminate or control the risk; and

Step 5

Identify the records, which are necessary to keep to ensure that risks are eliminated or controlled.

2.1 Main hazards in scaffolding

Hazards that have the potential to cause injury or illness are commonly associated with work involving the erection, use, maintenance, alteration and dismantling of scaffolds:

- Falls from heights
- Falling objects
- Work near overhead electric lines
- Mobile plant and traffic
- Mixing and matching scaffold components
- Scaffold collapse
- Manual tasks

2.2 Factors that may be contributing to the risk

After the hazards are assessed, hazard management should address the factors that may be contributing to the risk:

- Climbing and working at heights
- Working close to openings
- Proximity to power lines
- Possibility of scaffolders falling or dropping equipment
- Movement of vehicles, cranes, forklifts etc.;
- Scaffold components from different suppliers
- Scaffold collapse by incorrect erection/dismantle procedure.

2.3 Safety rules for scaffolding

Principle rules for the use of scaffolding, a scaffold must be:

- SAFE by design, type and construction.
- SAFE for access purposes.
- SAFE so that no persons or objects can fall or blow from it.
- SAFE so that any person can pass under or near it without being injured.
- SAFE from damage by vehicles, vessels, cranes or hoists.
- SAFE in its position from electrical wires, gases, explosives, chemicals, heat, nearby buildings or structures
- SAFE from collapse.

Particular rules for the risks-rule-based safety check:

Review the health and safety related rules developed by Safe Work Australia, which is relevant to the particular hazard.

2.3.1 Climbing and working at heights

Where it is necessary to climb and/or work at heights, the AS-NZS-4576-1995-guidelines for scaffolding basically states that where there is any possibility that anyone or objects could fall 2 metres or more, edge protection should be provided to the open sides and ends of platform:

Guardrail: at 900 mm to 1000 mm above the platform, set not more than 100 mm outside the edge of the platform.

Midrail: should be positioned approximately midway between the guardrail and the toeboard, the vertical gap between adjacent horizontal edge protection components shall not exceed 500mm, set not more than 100 mm outside the edge of the platform.

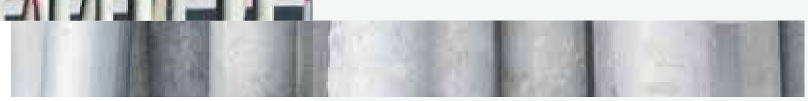
Toeboards: a height not less than 150 mm above the platform surface, the vertical and horizontal gap between the platform and the toeboard should not exceed 10 mm.

Where there is not a guardrail or a midrail provided adjacent to working face of building or a structure, the face should:

Be less than 225 mm from the platform edge.

Extend at least 900 mm above the top surface of the platform.

These regulations are to be adopted as minimum requirements.



2.3.2 Working close to openings

2.3.2.1 Openings in edge protection at points of access to stairways or ladders shall be adequately protected with self-closing gates.

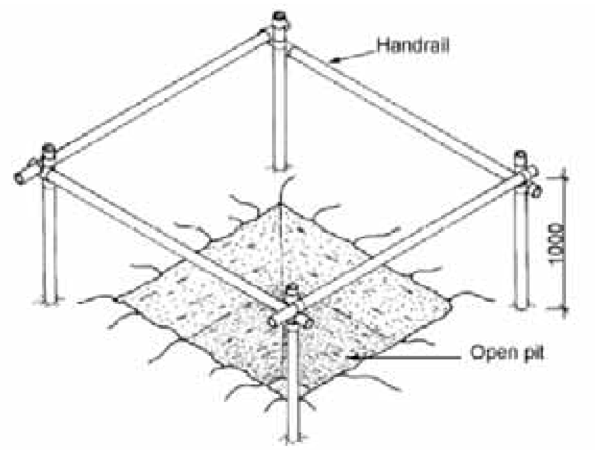


Figure 2.3.2.1: Opening in edge protection (picture from TAFE NSW Construction & Transport Division limited height scaffold report)

2.3.2.2 The internal gap: between the inner edge of the length of the platform and the face of the building or structure immediately beside the platform—on scaffolds, including hanging bracket scaffolds is greater than 225 mm, the edge protection or extra scaffold planks should be taken.

(a) The resultant gap between the face and the platform edge or adjacent horizontal member of the scaffold does not exceed 225 mm where the face is a working face; or100 mm where the face is not a working face.

(b) The floor has its upper surface not greater than 300 mm vertically below the surface of the platform [see Figure 1] or the soffit of the floor or dropdown beam is not greater than 300 mm vertically above the surface of the platform[see Figure 2].

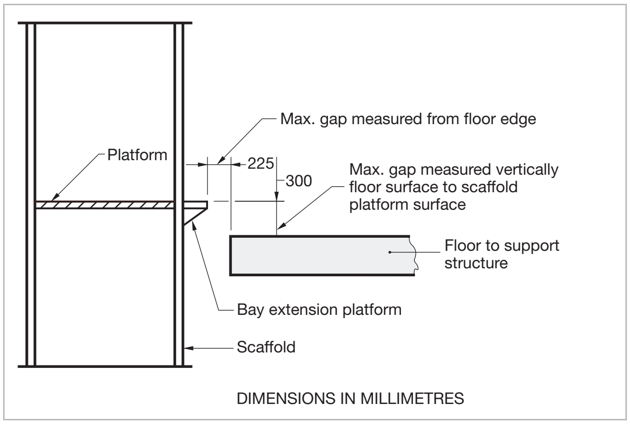


Figure 2.3.2.2: Internal gap a (picture from AS NZS 1576.1-2010 Scaffolding - General requirements)

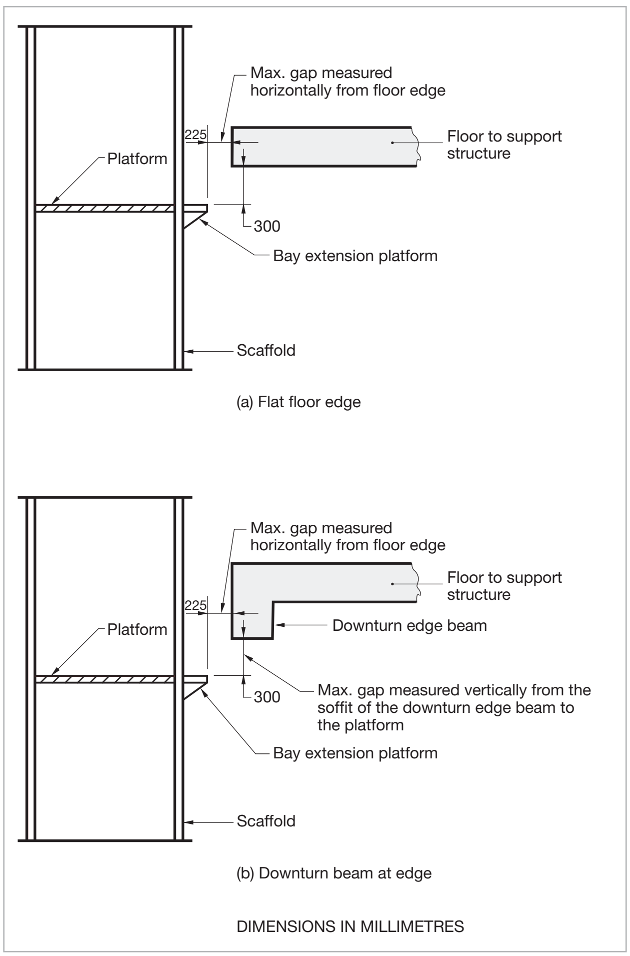


Figure 2.3.2.3: Internal gap b (picture from AS NZS 1576.1-2010 Scaffolding - General requirements)

2.3.3 Proximity to power lines

Where the scaffold stands in close proximity to power lines, the clearance between scaffolds and any transmission line, main apparatus or transmission apparatus should be not less than 4 m laterally and 5 m vertically where any metal member is used.

- Advice should be sought from the local electricity supply authority for any reduction to the above clearances.
- Do not erect scaffolding until the necessary measures have been taken to minimise risk and a written authorisation has been received from the electricity supply authority.
- High voltage mains (i.e. more than 600 V) near scaffolding should be de-energised, short-circuited and earthed, or re-routed prior to erection of the scaffolding. Low voltage mains (i.e. not more than 250 V) and medium voltage mains (i.e. in the range of 250 V to 600 V) should be de-energised, short-circuited and earthed, or re-routed where practicable.
- Low and medium voltage mains that cannot be de-energised should be insulated by the supply authority for the full length of the scaffolding plus a minimum distance beyond each end of the scaffolding of 5.0 m.

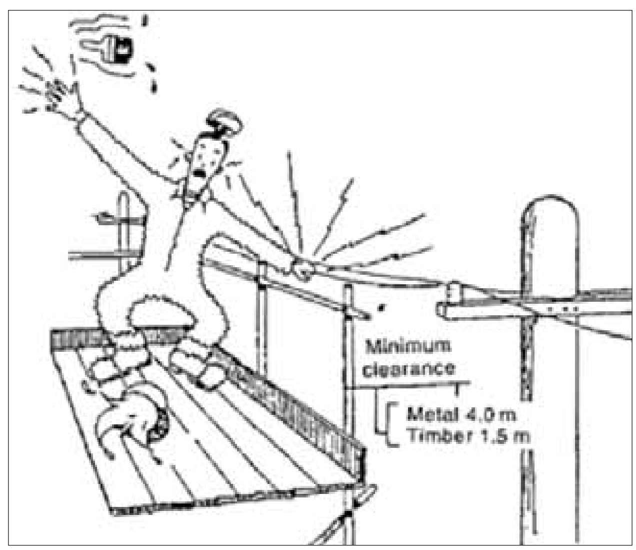


Figure 2.3.3.1: Clearances between scaffolds and any transmission line (picture from AS NZS 4576-1995 Guidelines for scaffolding)

2.3.4 Possibility of falling objects

Personal protective equipment must be used.

Safety helmets

Safety helmets complying with AS1801 should be worn, wherever there is a risk of objects falling from above and on any work site where a hard hat sign is displayed.

Safety belts

Safety belts should be used to safely carry essential scaffold tools for general scaffolding work.

Safety footwear

Footwear should be comfortable, provide maximum grip and give protection from pinching, jamming and crushing. A range of lightweight flexible footwear with steel or plastic protective caps is available.

Eye protection respirators

Safety glasses or goggles should be worn when driving steel pins or wedges on the scaffold to protect the eyes from small pieces of metal, which may fly off and cause serious eye injury.

Gloves

Gloves should be close fitting and non-slip.

Safety harness

Safety harnesses may be used to provide protection against a fatal or serious fall when a scaffolder is required to work over a void, or lean out from the scaffold or supporting structure without the protection of a guardrail.

2.3.5 Movement of vehicles, cranes, forklifts etc.

If the scaffold is to be built in an area that is used by vehicles and other mobile plant, the following precautions are recommended to prevent or minimise exposure from the hazards of mobile plant and traffic:

- Re-route the traffic away from the location of the scaffold,
- Provide physical barriers, guards and signs to prevent contact with the scaffold,
- Assign a person to direct the traffic.
- Ensure scaffolding does not have any unnecessary protrusions, such as over-length transoms, putlogs, tie tubes or over-height standards.

2.3.6 Scaffold components from different suppliers

Components from different manufacturers or suppliers, while looking compatible, are often of different dimensions and tolerances.

The following controls can be used to prevent or minimise the risk of injury and scaffold collapse due to the incorrect mixing of components:

- Do not mix scaffolding components from different manufacturers, unless a competent person, for example an engineer approves that the:
  - Components are of compatible size and strength
  - Components have compatible deflection characteristics
  - Fixing devices are compatible
  - Mixing does not lessen the strength, stability, rigidity or suitability of the scaffold.
- Do not mix scaffolding couplers and tubing of different outer diameters and strengths unless designed specifically for the task by a competent person or the coupler manufacturer has designed the couplers for this purpose. For example, do not mix aluminium and steel components as steel clamps may cause aluminium tubing to be crushed, reducing the strength of the tube.
- 'Beam clamps' or 'flange clamps' should be provided with information about safe use, including tightening torque required and when to use different types of couplers. If no information is provided contact the supplier, manufacturer or designer of the scaffold.
- Stairs should be secured to the scaffold bay. If not secured, the supplier should provide documentation illustrating the maximum amount of clearance allowed between the transom and the top and bottom of the stair module.
- Ensure the gap between the end of a stair module and a transom is as small as practicable. Large gaps can lead to stairs dislodging and falling when a load is placed onto it.

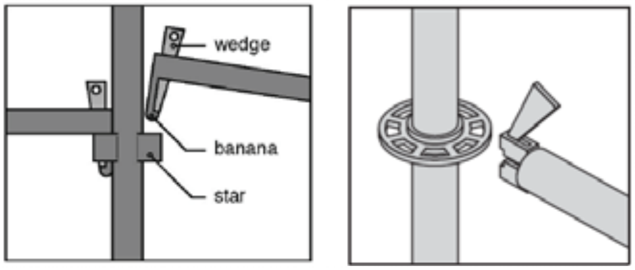


Figure 2.3.6.1: Scaffold components erection (picture from DRAFT-safe work Australia-scaffolding work COP)

2.3.7 Scaffold erection/dismantle procedure

Modular scaffold is a scaffold assembled from prefabricated individual components, braces and accessories. Modular System which is the most commonly scaffold used in Australia. Due to the systems flexibility, strength, being easy to install and dismantle.

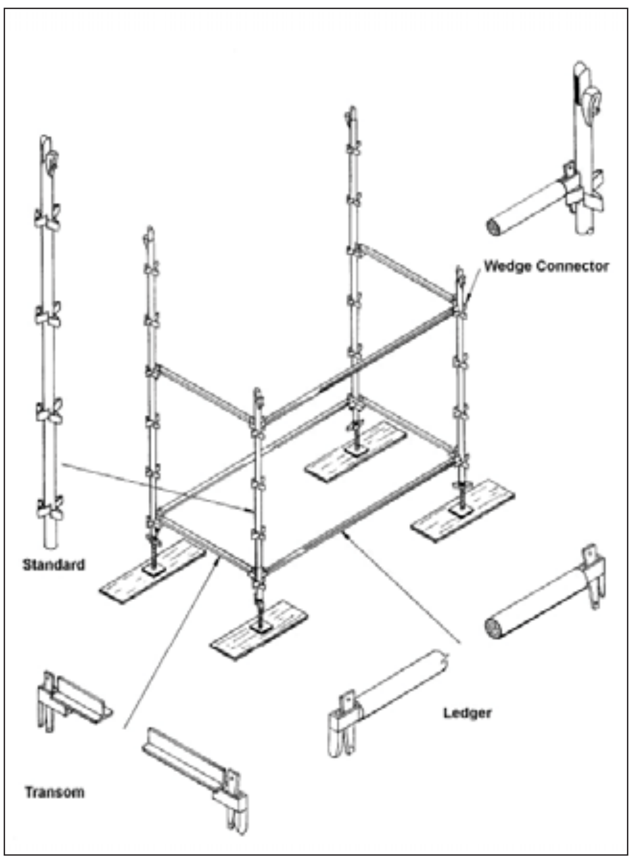


Figure 2.3.7.1: Modular scaffold components (picture from TAFE NSW Construction & Transport Division limited height scaffold report)
Typical modular components: standard, transom, ledger and wedge connector

Erection procedure for modular scaffold

a. Level the ground and/or clear the area on which the scaffold is to be erected of any debris.

b. Determine the point at which to start building the scaffold (placement of the first standard).

This will normally be at the high point of any slope.

c. Establish how far from the building or structure the inside standards have to be placed. Note – the maximum allowable gap between the building or structure and the edge of the working platform is 200mm however, we recommend a gap of 100mm. Look up to ensure that there are no obstructions and that the scaffold will not encroach on an electrical "No Go Zone".

d. Place a sole board on the ground ensuring that it bears evenly along its full length.

e. Place an adjustable base jack (jack) on the sole board.

f. Place a 2000 standard (vertical member) on the jack. This is the "1st Standard". (An "inside" standard)

g. While one person holds the first standard upright a second member of the crew lays a transom (platform support) at 90 degrees to the building from the base of the first standard.

h. The second person then places a jack and a 3000 standard on the sole board. This is the"2nd Standard".

i. While one person holds the two standards erect (one standard in each hand) the second person places the transom into the "v" pressing (connection point) on the inside of each standard to create an "H" type arrangement.

j. The second person then places a ledger (horizontal spacing member) into the "v" pressings of each standard at 90 degrees to the transom.

k. Using a suitable hammer the second person can now, firmly but without excessive force, knock the wedges on the ledgers and transoms into the "v" pressings of the first two standards.

l. You now have an "L" shaped configuration that, once the wedges have been knocked in, will support itself if laid over onto the ends of the ledgers.

Repeat steps d) to i) above to create a second "H" type arrangement. The inside standard is 2000 (the 3rd standard); the outside standard is 3000 (the 4th standard).

m. Whilst one person holds the standards plumb the second person carefully raises the ends of each ledger and locates them in the appropriate "v" pressing on the second set of standards ("H" type arrangement). It should be noted that this procedure is much easier and therefore safer using a third person in the crew.

n. Knock the wedges of the ledgers firmly into the "v" pressings on the standards.

o. Place a spirit level on the first transom and wind the second jack up or down until the transom is level.

p. Place the spirit level on the inside ledger and wind the third jack up or down until it is level.

q. Place the spirit level on the second transom and wind the fourth jack up or down until it is level.

r. You have now erected one "bay" of scaffold – (the rectangular area between 4 adjacent standards).

s. Make sure the "bay" is parallel to the building and is "square" – adjust as required.

t. Place a second transom between the 1st and 2nd and the 3rd and 4th standards 1.5metres above the lower set of transoms.

u. Place a second ledger between the 1st and 3rd standards and the 2nd and 4th standards 1.5 metres apart, i.e. at the same level as the upper and second set of transoms.

v. You have now erected the first "lift" of scaffold – a lift is the area between 2 vertically adjacent rows of transoms and ledgers. The effective top working platform is 2 metres above the supporting surface.

w. Place a diagonal cross (End) brace between and on the outer side of the 1st and 2nd standards.

x. Place a diagonal (Face) brace between and on the outer side of the 2nd and 4th standards.

y. The working platform is created by placing a platform on and between the second set of transoms. A double handrail (guardrail) should be fixed to the standards on any side of the working platform from which a person could fall. A toe board (kick board) must be fitted immediately underneath all handrails using toe clip boards or some other suitable means of fixing. .

Repeat steps d) to y) as required to base out the complete area to be scaffolded.

2.3.8 Working platform

Clear and unobstructed access should be not less than 450 mm wide, where passage is required by persons and hand tools only.

Working platforms should not be pitched at an angle steeper than 7º (slop of 1 to 8) to the horizontal and should have a slip-resistant surface.

The allowable load capacities on scaffolding are determined largely by the spacing of the standards.

Duty classification as specified in AS/NZS 1576.1	Approx. maximum total load for persons and materials in kilograms per platform per bay	Approx. maximum mass of any single concentrated load of materials or equipment	Minimum length & width of platform in millimetres
Light Duty	225	100	450
Medium Duty	450	150	900
Heavy Duty	675	200	1000

Table 2.3.8.1: Based on AS/NZS 4576-1995

2.3.9 Ladder access

Rules for ladder access systems include:

- Pitch ladders at a horizontal to vertical slope of not less than 1:4 nor more than 1:6.
- Secure ladders against displacement in any direction.
- Unless the base is at ground level or on a fully-covered supporting structure, provide ladder landings at the head and at the base of each ladder.
- Make sure the ladder extends at least 900 mm above the landing
- Make sure the height between successive ladder landings is never more than 6 m.
- Keep openings for ladders as small as practicable and provide trapdoors over guarding around any openings that may be in or directly beside a working platform.
- Offset the base of a ladder from the head of any ladder that may be directly below it, so that the ladders cannot take the form of a single continuous ladder.
- Make sure there is adequate access to and egress from ladders at each surfaces.

2.3.10 Scaffold collapse

Foundations

Scaffold foundations should be designed and constructed to carry and distribute all the weight of the scaffold including dead and live loads, for example perimeter containment screens, placed on the scaffold.

Ground conditions, the effects of the weather—particularly wind and rain—and loadings should be considered when designing the scaffold foundation.

Ground conditions

The principal contractor for a construction project and scaffolding contractor should ensure ground conditions are stable and inform scaffolders of factors which may affect ground stability before the scaffold is erected.

When a scaffold is erected on a surface it is important the surface is sufficiently stable to bear the most adverse combination of dead, live and environmental loads that can reasonably be expected during the period that the scaffold is in use.

Water and nearby excavations may lead to soil subsidence and the collapse of a scaffold. Any likely watercourse, for example a recently filled trench, which has the potential to create a wash out under the scaffold base, should be diverted away from the scaffold.

Loading

A scaffold should be designed for the most adverse combination of dead, live and environmental loads that can reasonably be expected during the period that the scaffold is in use.

The specifications of the designer, manufacturer or supplier should be followed for the maximum loads of the scaffold. The dead, live and environmental loads should be calculated during the design stage to ensure the supporting structure and the lower standards are capable of supporting the loads.

Consider environmental loads, particularly the effects of wind and rain on the scaffold. For example, environmental loads imposed by wind and rain may be heightened if perimeter containment screens, shade cloth or signs are attached to the scaffold. Staggering the joints in standards may help control the risk of scaffold collapse from environmental loads.

Dead loads relate to the self-weight of the scaffold structure and components including working, catch or access platforms, stairways, ladders, screens, sheeting, platform brackets, suspension ropes, secondary ropes, traversing ropes, tie assemblies, scaffolding hoists or electrical cables.

Live loads include:

- The weight of people
- The weight of materials and debris
- The weight of tools and equipment
- Impact forces.

Scaffolds should not be used to support formwork and plant, for example hoist towers and concrete pumping equipment, unless the scaffold is specifically designed for this purpose.

Supporting structures

Consider the capability of the supporting structure to bear the most adverse combination of loads possible when using the scaffold. Obtain advice from a competent person before erecting scaffolds on verandas, suspended flooring systems, compacted soil, parapets and awnings.

Propping may be required where the supporting structure is not capable of bearing the most adverse combination of loads.

Soleboards and baseplates

Soleboards and baseplates can be used to evenly distribute the load from the scaffold to the supporting surface. Both soleboards and baseplates may be required for use on less stable surfaces, for example soil, gravel, fill or other product which creates a system of beams and flat slabs.

The size of the soleboard will vary depending on the supporting surface. Where necessary a competent person should determine the bearing capacity of the ground or other supporting structure.

Soleboards should be level and some digging may be required to obtain a level surface.

Adjustable bases can be used on uneven surfaces for modular scaffold systems. No part of the baseplate or adjustable base should protrude over the side of the soleboard to ensure the loads are imposed evenly on the soleboard.

Needles and spurs should be considered where ground conditions are very unstable.

Stability

Scaffold stability may be achieved by:

- tying the scaffold to a supporting structure
- guying to a supporting structure
- increasing the dead load by securely attaching counterweights near the base
- adding bays to increase the base dimension.

2.4 Actions to eliminate or control risks

A demonstration has been undertaken to illustrate how current industry practices can be translated into design rules that facilitate automated generation and checking of scaffolding layouts for smarter and safer construction process. This demonstration is based on the specification for modular scaffolding, as it has a significant presence in the Australian market; however, it is easily adapted to suit other system as well.

2.4.1 Building Information Modelling

BIM can provide a powerful new platform for developing and implementing "prevention through design" concepts that can facilitate both engineering and administrative safety planning and control tasks at the design and construction stage of a project. Information modelling-enabled virtual safety controls can be used to detect potential safety hazards ("clashes").

3D visualisation and 4D simulations increase the ease and level of understanding of construction processes. These features are inherently embedded in BIM and thus can enable more effective safety planning before and during construction. Such technology can enhance safety through automated hazard identification early in the process, and propose inexpensive and easier ways to solve safety clashes. Utilisation of BIM technology thus can bring safety more closely to the construction planning phase.

2.4.2 Rule-based system

Rule-based hazards identification have been used in conjunction with existing three-dimensional (3D) design and schedule information to formulate an automated safety rule checking system to detect hazards automatically, visualise their location in a virtual 3D space, and provide solution and visuals of protective systems to mitigate the identified hazards.

Rule-based design for scaffolding

Scaffolding lends itself to rule-based design as it is a modular structural system, seen in Figure 2.4.2.1, which is assembled from a finite kit of components according to clear patterns of composition or 'rules'. The use of rule-based logics for the generation and evaluation of systems possessing these traits is already well-established within AEC research and development. Highlighting the relevance of this approach for scaffolding design in particular are commercial applications that automate comparable tasks of building layout. Examples include software developed by Robertson Ceco Corporation (RCC) that automates the design of pre-engineered metal buildings, and the Bluethink House Designer , an application from Selvaag Buethink that generates detailed drawings from residential design sketches in accordance with user- and application-defined constraints . A review of scaffolding practices has revealed that like these cases in point, rule-based logics are the principal means by which design constraints are deemed-to-satisfy. Structures are set out according to patterns of assembly derived from legislated standards and manufacturers' specifications, and under typical circumstances do not require verification by way of performance analysis or simulation, as structural behaviour is tried and tested. These assembly requirements govern the modular composition of the basic structure, which in turn governs the installation of features ensuring the safety of the scaffolding, such as bracing, ties and handrails. However, as RCC have established in their work, the rule-sets needed for successful design automation are not derived from standards and specifications alone. To match and marry with industry practices, rules emulating the expertise that practised contractors apply to design tasks are also required. The ability for a rule-based design system to automate scaffolding layout thus relies not only on the technology that it employs, but also on how accurately it captures the tacit practical knowledge possessed by contractors who have extensive onsite experience in working with these structures.

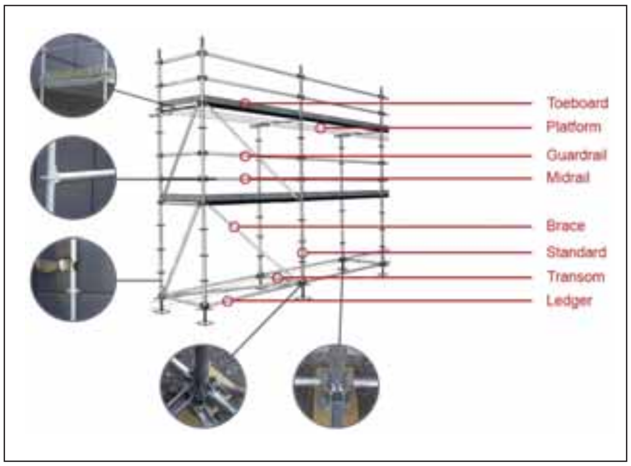


Figure 2.4.2.1: Basic scaffolding structure, adapted from http://www.roundscaffolding.com.au/image-gallery

2.4.3 Streamlining design and construction processes

While there is potential productivity gains associated with the automation of layout tasks, due to reduced design times, these become void if users cannot manually modify the resulting assembly to accommodate unique conditions for which the rules were not foreseen. It is therefore critical that users be allowed to manipulate individual scaffolding components directly, rather than relegating their interaction with the model to indirect controls afforded by the design rules. For this to occur, it is necessary to support not only the rule-based generation of scaffolding designs as demonstrated, but also the iterative evaluation of these designs against the same rules subsequent to any manual adjustments. This three-part design process, illustrated in Figure 9, highlights the hierarchical distinction between object- and system-level controls, a difference that is critical to the manner in which this process is implemented in BIM software and what constitutes a BIM object.

Since contractors onsite engage with the scaffolding structure one component at a time, it follows suit that BIM objects correspond to individual components, and not partial assemblies. A single object is sufficient to describe all variations of each given type of component, through the provision of length or sizing parameters linked to manufacturers' specifications that offer users a list of options from which to select. As well as the relevant geometry, these objects would also include other non-geometric information such as:

- material properties;
- object weights;
- load capacities and tolerances;
- permissible connections;
- manufacturers' product codes;
- transport and storage information; and
- Object age.

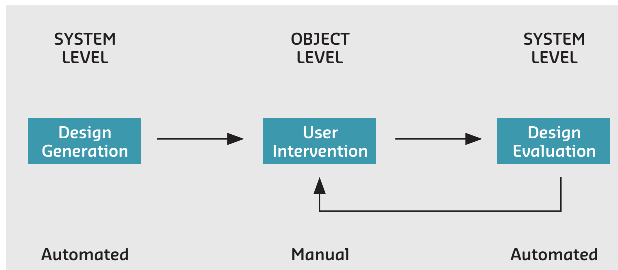


Figure 2.4.3.1: Three-part design process

Defining rules for design automation as constraints within these BIM objects, however, poses inherent problems as these rules apply to the relationships between components rather than the components themselves. Since these rules function to maintain the integrity of the structure as a whole, they are difficult to reconcile within an object definition that is based on an individual scaffolding component. While this issue could perhaps be resolved if instead BIM objects were defined in terms of the entire assembly or identifiable subassemblies, such objects would simultaneously generate even larger problems by compromising support for manual adjustment of the scaffolding design. As this is non-negotiable prerequisite in the eyes of the contractors, rules must instead be maintained in separate automation routines that users can invoke when necessary to generate and evaluate scaffolding models comprised of component-based BIM objects.

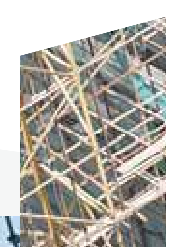
2.4.4 Onsite safety and construction

To link with onsite safety and construction processes, it is critical that the overall system is simple and intuitive to operate, so that users who do not possess a detailed knowledge of BIM can still take advantage of the benefits that it offers. Above all else, quick, easy and flexible visualisation of scaffolding models is needed to assist contractors with the assembly and disassembly of these structures. Solibri Model Viewer is a lightweight application that supports the required model visualisation and querying, and as a short-term solution offers the advantage of a built-in connection to Solibri Model Checker that allows users to view and comment directly on any unresolved design issues detected by its counterpart. The model information that it supplies is more comprehensive and less ambiguous than traditional 2D documentation, and can be easily accessed via a tablet or laptop onsite to help contractors minimise discrepancies between the scaffolding construction and design. However, without model-editing functionality or a published API (Application Programming Interface), Solibri Model Viewer offers only limited options for documenting design changes or communicating them back to other members of the project team. Furthermore, it restricts the information that can be described to what is specified in the IFC schema, which currently does not define objects for temporary works such as scaffolding.

To overcome these challenges in the future, a better solution is needed. The more flexible alternative would be to develop an open, standalone version of the plugin proposed for Revit, which incorporates functionality for model viewing, querying and editing, and can be extended as required to ensure automated propagation of design updates to all project models. For example, by creating a simple interface that enables controlled manipulation of the scaffolding model via the same input parameters that were originally used to generate it, this lightweight application could support the rapid testing of change options during construction in response to unforeseen site constraints, work variations and equipment shortages. Follow-on impacts for project scheduling and cost could then be evaluated by pushing these changes out to 5D analysis software like Navisworks, as well as any other applications needed to confirm project outcomes, so that designs could be amended on the fly with minimal risk. Once a decision had been made, modifications would then be committed to the project's model repository, notifying other stakeholders in the process so that any coordination errors could be resolved quickly.

This added flexibility becomes critical when considering potential links between the construction management process and safety-checking procedures onsite, since this entails the integration of different types of information structured in vastly dissimilar ways. The issue is no longer simply one of modelling standards, but how to combine these standards with unstructured positional data, and how best to determine the position of constructed elements to support this in the first place. Recent research into construction monitoring has focused around two main methods for automating onsite checks – RFID (Radio Frequency Identification) and 3D laser scanning. RFID tracking is typically used to identify objects within a certain proximity to a checkpoint or receiver, and a means of location better suited to monitoring construction progress than determining object shapes and positions within a structure. Scaffolding also presents a number of challenges for the application of RFID, including the cost of long-range metal-mount tags able to withstand harsh conditions; signal interference with long-range tags; and tag collisions from overlapping signals in the same RF field resulting in incorrect readings. Laser scanning, on the other hand, does not have comparable practical difficulties associated with data acquisition, and is better able to capture 3D information about object shape and position. Information is collected by measuring the distance from the scanner to a visible surface at each point in the field of view, along with the corresponding surface colour, and used to create a point cloud of the construction site, typically from multiple scans.

With the method of data collection established, focus can then shift to the matter of comparing this point cloud data to the scaffolding model. The use of brightly-coloured scaffolding components, for example yellow-painted Kwikstage, would assist with the culling of point cloud data using colour as a selection filter, so that just the points associated with the scaffolding structure could be extracted. From there, Autodesk ReCap supports point cloud editing and can be used in conjunction with Navisworks to verify as-built structures.



The greatest advantages stand to be gained by streamlining the connection between the system and onsite construction and safety practices. By achieving this in a manner that allows the tacit knowledge of experienced practitioners to be embedded in the system, this research will extend beyond current top-down and technologically-oriented approaches to BIM and safety to connect more directly with the needs of contractors and subcontractors onsite. This provides greater opportunities to address the issues that factor directly in accidents onsite and lead to smarter and safer scaffolding structures and procedures.

2.4.5 Recommendations for prototype validation

Preliminary validation of the prototype requires comparative analysis of manual and automated scaffolding designs on live projects. There are two distinct aspects to this validation – construction and safety. The design outputs of the prototype must therefore be checked to ensure that they satisfy both the construction needs of scaffolding contractors going and the safety requirements of Workplace Health and Safety Authorities in Australia. There are two parts to validating the prototype's suitability for use by scaffolding contractors:

- Performing a comparative analysis of conventional scaffolding modelling techniques to ensure that the encoded design rules capture the knowledge and logic that contractors apply to the scaffolding design process and are aligned with their working practices.
- Ensuring alignment between the model outputs and manually-calculated quantity take-offs and other information required for tendering.

Validating the prototype against safety requirements involves the following:

- Confirming that the scaffolding model adheres to the design criteria specified in safety checklists used to inspect these structures onsite.

Researchers must work on live projects alongside scaffolding designers and contractors, in order to gain an understanding of how the prototype will be used in practice and propose opportunities for both refining current features and further developing its functionality for improved application to real-life construction processes. At the same time, the productivity benefits of the prototype for everyday practice can also be determined by recording the time and cost associated with both its use and the use of conventional design methods in performing the same tasks.

3.0 Scenarios of BIM for Smarter and Safer Scaffolding Construction

3.1 BIM for 3D parametric-driving scaffold design

Information analysis

Parametric design is dynamic design method. Designers define the geometric figures of parts applying the dimension parameters and constraints. The geometric figures and models will be renewed as the dimension parameters and constrains changing. Parametric model construction, constraint relation extraction, as well as solving method of constraints are the crucial steps in parametric design.

In a BIM model, objects are defined by built-in and user-specified parameters, and external data such as physical, aesthetic, functional data accessed through databases. Parametric modelling enables parameters to be processed by mathematical formulas and computational algorithms before being passed among objects.

Discussions with contractors have revealed that there are a number of decisions which play a role in how the rules derived from manufacturers' specifications and safety standards affect scaffolding composition. What these decisions reflect are the influence of specific project constraints, including the component types and sizes readily obtainable, and practices that individual contractors have observed to increase onsite productivity, generally by reducing assembly times. In order to accurately reflect both project requirements and contractor preferences, it is essential to provide users with control over input parameters relating to both the chosen scaffolding system and applicable design codes and construction standards for the given location and conditions. At the same time however, certain restrictions must be put in place that limit allowable inputs to options within the range of compliance defined by scaffolding specifications and standards, as this ensures that minimum safety requirements are always met and designs can be deemed-to-satisfy.

Illustration

The parametric models include modular scaffold, mobile scaffold and stairs.

Different preferences are accommodated within the prototype through user-controlled variables that act as modifiers on fixed project and scaffolding parameters, altering the inputs to design rules and thus the scaffolding composition generated. Combined with individual project constraints, these preferences manage the rule algorithms that control face conditions and corner junctures. The prototype is based on the specification for a type of scaffolding known as modular scaffolding, since it has a significant presence in the Australian market; however, the following inputs are just as applicable to other systems and brands also:

- **Building footprint** – input as a flat polyline drawn in the anticlockwise direction.
- **Roof outline** – input as a planar polyline (flat or angled) drawn in the anticlockwise direction.
- **Clearance from building face** – user-defined value up to a maximum allowance of 225mm.
- **Floor to floor height** – user-defined value that determines the height between working platforms in the structure, which should be set to a multiple of the preferred standard height if the platforms don't need to be matched to the building floors.
- **Vertical overrun** – user-defined value that determines the height that the scaffolding extends above the upper edge of the building to allow for roof access.
- **Depth of the scaffolding bays** – single user selection from a list of transom lengths defined in the manufacturer's specification; future work would allow for different depths to be set for each façade.
- **Width of scaffolding bays** – each ledger length defined in the manufacturer's specification is given a user-allocated priority, and if more than one ledger length is given a priority of 1, the bay widths alternate between the different lengths; future work would allow priority values to be allocated based on the amounts of each ledger size available.
- **Height of scaffolding bays** – each standard length defined in the manufacturer's specification is given a user-allocated priority, and if more than one standard length is given a priority of 1, the bay heights alternate between the different lengths (and keep to the floor to floor height as closely as possible); future work would allow priority values to be allocated based on the amounts of each ledger size available.
- **Diameter of members** – fixed value defined in the manufacturer's specification, used for ledgers, transoms and standards.
- **Steel plank dimensions** – fixed value defined in the manufacturer's specification, with planks used in multiples for working platforms and in singular for toeboards.
- **Hop-up platforms** – single user selection from the options of 1, 2 or 3 board hop-ups, or no hop-ups at all, which defines the depth of these platforms and together with the clearance establishes the distance between the building and the inner scaffolding face.
- **Height of the hop-up platforms** – user-defined value that specifies the height of the hop-ups in relation to the working platforms as a variable between -500mm and 0mm.
- **Timber board dimensions** – fixed value defined according to contractor's specification, with boards spanning gaps that are too small or irregular for standard platform planks.

- **Maximum gap without guardrail** – user-defined value up to a maximum of 125mm, gaps greater than this that don't allow a standard guardrail size use a clipped-in pipe instead of a ledger (and the largest mesh panel that does not exceed guardrail length is used as infill).
- **Mesh infill panel** – user-set true/false value that specifies whether mesh infill panels are used as handrails or a simple ledger as a midrail.
- **Number of bays for bracing** – user-defined value up to a maximum of 4, specifying the number of bays on the outer scaffolding face in which there is one bay of bracing.

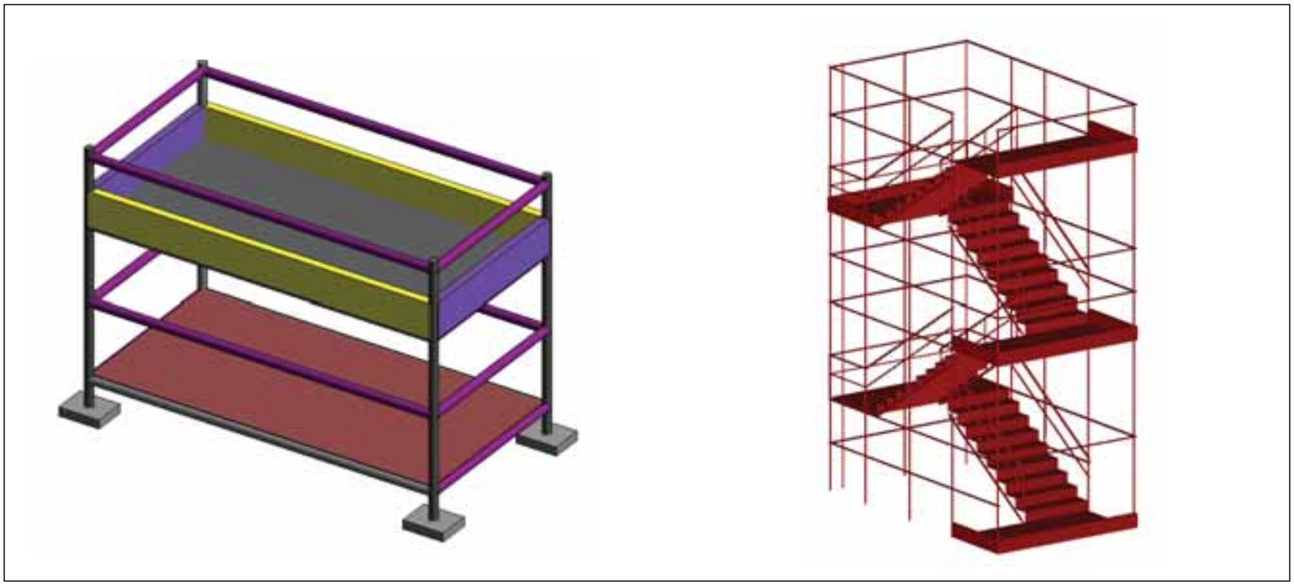


Figure 3.1.1: Parametric-driving modular scaffold designs

Figure 3.1.2: Parametric-driving mobile scaffold designs

3.2 BIM for corner configuration in the building footprint for scaffolding design

Information analysis

A number of other rules have been devised to control various aspects of the scaffolding design in relation to construction and safety constraints. All rules are built up from an initial test of the corner configuration in the building footprint, seen in Figure 3.2.1.

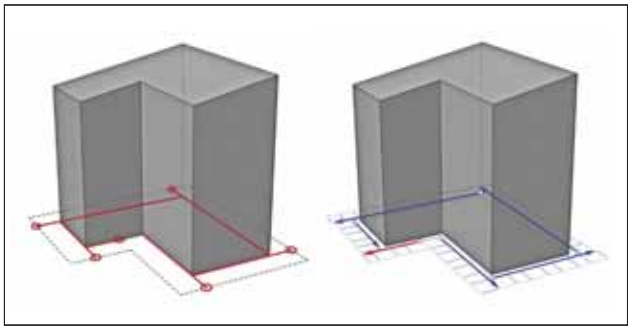


Figure 3.2.1: Testing corner configuration in building footprint and resulting scaffolding layout lines

To determine corner configurations, the building footprint is offset and tested for intersection with the original edges, each extended by the offset distance. No intersection indicates a non-convex corner in the footprint, so the layout line for that edge is reversed and shortened to avoid clashes in the structure. From here, the rules are applied to generate the scaffolding structure as follows:

- Where possible, corners are constructed with fly-past bays on one of the scaffolding faces to ensure overlap with the other's end, as seen in Figure 3.2.2; for a non-convex corner, potential collision is avoided by one face instead stopping short, resulting in a board-spanned gap less than the smallest bay width.
- To accommodate restrictions in the supply or use of base components, if consistent length-sizes cannot be used throughout the structure for each object type, ledgers and standards of several different sizes can be evenly distributed according to user prioritisation.
- If platforms are positioned in relation to building floor levels, user-prioritised standard lengths are used where possible for each stratum of scaffolding, except when this results in bays whose height overshoots the next floor level and a better fit is determined to exist.
- When there are slopes in the rooflines or parapets, bays are stepped accordingly, taking into account user-specified height overruns required for roof access; future work would accommodate the same stepping in the ground plane.
- For each working platform in the structure, regulation-height handrails are installed at edges on an external scaffolding face, with infill below the top guardrail configured as either a midrail and toeboard or a mesh panel (with built-in toeboard), as specified by the user.
- Similar to above, adjustable hop-up platforms of user-defined depth are installed on the internal scaffolding face for each fixed working platform.
- Bracing is applied across the structure as discussed previously.
- Timber boards are placed across any gaps between working platforms at the same level in the structure, making sure to avoid any clashes with the structure itself.

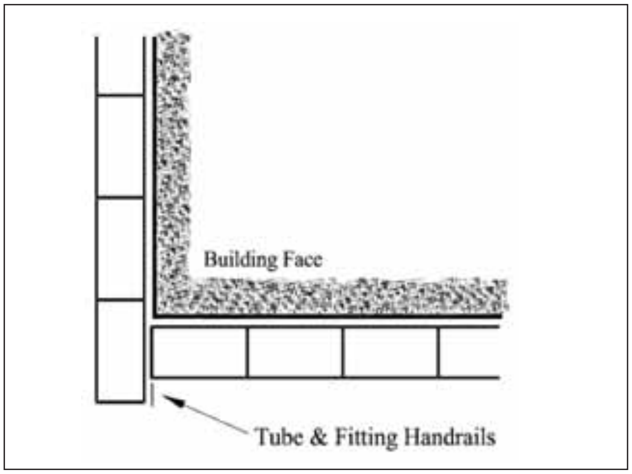


Figure 3.2.2: Fly-past bays

Illustration

These rules allow the scaffolding model to be built up in the order illustrated in Figure 3.2.3: (1) Inner scaffolding faces; (2) Outer scaffolding faces; (3) Transoms; (4) Working and hop-up platforms; (5) Handrails with mesh guards; (6) Bracing. Timber boards are the last element to be created following the bracing, but have not been illustrated as they are not clear in this visualisation.

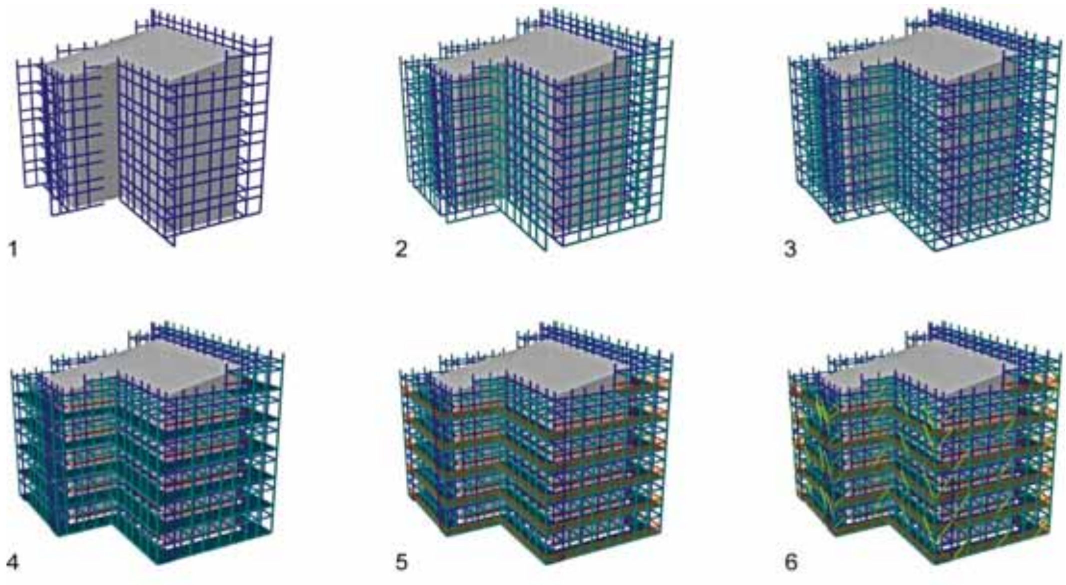


Figure 3.2.3: Building up of scaffolding structure

The system has been tested successfully against several building footprints, as seen in Figure 3.2.4.

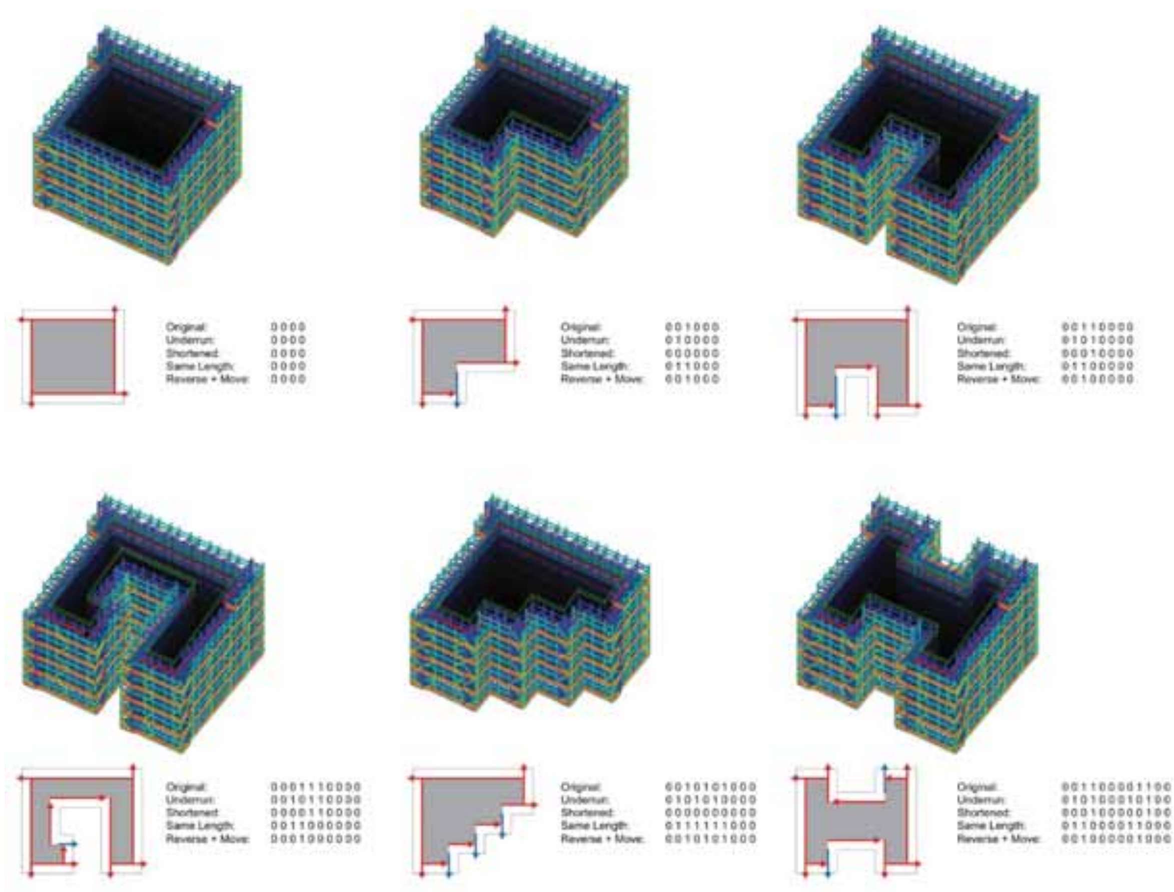


Image courtesy Bianca Toth @ QUT

Figure 3.2.4: Testing of scaffolding generation system against various building footprints

For orthogonal footprints, on/off codes are used to define the specific characteristics of each face of scaffolding in relation to the original length of the corresponding building side and its juncture with the following scaffolding face. These codes act as modifiers on the default condition of a fly-past bay on the end corner, moving in an anti-clockwise around the building footprint. When the prototype was extended to accommodate curved walls, these codes no longer accurately described the required scaffolding configurations. As a result, the test-case scenario was changed from whether an intersection could be found at a corner, as previously illustrated in Figure 3.2.1, to a test of the change in angle from one scaffolding face to the next at any given corner, measured as an anticlockwise rotation. Consequently, if the angle is greater than or equal to 270º, the corner is non-convex and uses the same codes as for non-convex corners in an orthogonal building footprint (i.e. no intersection found). If the angle is less than 90º, the corner is non-convex and also non-orthogonal and new codes are used to deal with the junction between two faces. These codes, and their relationships to the old codes, are illustrated in the planning sketch seen in Figure 3.2.5.

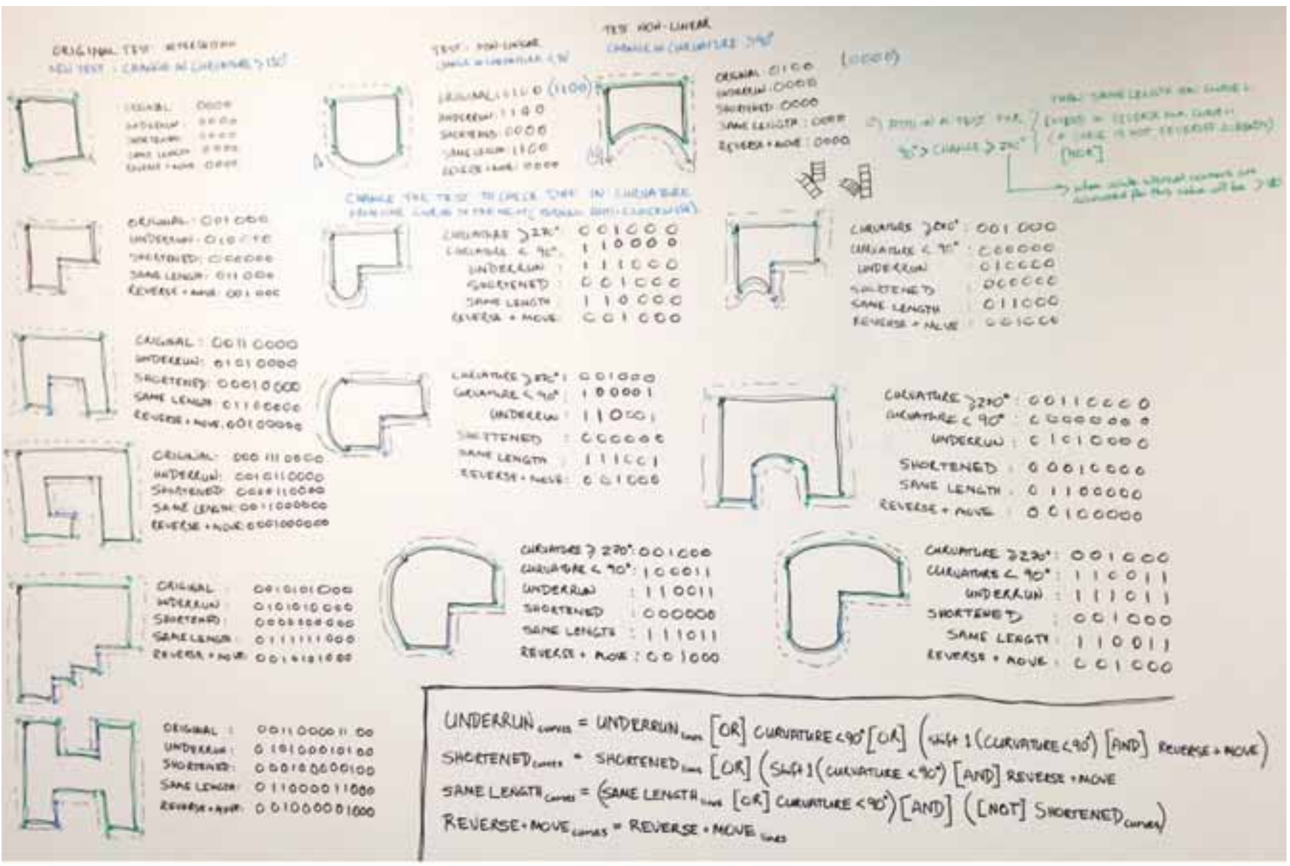


Figure 3.2.5: Codes and test-case scenario for curved wall scaffolding configurations

Image courtesy Bianca Toth @ QUT

3.3 BIM for automatic detecting of different types of openings and falling prevention planning

Information analysis

Developing BIM-based falling prevention planning and opening detection is one of the main targets of the research project. BIM was used for detailed falling prevention planning, including temporary safety railings and floor opening coverings.

The different contexts are determined by acquiring the corresponding spatial and geometric information of each object: (1) the internal gap between the inner edge of the length of the platform and the face of the building or structure immediately beside the platform are detected to define where edge protection is needed; (2) holes in scaffold platform are detected to prevent fall through openings; (3) openings in edge protection at points of access to stairways or ladders are detected to determine where additional opening protection is required. After object identification, firstly, safety rules of different types of openings are inputted to scaffold model and different conditions are categorised according to specific geometry attributes. Secondly, corresponding rules are executed and visualised for supporting decision-making. After applying and visualising an automated version of rule checking, human input is optional to assist in the final decision making process. Finally, the checking results and visualisation are updated in the BIM. Each hazard is detected and the proper protection method is shown. The geometry of the created safety equipment is based on identifying the unprotected leading edges, holes, and openings in scaffolding, etc... Two types of fall protection scenarios were identified and are listed in illustration.

Illustration

A test model was created; the model includes different types of openings that could be a potential fall hazard. The identified openings have different sizes and geometric shapes (polygonal, rectangular, and circular). The holes are located on platform and open edge.

The rule-checking steps are listed as follows:

1) Customise the spatial (opening sizes: length*width)and geometric (objects location) information in BIM model;
2) Automatically check the model and detect holes and opening in scaffold;
3) Install guardrail system at edge and cover access opening.

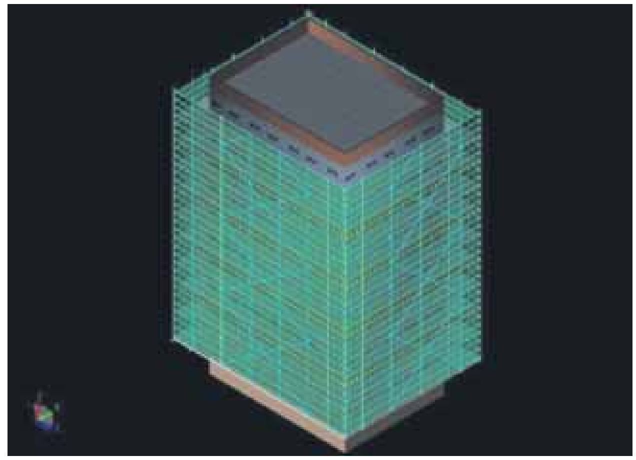


Figure 3.3.1: Building with scaffold

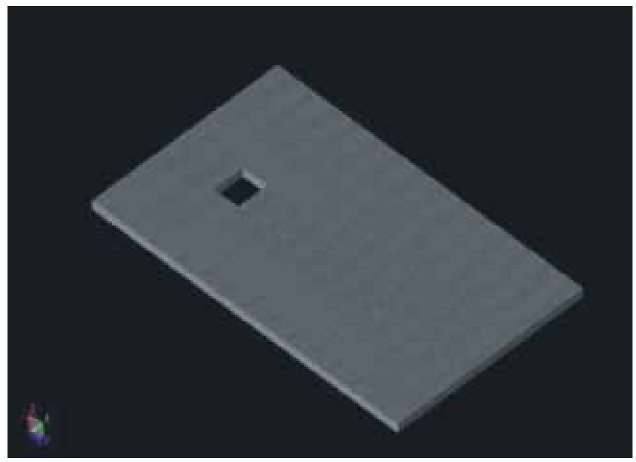


Figure 3.3.2: Rule-based hole and edge detection in scaffold

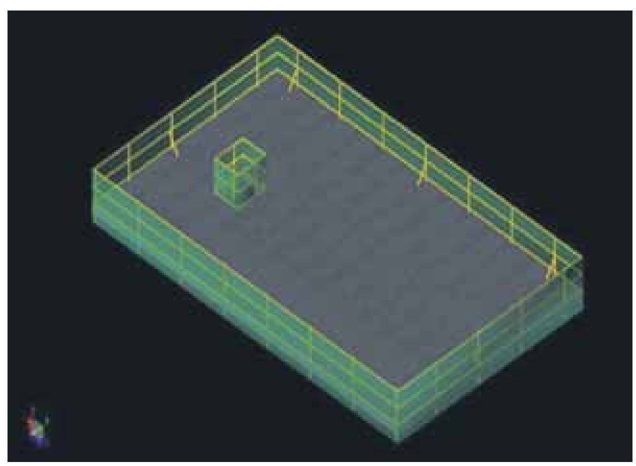


Figure 3.3.3: Guardrail systems at edge and cover access opening

3.4 BIM for layout of the workplace, including traffic route

Information analysis

In the BIM Safety project, a BIM-based 3D site layout plan was selected to be the subject to study possibilities of safety related automated checking. The geometry information is sufficient for such automatic analysis as collision detection.

Elements of a BIM-based site layout plan are 1) the construction site area and adjoining streets, and other immediate surroundings, that the construction site may impact 2) temporary site facilities, structures and equipment 3) temporary site arrangements, such as area reservations for material storage, and 4) visualisations of safety related issues, such as illustration of risk distance between scaffold and vehicles, cranes.

Illustration

The visualisation was based on the site engineer's site layout plan.

First, a BIM-based visualisation was carried out relating to the erection and demolition plans of scaffolding based on the installation in practice (figure 3.4.1).

After this, BIM-based modelling and visualisation of site layout and traffic route plans nearby scaffolding was carried out based on textual specification describing the planned site layout (figure 3.4.2).

Finally, potential clashes between scaffolding, building and mobile devices, location-decision of mobile crane (figure 3.4.3), safety clearance distances checking results and visualisation is demonstrated in the BIM (figure 3.4.4). Each clash is detected and potential conflicting building component is shown in colour code; optimal mobile crane location is decided based on visualisation and mathematic algorithm; and unsafe distance between vehicle and scaffolding work is detected and warning system is shown (figure 3.4.5), corresponding manual work is required to rearrange the traffic route and moving track. The geometry of the created warning system is based on identifying the clearance distance of traffic and scaffold working.

Figure 3.4.1: Modular scaffold installation in practice

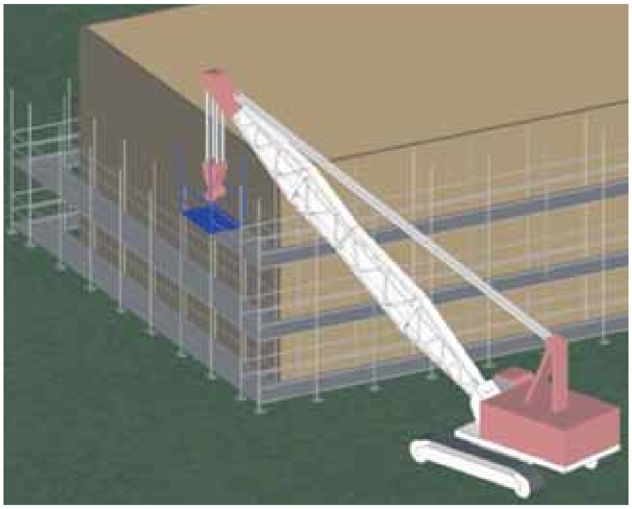


Figure 3.4.2: Modular scaffold installation in BIM

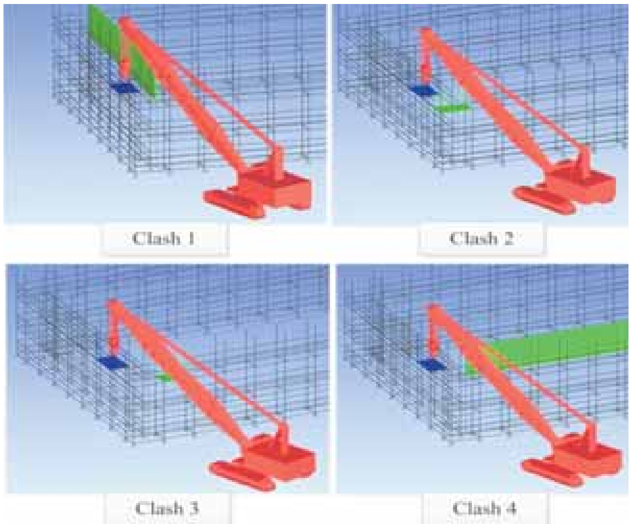


Figure 3.4.3: Clash detection in BIM between building, scaffold and mobile devices

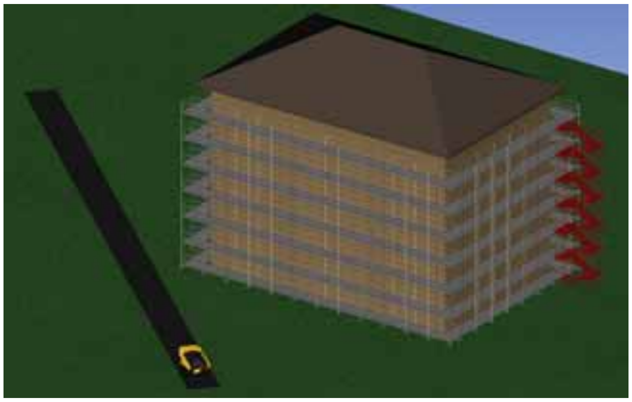


Figure 3.4.4: Site traffic simulation and verification

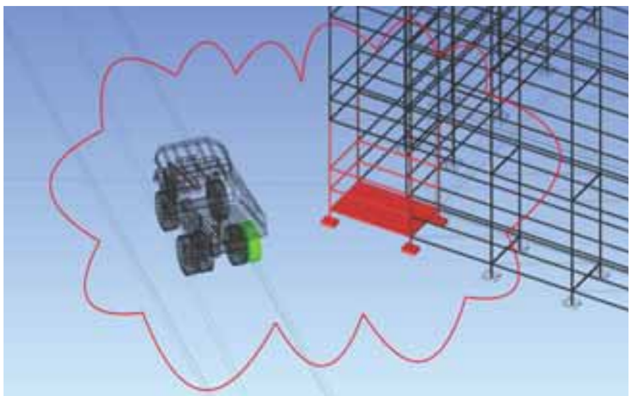


Figure 3.4.5: Site traffic analysis and verification

Figure 3.4.6: Unsafe distance warning in site traffic planning

3.5 BIM for 4D scheduling of the scaffolding work

Information analysis

BIM-based modelling and 4D-visualisation presenting the planned phases and sequence of scaffolding erection work, following rules introduce the general rules for scaffolding construction.

- The width and depth of scaffolding bays, defined by preferred transom and lengths respectively.
- The vertical height between platforms, defined either by preferred standard length alone or with the added constraint to match building floor levels as closely as possible;
- The clearance to the building face required for working structures like hop-up platforms;
- The location and size of working and access structures like hop-up platforms and stairs;
- The vertical overrun past the upper edge of the building required for roof access; and
- The maximum distance to be spanned using timber bridging planks.

A 4D simulation visualises construction sequences on bay level. Each active bay is visualised by highlighting associated construction elements. According to scaffolding physic construction process, scaffolding erection scheduling is progressed by floor.

Illustration

The rules and erection procedure allow the scaffolding model to be built up as illustrated below, according to the following steps (figure 3.5.1):

At the beginning of the visualisation, a parametric-driven bay has been installed in the first construction area of the foundation, as well as all needed safety railings. In the second phase scaffolding works are to be installed bay by bay along building of level one. In the third phase ladders, which are needed while second floor scaffolding installation, are installed. After this, scaffolding erection schedule is matching with building construction schedule starts floor by floor. In the last phase, also edge protection of opening and safety guardrails have to be installed.

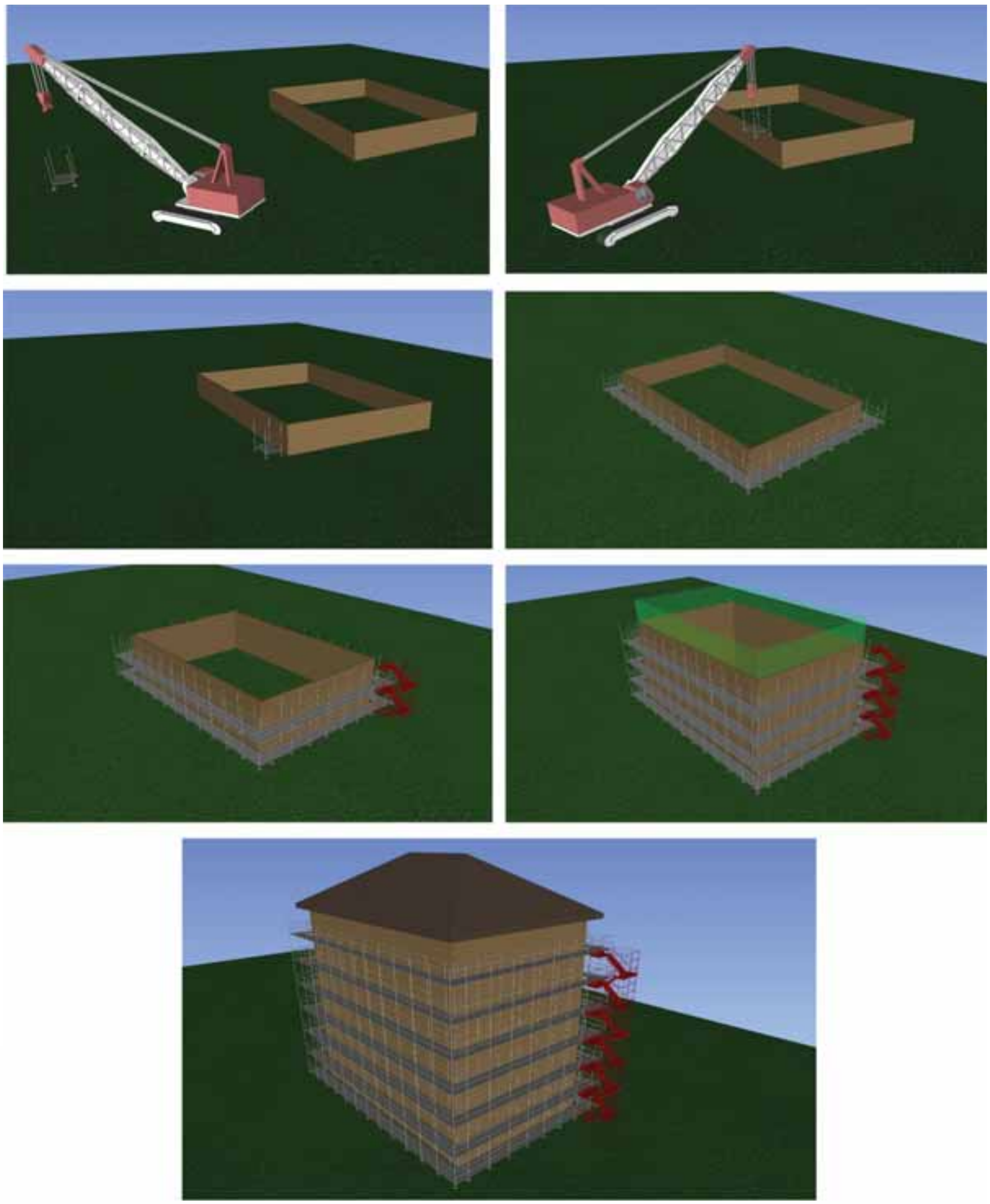


Figure 3.5.1: BIM for 4D scheduling of the scaffolding work

3.6 BIM for quantity takeoff for competitive tendering

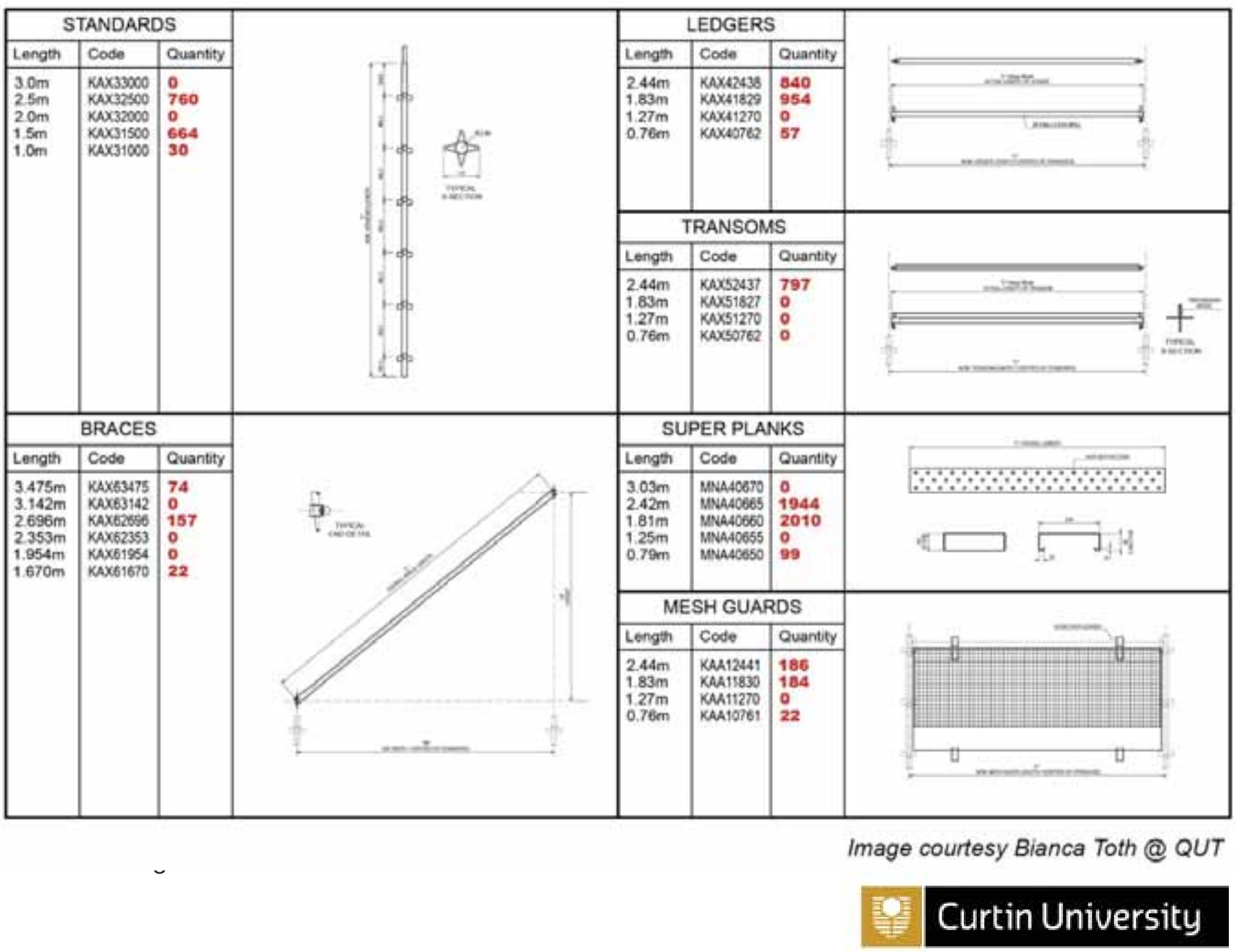
Information analysis

While automatic BIM based quantity takeoff is one of the potentially most important and profitable applications for BIM. With BIM based visual estimating the quantity take-off can be greatly speeded up. As the model gets the information about all the objects in the building as well as their dimensions the quantity take off can easily produce necessary information within a very short period.

Once the scaffolding construction and safety rules are executed, the prototype calculates the quantities needed for each type of component in the design. These quantities are read out into a specification table, as seen in Figure 3.6.1.

Illustration

The rules allow the scaffolding model to be built up and export quantity automatically.



STANDARDS

Length	Code	Quantity
3.0m	KAX33000	0
2.5m	KAX32500	760
2.0m	KAX32000	0
1.5m	KAX31500	664
1.0m	KAX31000	30

LEDGERS

Length	Code	Quantity
2.44m	KAX42438	840
1.83m	KAX41829	954
1.27m	KAX41270	0
0.76m	KAX40762	57

TRANSOMS

Length	Code	Quantity
2.44m	KAX52437	797
1.83m	KAX51827	0
1.27m	KAX51270	0
0.76m	KAX50762	0

BRACES

Length	Code	Quantity
3.475m	KAX63475	74
3.142m	KAX63142	0
2.696m	KAX62696	157
2.353m	KAX62353	0
1.954m	KAX61954	0
1.670m	KAX61670	22

SUPER PLANKS

Length	Code	Quantity
3.03m	MNA40670	0
2.42m	MNA40665	1944
1.81m	MNA40660	2010
1.25m	MNA40655	0
0.79m	MNA40650	99

MESH GUARDS

Length	Code	Quantity
2.44m	KAA12441	186
1.83m	KAA11830	184
1.27m	KAA11270	0
0.76m	KAA10761	22

Figure 3.6.1: Automated quantity take-offs

3.7 BIM for structural analysis and load calculation

Information analysis

Load calculation mainly for the surface on which the scaffold will be erected, i.e. ground conditions and the structural integrity of the surface to support the scaffold and its load. With BIM, the scaffolding analytical and physical representations are created simultaneously, and are just different views of the computable building model, containing the necessary information needed for third-party analysis application.

- Import the physical model to BIM model
- Perform the structural analysis and computation of the scaffolding component in BIM model
- Export the structural analysis result to collaborate and coordinate within designer and structure engineer.

Illustration

The rules allow the scaffolding model to be built up as illustrated below, according to the following steps:

A BIM-based scaffolding model can be transferred as structural model to process point, line or area load. Potential load quantity of each point, line and area is modified in BIM software;

Inputting scaffolding structural model into professional structural analysis software, structural load is calculated and final load analysis report is exported.

Scaffolding structural reactions, forces and stresses reports are generated based on the load quantity of scaffolding.

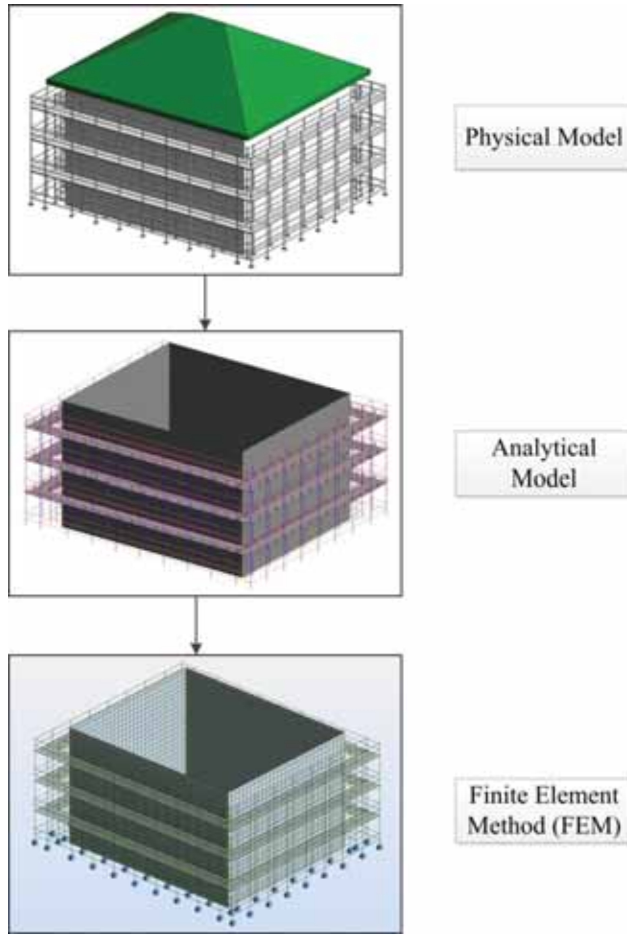


Figure 3.7.1: BIM-based scaffold structural analysis

4.0 Scaffolding Erection Optimisation

Construction concerns a wide range of activities with different natures. As highlighted in the industrial support letters, scaffolding becomes an irremovable concern to industries across oil and gas, building, and infrastructure, considering the relatively low productivity and high labor shortage and cost in this country. Poor design, planning and scheduling of scaffolding often lead to issues such as idling, rework, unnecessarily long travelling time between activities, which substantially reduce productivity. Scaffolding refers to the high framework supporting system for workers to stay and transport materials at height vertically and horizontally. In construction sector, it is normally used in exterior walls and other places of multi-storey buildings. Scaffolds can also help construction workers install and maintain the peripheral safety nets. The scaffolding materials are usually chosen from bamboo, wood, metal or synthetic materials. In addition, it is also widely used in the other industries such as advertising, transportation, civil engineering, mining and other sectors.

In recent years, the universality of scaffolding application has drawn the public attention to in terms of safety. There is a high occurrence of safety accidents in scaffolding construction. Detecting the hazards of a site that could cause harmful effects on workers is crucial for successful safety management, because a hazardous work environment affects not only site safety but also the time and cost of the project. There are numerous factors that cause serious injury or death, for example, overturning or collapse due to scaffolding instability, falling from height during constructing and dismantling, and so on. As the causes to scaffolding accidents normally vary and are complex, if the hazardous they are incorrectly foreseen, workers will still suffer from the potential risks. On the other hand, to prevent from danger, workers might pay more attention to their workspace, slow down their operations and spend more time on preparing preventive measures. This will undermine the productivity as well. In this sense, excessive or unnecessary Occupational Safety and Health (OSH) warning may result in both delays in the schedule and impacts on the costs. The study therefore aims at addressing scaffolding OSH issues by applying mathematical models as important analysis tools. The focal point is placed at optimising scaffolding schedule for the sake of reducing the occurrence rate of scaffolding accidents.

4.1 Safety and scheduling optimisation engine

As the primary objective of scaffolding OSH planning is to minimise the accident risk, the risk itself must be first identified as specifically as possible.

Table 4.1 states the risk sources that affect OSH. Various factors include human, environmental, process and so on.

SCAFFOLDING ACTIVITY	CAUSE OF RISKS		
	SOURCE OF RISKS	CONDITIONS FOR OCCURRING RISKS	POSSIBLE OUTCOMES
Preparation of Scaffolding Scheme	Managerial Personnel	1. Lack of schemes 2. Lack of technical details 3. Lack of approval	Collapse
Technical Clarification and Receipt	Managerial Personnel	1. Lack of communication with onsite workers 2. Lack of instruction	Collapse
		1. Not sign the receipt of scaffold 2. Sign without evaluation	Collapse
Workforce	Scaffolder	1. Not meet OSH standard 2. Dismantling connective components randomly	Fall from height
		1. Not follow scheme	Collapse
		1. Violation of OSH codes of practice 2. Lack of personal protective measures, e.g., not wears safety belt, helmet, etc 3. Work in bad weather	Fall from height
Scaffolding Framework	Material	1. Scaffold bridge, scaffold floor, scaffold trestle, scaffolding bearer, scaffolding platform, stud, traversing lever, lock, etc. not meet quality standard 2. Component bending, corrosion, welding and rust issuescorrosion, welding and rust issues	Collapse
	Facility	1. Scaffold is uneven and without stow-wood 2. Stud lacks base, stow-wood and traversing lever 3. No drainage design	Collapse
Preventive Measures	Facility	1. No prevention net around scaffold 2. No guardrail	Fall from height
Load	Load	1. Overloading 2. Load distribution is not uniform	Collapse
Build Scaffolding Platform	Facility	1. Miss scaffold floor and trestle somewhere 2. Scaffold platform not stable 3. Miss lock 4. Use materials with wrong specifications	Fall from height
Dismantling	Scaffolder	1. Not remove components in order 2. Throw components randomly 3. Stack components unstably 4. Work in bad weather	Object strike

Table 4.1: Risk identification of scaffolding engineering activities

The safety planning plus scheduling would definitely involve risk identification, evaluation, and control. Similar the study in (Yi and Langford, 2006), addressing OSH issues in scaffolding is composed of the following three steps:

1. Identifying alternatives of each activity;
2. Estimating risk associated with each alternative
3. Enhancing safety through scheduling optimisation.

The traditional scheduling optimisation is only considering time and cost (Zheng, 2004). Few of them have taken consideration of safety. It has been identified that scaffolding is one of the most hazardous job in construction industry. Thus, the planning of scaffolding should put more emphasis on safety rather than time and cost. To achieve this task, we first need to identify the alternatives and estimate their risks for each activity involved in scaffolding. Every activity in the schedule has its own starting and finishing time. In mathematics, we adopt an activity-on-node network representation for the graph, where there are J nodes which are labelled as$i=1,\cdots,J$ such that each node has a lower number than its successor nodes. Assume that the activity $i, i=1,\cdots,J$, has $a(i)$ alternatives of which alternative $j, j=1,\cdots,a(i)$ requires t_{ij} time and c_{ij} cost. We further assume that if k and r are two alternatives for activity i such that $k<r$, then $t_{ik}<t_{ir}$ and $c_{ik}<c_{ir}$. Introduce two dummy activities 0 and J+1 for the start and finish nodes, respectively, and assume that the time and cost requirements for them both zero. Now the scheduling of the scaffolding is transform to select a particular alternative for each activity. Define

$$\sigma = \{(i,j): \ i = 1, \cdots, J\}$$

where the alternative j is selected for the activity i. The overall time.

$$t(\sigma) = \sum_{i=1} \sum_{j=1} t_{ij} X_{ij},$$

and the cost

$$c(\sigma) = \sum_{i=1} \sum_{j=1} C_{ij} X_{ij},$$

Now our task is to estimate the risk for each alternative of each activity. Let the total risk be R_{ij}. In Mol (2003), R_{ij} can be computed through the following formula:

$$R_{ij} = P_{ij} \times H_{ij} \times T_{ij} \times E_{ij},$$

Where P_{ij} = process risk score, H_{ij} = human resources risk score, T_{ij} = technology risk score and E_{ij} = physical environment risk score. The factors P_{ij}, H_{ij}, T_{ij} and E_{ij} can be estimated through the historical data. Then, the total risk $R(\sigma)$ can be computed as:

$$R(\sigma) = \sum_{i=1} \sum_{j=1} R_{ij} X_{ij}.$$

To represent the precedence relationships among the activities, we suppose that s_i ($s_i \geq 0$) be the start time for activity i and S(i) be the set of immediate successors of i. Now we formulate the scheduling of the scaffolding as the following multi-objective optimisation problem:

$$\min \{t(\sigma), c(\sigma), R(\sigma)\} \qquad (1)$$

subject to the following constraints:

$$\sum_{j=1} X_{ij} = 1, \quad \text{for all } i = 1, \cdots, J, \qquad (2)$$

$$\sum_{j=1} t_{ij} X_{ij} + S_i \leq S_k, \quad \text{for } k \text{ all} \in S(i),\ i = 1, \cdots, J \qquad (3)$$

$$x_{ij} \in \{0,1\}, \quad \text{for all } i = 1, \cdots, J,\ j = 1, \cdots, a(i), \qquad (4)$$

In the above formulations, (1) is the objective function where not only time and cost are included, but also the criterion of safety is included, (2) together with (4) ensures that exactly one alternative is chosen for each activity and (3) maintains the precedence relationships among the activities. Let this optimisation problem be referred to as Problem (TCR). It is obvious that Problem (TCR) is a multi-objective integer optimisation problem. There are two challenges to solve such an optimisation problem: multi-objective and integer constraints. Multi-objective is usually transformed to single-objective through weighting them as a single-criterion. It is also can be handled through searching the optimal solution in the Pareto front. Here we would like to adopt the former method since the weighting method offers trade-off among different criteria clearly while the last method cannot. Solving the integer optimisation problem is NP hard in theory. This means that we cannot find a computational method to solve this class of optimisation problems in polynomial time in general. Generally speaking, there are two kinds of methods available for solving Problem (TCR). One is exact search method and the other one is heuristic search method. Exact search method is possible only for small and sometimes medium sized problems. For big instances, heuristic search method is inevitable. Exact search methods are including branch and bound, branch and cut and cutting plane method. All these methods are heavily dependent on construction of upper and lower bounds. Comparing with exact search methods, heuristic search based methods are more fruitful.
The dominated heuristic search methods are met heuristics which are improvement heuristics, including simulated annealing method, genetic method, swarm particle method, ant colony method, shuffled leap frog algorithm, firefly algorithm and cuckoo search method. They tend to produce very good solutions in reasonable time. However, none of them is ensured to produce an optimal solution. In our optimisation engine for the static scaffolding scheduling process, we would like to adopt several of these methods to solve Problem (TCR) and choose the best one among the produced solutions.

5.0 Conclusion

This research has developed a prototype scaffolding design system that encodes construction and safety constraints as rules governing structural configuration, and embeds scheduling, cost and lifecycle management information into scaffolding models. It is innovative in that it proposes a more holistic approach to digital-modelling support for scaffolding structures through the development of a series of modular and interconnected tools that link flexibly with each other and existing design and construction processes. Methods by which software for the design and evaluation of temporary works might better form part of a holistic lifecycle-management strategy, rather than acting as standalone applications, are proposed to help mitigate safety risks onsite and improve productivity. Altogether, this will allow contractors to tender more competitively on projects, and aid in design and construction processes that are more practically-focused in terms of time, cost, and safety.

5.1 Project benefits

This project is aligned with the national harmonisation of the new Workplace Health and Safety (WHS) act across all Australian states and territories, requiring designers to consider and assess safety and constructability issues early on in a project. It improves the industry's ability to meet requirements for the design of structures that are within appropriate risk limits to the health and safety of the persons using them. It also results in significant productivity benefits by streamlining the links between the design and construction of temporary scaffolding structures. The prototype allows work that would previously have taken several days to be computed in less than a minute for each iteration of the scaffolding design alternative. It also reduces duplications in tender estimation across the contractual chain by making design assumptions clear to all stakeholders upfront.

The research that has been undertaken also advances knowledge concerning the uptake of digital modelling in the delivery of temporary structures relating to:

- rule-based design logics integrating construction and safety constraints against which scaffolding structures can be deemed-to-satisfy;
- incorporation of scaffolding objects and object relationships into building information models and systems; and
- information dependencies between scaffolding design, analysis and construction tasks.

This work is also aligned with a number of objectives of the National Research Priority, Frontier Technologies for Building and Transforming Australian Industries, which reflect emergent trends in the uptake of digital modelling:

> **Frontier technologies:** the application of BIM to temporary construction works will address critical issues of onsite safety and enhance industry-wide uptake of digital technologies across the project supply chain.
>
> **Promoting an innovation culture and economy:** given that the construction industry is the 4th largest contributor to GDP at 6.8%, and employs 10% of the Australian workforce, the increase in productivity facilitated by improved digital modelling tools and processes will have significant impact on living standards, the production of other goods and services, and trade.
>
> **Strengthening Australia's social and economic fabric:** fostering safer work practices through Australian government and industry engagement will reduce construction accidents, providing direct benefits to workers and their families as well as the health care system.

Overall, this project enhances the integration between building design and construction stakeholders and eases the knowledge gap in the management interface between design and construction activities.

Common Scaffolding Terms

Bay - The space enclosed by four standards, two ledgers and two transoms.

Lift - The vertical distance between ledgers where a working platform is created. The maximum lift is 2 metres although most unit frames have a lift of 1.8 m.

Unit frame - A prefabricated structural scaffold frame placed vertically to transmit load to a supporting surface.

Standard - A vertical member of a scaffold which transmits load to a supporting surface.

Ledger - A horizontal scaffold member used to tie standards along the length.

Transom - A horizontal scaffold member used to tie standards across the width.

Putlog - A horizontal scaffold member placed transversely on top of ledgers to support planks.

Plan brace - A diagonal bracing system in the horizontal plane along the length of the scaffold linking diagonally opposite standards.

Face brace - A diagonal bracing system placed on the vertical face of the scaffold linking pairs of standards for the full height of the scaffold.

Outrigger - An inclined bracing system placed at 90º on plan from the standards to the supporting surface. This system increases the base area of the scaffold thus allowing greater heights without the scaffold overturing.

Working platform - A surface created by planks at nominated lifts to allow the support of persons and materials to carry out work safely. (min. 2 planks wide)

Reference

Scaffolding codes of practice

A guide to safe scaffolding-QLD

Scaffolding Codes of Practices 2009- Queensland

DRAFT: Scaffolds and Scaffolding Work-safe work Australia

Guide note-Fall prevention for scaffolders – West Australia

Scaffolding guidelines and series

AS/NZS 4576-1995 Guidelines for scaffolding

AS/NZS 1576.1-2010 Scaffolding - General Requirements.

AS 6001 - 1999 Working Platforms for Housing Construction

Acrow Formwork & Scaffolding Pty Ltd, Acrow Cuplok Scaffolding System: General Technical and Application Manual, Brochure, retrieved from: http://www.specifier.com.au/media/pdf/5/0/9/0/50941-2_O.pdf

Markku Kiviniemi, Kristiina Sulankivi, Kalle Kähkönen, Tarja Mäkelä & Maija-Leena Merivirta. BIM-based Safety Management and Communication for Building Construction. Espoo 2011. VTT Tiedotteita – Research Notes 2597. 123 p., retrieved from: http://www.vtt.fi/inf/pdf/tiedotteet/2011/T2597.pdf

C. Eastman, J. Lee, Y. Jeong, J. Lee, Automatic rule-based checking of building designs, Automation in Construction, 18 (8) (2009): 1011-1033.

General Contractors of America (AGC), The Contractors Guide to BIM. 2005

L. Khemlani, Automated rule-based building design and engineering at Robertson Ceco Corporation, AECbytes, 2005, retrieved from: http://www.aecbytes.com/buildingthefuture/2005/RCCstudy.html

L. Khemlani, Bluethink House Designer: Automating the re-use of design knowledge, AECbytes, 2009, retrieved from: http://www.aecbytes.com/buildingthefuture/2009/BluethinkHouseDesigner.html

S. Azhar, Building Information Modeling (BIM): Trends, Benefits, Risks, and Challenges for the AEC Industry. Leadership and Management in Engineering, 11 (3) (2011):241-252.

Zhang, Sijie, Jochen Teizer, Jin-Kook Lee, Charles M. Eastman, and Manu Venugopal. "Building information modeling (BIM) and safety: Automatic safety checking of construction models and schedules." Automation in Construction 29 (2013): 183-195.

http://www.rmdaustralia.com.au/scaffolding-rapidstage.htm

http://www.autodesk.com.au/products/revit-family/overview

http://www.solibri.com/products/solibri-model-checker/

http://www.solibri.com/products/solibri-model-viewer/

http://www.autodesk.com.au/products/navisworks/overview

http://www.bslaustralia.com/qstage.html

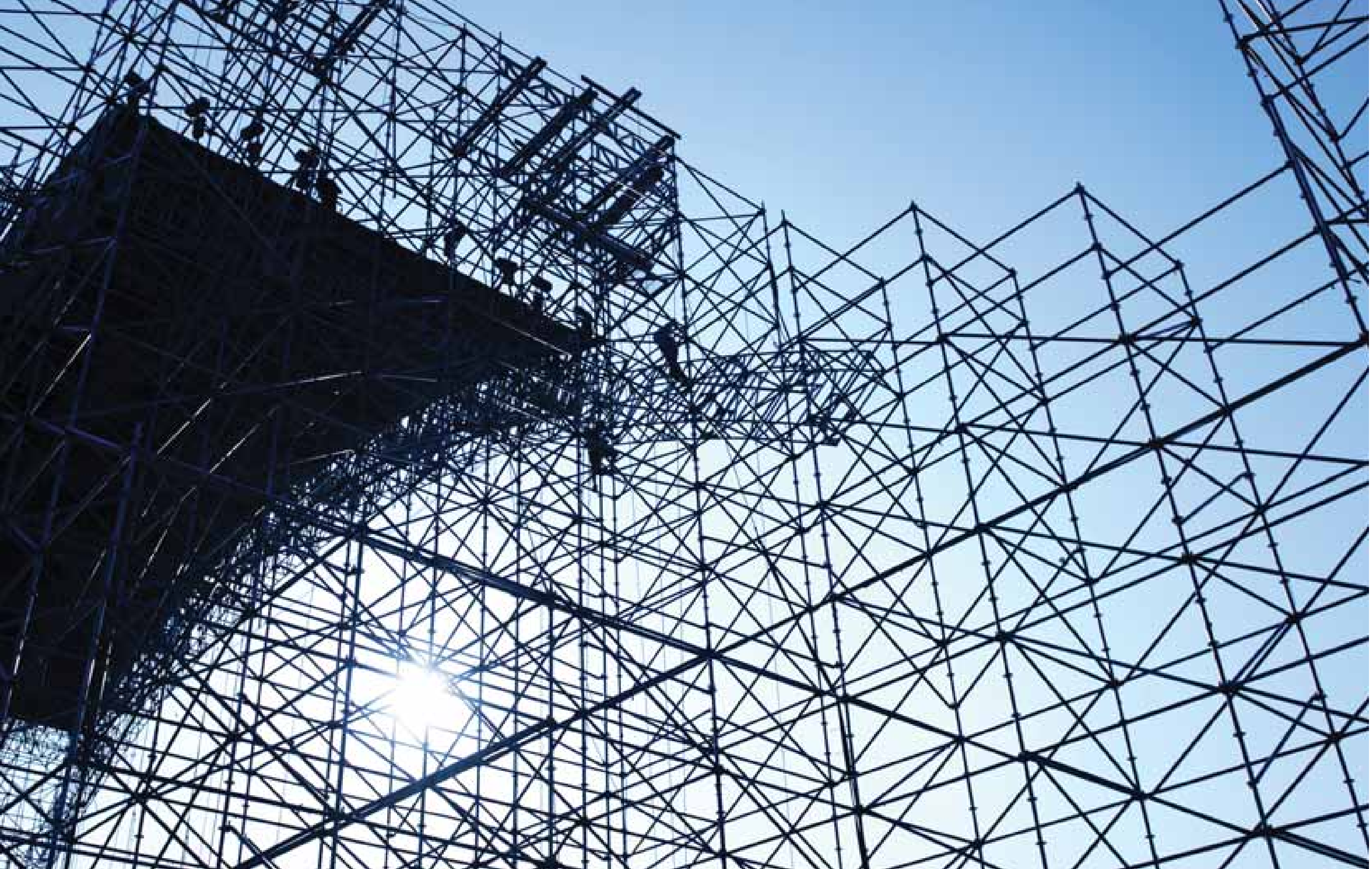
http://www.autodesk.com/products/recap/overview

http://tortoisesvn.net/

Appendix

Appendix A: Journal paper

Hou, Lei, Changzhi Wu, Xiangyu Wang, and Jun Wang. "A Framework Design for Optimizing Scaffolding Erection by Applying Mathematical Models and Virtual Simulation." In *Computing in Civil and Building Engineering (2014)*, pp. 323-330. ASCE.



CONTACT

Professor Xiangyu Wang
Curtin Director
Australasian Joint Research Centre
for Building Information Modelling
Curtin University
Kent Street Bentley WA 6102
GPO Box U1987 Perth WA 6845

Tel: +61 8 9266 9059
Email: xiangyu.wang@curtin.edu.au
Web: curtin.edu.au

This report was compiled September 2016. ADV072197