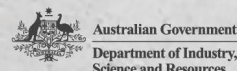
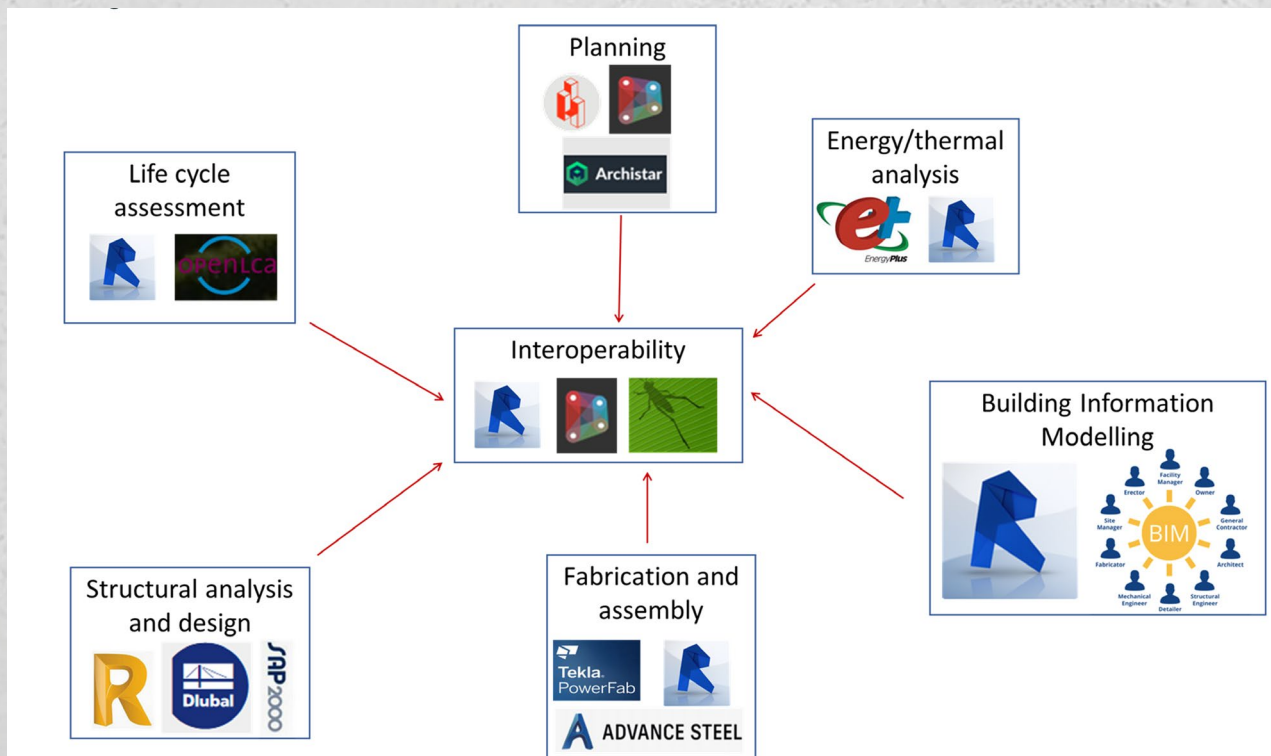


building 4.0 crc

PROJECT #22: GENERATIVE DESIGN AND BIM-BASED DESIGN AUTOMATION METHODS FOR STEEL FRAMED BUILDINGS – PHASE 1

FINAL REPORT



CONTENTS

EXECUTIVE SUMMARY	5
1. INTRODUCTION	7
1.1. Aims.....	7
1.2. Recent research evaluating LGS against traditional structural systems in mid-rise buildings.....	7
1.3. Case studies of mid-rise buildings adopting LGS structural systems.....	11
1.4. Breakdown of this scoping study	14
2. EVALUATION OF INDUSTRY ACCEPTED GENERATIVE DESIGN AND RAPID ENGINEERING TOOLS	15
2.1. Traditional GD methods and systems	15
2.2. Building information modelling software.....	26
2.3. Common stakeholder problems with existing GD/BIM tools	32
2.4. Methods/plugins to address these problems to increase the adoption of LGS	33
2.5. Common rapid structural engineering software	45
2.6. Energy/thermal and daylighting analysis tools	53
2.7. Emerging planning technologies	60
3. LEADING RESEARCH ON GENERATIVE DESIGN (GD) AND RAPID ENGINEERING (RE) TOOLS FOR STRUCTURAL SYSTEMS.....	62
3.1. Application of GD in architectural design considering energy performance	62
3.2. Design workflow using GD	65
3.3. Application of GD for LGS systems.....	67
3.4. Application of GD in design and manufacturing processes.....	67
3.5. Application of GD in modular design and construction.....	68
3.6. Application of GD in structural design	69

4. CRITICAL TOOLS FOR RAPID EVALUATION OF STRUCTURAL SYSTEMS FOR LOW TO MID-RISE COMMERCIAL PROJECTS	70
4.1. Software design logic.....	70
4.2. Critical data required for each stakeholder	72
4.3. Recommendations	75
5. INPUTS REQUIRED BY GD TOOLS TO ASSESS STRUCTURAL SYSTEMS	80
5.1. Project cost and cost-based comparisons of different construction systems/materials	80
5.2. Structural feasibility/efficiency of design	82
5.3. Tools to select materials based on performance requirements.....	82
5.4. Methods to select prefab components, floor and wall assemblies, and other members	84
5.5. Management of clash detection of services with structural elements in building design	87
6. INTEROPERABILITY OF GENERATIVE DESIGN TOOLS WITH DETAILED LGS DESIGN AND ENGINEERING SOFTWARE	88
6.1 Compatibility issues and rework/integration requirements	88
6.2 Recommendations on minimising rework	89
7. CONCLUSIONS AND RECOMMENDATIONS.....	90
REFERENCES	92

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

CONFIDENTIAL:

Yes No

Author/s of this report:

Van Tu Le, Yousef Alqaryouti, Muhammad Wasim, Abdallah Ghazlan, Sara Omrani, Tai Thai, Hafizah Ramli Sulong, Tuan Ngo, Nelson Lam, Robin Drogemuller

Date of this report:

December 2021

Project completion date:

December 2021

Program Leader reviewer:

Tuan Ngo

Project title:

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

Project duration:

6 months

Partners:

- University of Melbourne
- Queensland University of Technology
- BlueScope

Project team members:

- Van Tu Le
- Yousef Alqaryouti
- Muhammad Wasim
- Abdallah Ghazlan
- Sara Omrani
- Tai Thai
- Hafizah Ramli Sulong
- Tuan Ngo
- Nelson Lam
- Robin Drogemuller
- Michelle Gissel

Disclaimer

The Building 4.0 CRC has endeavoured to ensure that all information in this publication is correct. It makes no warranty with regard to the accuracy of the information provided and will not be liable if the information is inaccurate, incomplete or out of date nor be liable for any direct or indirect damages arising from its use. The contents of this publication should not be used as a substitute for seeking independent professional advice.

EXECUTIVE SUMMARY

Light gauge steel (LGS) offers significant advantages over other construction materials including good strength for weight properties, ability to pre-fabricate, quicker construction times, non-combustibility and resistance to rotting, shrinking, warping and termite attack.

Today, it is not clearly understood what tools and inputs should be considered at the early planning phase, for a LGS solution to be a viable structural construction alternative to reinforced concrete, timber, hot rolled steel and other structural systems, particularly in mid-rise building applications. The overarching aim of the project is to develop a generative design workflow that provides an automated side-by-side comparison of LGS and other traditional structural systems (e.g., reinforced concrete and timber) in the early planning phase of a project. The workflow should consider the following criteria for adopting LGS in mid-rise buildings in Australia:

- Developers require a demonstration of 15% savings to instill their confidence in replacing traditional systems such as reinforced concrete with LGS
- Given that the engineering processes for mid-rise buildings are centred around traditional systems such as reinforced concrete, which also has a well-established supply chain, the workflow should demonstrate LGS as a viable alternative with minimal disruption to current engineering processes
- The project should consider current IP sensitive work from the Steel Research Hub on the development of computational tools to evaluate LGS against several performance criteria.

This scoping study report identified the challenges that are hindering the adoption of LGS systems over traditional structural systems (such as RC and HRS) in mid-rise buildings. The Steel Research Hub listed the following challenges as the most prevalent:

- LGS is currently used in low-rise buildings that do not require a high production capacity. In order to adopt LGS in mid-rise buildings, a high production capacity is required, which incurs significant set-up costs for a new production line
- The adoption of LGS in mid-rise buildings requires a shift in the Australian construction process. More logistics and planning are required to adapt current construction processes for reinforced concrete and hot rolled steel to LGS
- Due to the nature of LGS structures, which are mainly manufactured in factories, design for transportation must be considered in the early phase of a project.

Although these challenges with production capacities and LGS supply chain need to be ultimately tackled in future projects to increase the speed of adopting LGS in mid-rise buildings, this project can add value by using GD automation to rapidly demonstrate the significant savings that can be incurred by LGS over RC, timber and HRS structural systems in the early planning phase of a project. Proving the cost-effectiveness of LGS against other materials will be the key barrier to the success of adopting LGS in mid-rise buildings.

The following key topics were covered with a view of demonstrating significant savings incurred by LGS over RC, HRS and timber systems:

- Recent research and case studies of LGS buildings: the review showed the advantages of LGS in mid-rise buildings compared to RC and HRS in terms of savings in material, construction and foundation costs
- Evaluation of industry accepted generative design (GD) and rapid engineering (RE) tools: the review demonstrated the need to adopt GD and RE for LGS buildings to assist decision

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

making in the early phase of a project, and increase the acceptance of LGS for mid-rise buildings

- Leading research on GD and RE tools for structural systems: this section covered broad applications of GD and RE tools in several fields of the construction industry namely design workflow, architectural design, structural design, design and manufacturing processes, modular design and construction, and also LGS systems
- Critical tools for the rapid evaluation of structural systems for low- to mid-rise commercial projects: Revit was shown to be the most common BIM platform to enhance collaborations between different departments and parties during a construction project. AGACAD was identified as the most powerful plugin to expedite the evaluation of LGS against HRS, RC and timber structural systems in the early planning phase of a project
- Inputs required by GD tools to assess structural systems: the list of critical inputs required by GD tools to assess structural systems was outlined against several criteria including project costs and cost-based comparisons of different construction systems, structural feasibility and design efficiency, material selection based on performance requirements, methods to select prefab components, and clash detection and management
- Interoperability of generative design tools with detailed LGS design and engineering software: the compatibility issues associated with LGS structures were discussed to provide recommendations on minimising rework for expediting the evaluation of LGS mid-rise buildings in the early project planning phase. A BIM platform with plug-ins designed for LGS framing is necessary to minimise rework, thereby ensuring seamless data exchange between different departments in a construction project namely architectural design, structural design, quantity take-off, manufacturing, and assembly.

The following key recommendations were provided for Phase 2 of the project, which are targeted at expediting the evaluation of LGS over other structural systems in mid-rise buildings in the early planning phase of a project:

- A generic GD workflow should be developed in Revit-Dynamo or Revit-Grasshopper to enhance interoperability between BIM and structural analysis and design software packages
- Revit is recommended as the BIM platform to evaluate the costs of LGS against other structural systems, which has been extensively employed in Australia and abroad
- AGACAD plugin for Revit is recommended as it supports the generation of different structural systems, including LGS, timber, RC and HRS, and has capabilities of computing costs and generating LGS geometry for CNC fabrication machinery
- Any structural analysis and design software package may be used (ETABS is selected by the Steel Research Hub)
- A library of LGS sections adopted in Australia should be developed in Revit and the selected structural analysis and design package
- AS 4600 conceptual design checks should be implemented in structural analysis and design software
- Logic may be implemented to provide a load rundown and replace LGS systems with HRS systems where the loading demand is exceeded
- Energy, acoustic and fire analysis tools developed in other projects in the Building 4.0 CRC may be added to the workflow to perform multi-objective optimisation and yield the most benefits in future.

1. INTRODUCTION

1.1. Aims

Light gauge steel (LGS) offers significant advantages over other construction materials including good strength for weight properties, ability to pre-fabricate, quicker construction times, non-combustibility and resistance to rotting, shrinking, warping and termite attack. Today, it is not clearly understood what tools and inputs should be considered at the early planning phase, for a LGS solution to be a viable structural construction alternative to reinforced concrete, timber, hot rolled steel and other structural systems, particularly in mid-rise building applications. The overarching aim of the project is to develop a generative design workflow that provides an automated side-by-side comparison of LGS and other traditional structural systems (e.g., reinforced concrete and timber) in the early planning phase of a project. The workflow should consider the following criteria for adopting LGS in mid-rise buildings in Australia:

- Developers require a demonstration of 15% savings to instil their confidence in replacing traditional systems such as reinforced concrete with LGS
- Given that the engineering processes for mid-rise buildings are centred around traditional systems such as reinforced concrete, which also has a well-established supply chain, the workflow should demonstrate LGS as a viable alternative with minimal disruption to current engineering processes
- The project should consider current IP sensitive work from the Steel Research Hub on the development of computational tools to evaluate LGS against several performance criteria.

This project will thereby determine the generative and engineering design, methods, tools and software critical for rapid evaluation of LGS structural solutions within low to mid-rise commercial projects, both now and into the future. Specifically, the project will investigate the goals being achieved by these design tools for stakeholders in the early planning phase of a project, and how LGS solutions are currently being considered within these tools and software. The critical tools that can expedite the evaluation of structural solutions against LGS will be considered, and recommendations will be provided on the methods, tools and software that are critical to accelerate LGS adoption in the early planning phases, in terms of:

- Providing design alternatives based on inputs of performance objectives and constraints from designers and engineers including spatial requirements (e.g., design layout, minimum room dimensions, wall and ceiling build-ups)
- Structural criteria (e.g., load transfer paths, structural spans and capacities)
- Rapidly evaluating the fire, thermal and acoustic performance
- Cost data, cost constraints and comparisons to alternative materials
- Automated materials selection and estimation (based on cost, and structural, fire, acoustic and thermal performance requirements)
- Guiding the management of services.

1.2. Recent research evaluating LGS against traditional structural systems in mid-rise buildings

There are limited research studies in the literature that demonstrate the advantages of LGS over hot-rolled steel (HRS) and reinforced concrete (RC) options in terms of materials, cost, time, foundation savings, embodied energy and so on [1-6]. The Steel Research Hub has conducted investigations into the viability of LGS for mid-rise buildings in Australia. The advantages of LGS compared to traditional materials employed in low- and mid-rise buildings are summarised and referenced in Table 1.

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

Table 1: Comparison between LGS and traditional material (RC and HRS).

Category	Mid-rise (4–6 stories)		Low-rise (1–2 stories)	
	LGS vs RC	LGS vs HRS	LGS vs RC	LGS vs HRS
Governing axial load of superstructure	53% reduction [1]			
Earthquake actions	58% reduction [1]			
Total weight	60% reduction [1] 67% reduction [4]	5% increase [4]	65% reduction [3]	50% reduction [3]
Total concrete volume in substructure	40% - 42% reduction [1]		7% reduction [3]	7% reduction [3]
Total steel reinforcement weight in substructure	45% - 59% reduction [1]			
Material cost	34% reduction [4]	89% reduction [4]		
Total construction cost	46% reduction [4]	18% increase [4]	2% reduction [3]	4.5% reduction [3]
Life cycle embodied energy			64% reduction [6]	53% reduction [6]
Life cycle greenhouse gas emissions			37% reduction [6]	51% reduction [6]

The above studies, which evaluate the benefits of LGS systems for mid-rise buildings are explored hereafter, focusing on the software tools employed (BIM, structural, life cycle analysis, planning/property development, and so on), adopted LGS design guidelines and key advantages. The advantages of LGS over traditional structural systems such as HRS and RC are determined based on several criteria including construction costs, gravity and lateral load demand on the foundation, and so on.

Franklin [1] developed archetype models of six storey mid-rise buildings (see Figure 1a) located in Brisbane and Sydney, to compare the performance of three structural systems, namely LGS, RC and HRS (and hybrids of LGS and HRS systems). The Building Information Model (BIM) was developed in Revit (see Figure 1b), and the structural analysis and design was conducted using ETABS, which supports Australian Standards for loading actions (AS1170) and RC design (AS3600), and American Standards (AISI S100-12, AISI S200-07, AISI S400-15) for LGS design. It can be observed in Figure 1 that the LGS building was 40% lighter than RC, which significantly reduced the loading demand on the foundation (53% decrease in the governing axial load (Figure 1c) and a 58% lower base shear (Figure 1d)). Two foundation options, namely pile foundations and pad footings, were designed using soil conditions (obtained from geotechnical data) in the Sydney CBD and a North Sydney suburb. It was shown that the application of LGS in the superstructure reduced the required volume of concrete by 42% in the pile foundations compared to the building constructed with RC. Furthermore, a 45% reduction in steel reinforcement in the foundation was also observed when choosing LGS over RC. In the pad footing foundations, these reductions were 40% and 59% for the volume of concrete and total weight of steel reinforcement for the substructure, respectively. Generally, the lightweight and high strength-to-weight ratio of LGS members, as well as the high degree of modularity of LGS systems, were found to be the key factors that yield prominent savings over RC systems in terms material and construction costs.

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

Franklin et al. [2] proposed a modelling method for analysing the lateral behaviour of LGS buildings. This study also considered the contribution of non-structural wall sheathing and other components for fire and acoustic compliance in ETABS. The LGS wall panel was simulated using four-node orthotropic shell elements with an effective shear modulus, which is a simplified approach that prevents modelling of the individual wall elements. The model was validated using data from a shaker table test of a two-storey building prototype. This calculation method predicted a reduced lateral storey drift, which is more accurate compared to conventional methods since the contribution of non-structural wall sheathing was taken into consideration. The model can thereby help to justify the feasibility of applying LGS in taller buildings where lateral stability becomes dominant in structural design.

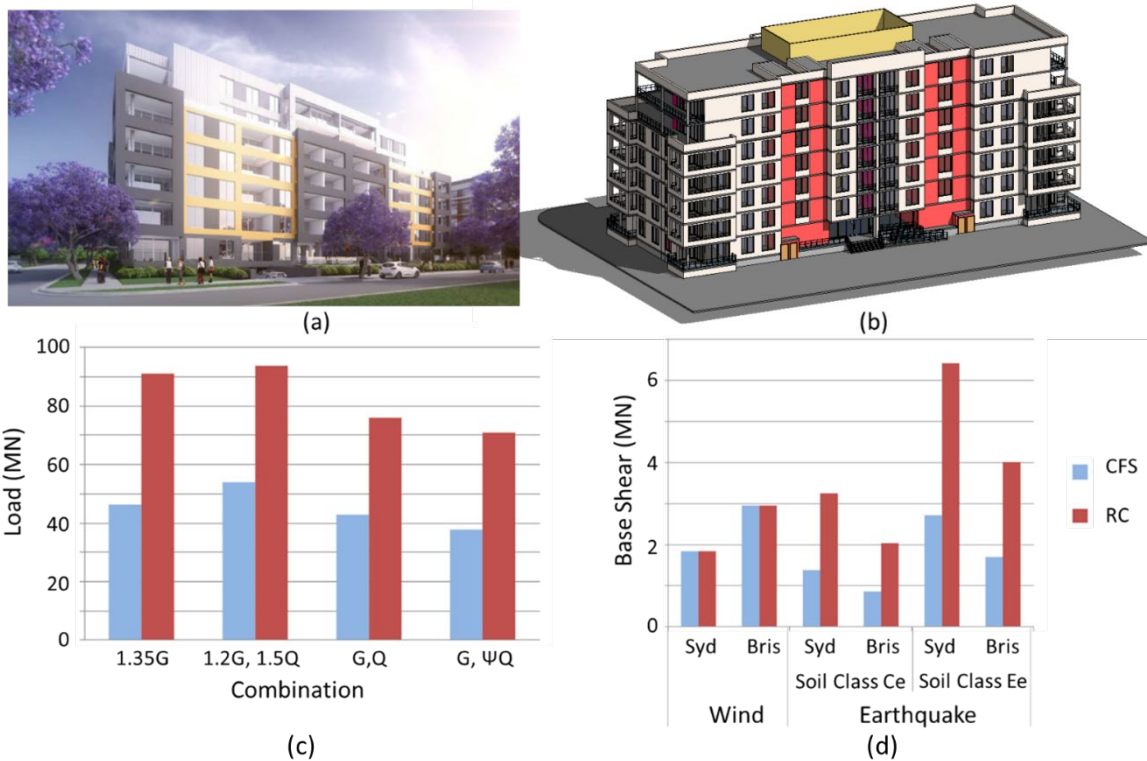


Figure 1: An archetype building comparing RC and LGS systems (a), Revit model (b), and the comparison of axial load (c) and base shear (d) in the foundation [1].

Harshavardhan et al. [3] compared the performance of LGS, HRS and RC in low-rise buildings using BIM modelling, and structural analysis and design software packages. This study is highly relevant as the modelling approaches and software tools adopted are transferrable to mid-rise LGS structures. The authors used Vertex Bd and STRAP 2018 for BIM and structural analysis of LGS, and Staad Pro for HRS and RC. Similar to the findings reported by Franklin [1], LGS was found to reduce the total weight of the building by 50% and 65% compared to HRS and RC options, respectively. The study showed that LGS reduced construction costs by 2% and 4.5% compared to RC and HRS structures, respectively. The LGS structure required 7% less volume of concrete in the foundation due to its lightweight. It can be noted that the building considered in this study was a single-storey resort building. As a result, the reduction of volume of concrete in the foundation was significantly lower than that reported for mid-rise structures in the study of Franklin [1]. The results also revealed that using LGS decreased the on-site construction time of the building by 75% compared to other systems due to its high degree of prefabrication. As a result, the total construction cost of the LGS building is 2% lower than that of the concrete structure and 4.5% lower than that of the HRS structure.

Doctolero et al. [4] conducted a comparative study on 4-storey LGS, RC and HRS office buildings. The structures were designed using Eurocodes 1, 2, 3 and British Standard BS 5950-5:1998

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

standards, and analysed using structural hand calculations. The authors reported that the LGS system is 67% lighter than the RC building but 5% heavier than the HRS alternative. The material cost of the LGS system was found to be only 66% of the RC system and only 11% of the HRS system costs. Using LGS saves 85% of the construction cost compared to RC. However, the construction cost of LGS was reported to be 15% higher than that of the HRS system because the total number of LGS elements required is higher than that of HRS to provide the same load-bearing capacity, leading to a higher cost of erection. Overall, the total cost of a building from LGS was only 39% and 65% of buildings comprising RC and HRS, respectively. Another benefit of using LGS is the reduction in construction time. It was revealed that using LGS reduced the on-site construction times by factors of 2.6 and 1.4 compared with RC and HRS buildings, respectively.

Torabian et al. [5] investigated the feasibility of LGS buildings with different heights (from 4 to 20 storeys) through archetype design. The authors reported that the LGS system satisfied the structural requirements for mid-rise buildings up to 20 storeys according to their hand calculations following American Standards ASCE7-10 and AISI-400-15. However, the study also determined that the capacities of the chord studs and ties/hold downs are only adequate for up to 4 storeys due to the high overturning moment (lower stability) in taller buildings. As a result, improving the performance of ties/hold downs and chord studs is vital to the success of employing LGS in mid-rise buildings.

Abouhamad et al. [6] compared the structural performance and life cycle embodied environmental impacts of two-storey LGS, RC and HRS buildings. They used Revit as the BIM modelling software, and STAAD PRO 3D for the structural analysis and design of the three construction systems namely LGS, RC and HRS. The building was first designed using three construction systems. Next, the total material used was calculated using the BIM model. Finally, the life cycle embodied energy of the building was assessed based on the material quantities and relevant life cycle inventory data. The study showed that the life cycle embodied energy of the LGS building was 64% and 47% lower than that of the RC and HRS buildings, respectively. No significant difference in the operational energies was observed in the three systems. Similarly, the life cycle greenhouse gas emissions from the LGS building were only 37% and 51% lower than those from the RC and HRS buildings, respectively.

In summary, the aforementioned research evaluating LGS against traditional structural systems in low- and mid-rise buildings shows significant improvements in terms of structural performance, costs and environmental aspects as presented in Table 1. The advantages and disadvantages of LGS are also summarised in Table 2. Generally, the advantages of the application of LGS increase with the number of stories. Common software packages used for modelling LGS systems are listed in Table 3. They will be reviewed and discussed further in the latter sections of this report.

Table 2: Advantages and disadvantages of LGS compared with traditional structural systems.

Advantages	Disadvantages
<ul style="list-style-type: none"> • High strength-to-weight ratio • High quality (consistent and reliable) • Durability (non-combustible and insusceptible to termites and mould) • Prefabrication • Fast construction • Cost-efficiency due to a reduced construction time and lower insurance premiums • Safety due to off-site manufacturing • Recyclable materials • Simple connection and assembly method 	<ul style="list-style-type: none"> • Height limitations • Thermal bridging due to high heat conductivity • Limited codes and permits • Limited architectural flexibility due to the requirement of wall alignment • Supply chain immaturity (requires high production capacity and high set up cost) • Transport requirements • Disruptive to the Australian industry (requires adaptation of the Australian construction process and more established supply chain) • Requires more training to improve the awareness of investors, architects and engineers of the benefits of LGS

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

Table 3: List of available software tools for evaluating LGS systems in the early project planning phase.

Category	Software Package
BIM modelling and detailing software	Autodesk Revit
	Autodesk Navisworks
	Autodesk BIM 360
	Tekla Structures
	ArchiCAD
	AGACAD
	StructSoft
	FRAMECAD
	SteelSmart Framer
Generative design and rapid engineering tools	Grasshopper
	Dynamo
	ArchiCAD API
	Giraffe
Structural analysis and design	SPACE GASS
	ETABS
	SAP2000
	Robot Structural Analysis
	STRAP
	DLUBAL
	Tekla Structural Designer

1.3. Case studies of mid-rise buildings adopting LGS structural systems

LGS is abundantly employed in mid-rise buildings in US, UK and Canada, where it has a well-established supply chain. Several case studies adopting numerous LGS structural systems are explored hereafter, focusing on the building details (number of storeys, structural systems and so on), project costs, and BIM/analysis software and their automation features. A summary of case studies adopting LGS for mid-rise buildings is presented in Table 4.

Table 4: Summary of case studies adopting LGS for mid-rise buildings.

Company	Building	No. of Storeys	Cost	LGS Structural System	GD/BIM Software Employed
Intelligent Steel Solutions	Vita Student Westgate [7] Newcastle, UK	6		LGS load-bearing walls as the main structure	Tekla Structures – Howick roll former extension
	The Brent House [8] London, UK	7-10	£76 mil.	LGS load-bearing walls as the main structure	
	Whiting Avenue [9]	4-6	£11.4 mil.	95% load-bearing panels were manufactured using LGS.	

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

Metek	Streatham Regeneration [10] London, UK	6	£80 mil.	LGS wall panels 100 mm x 50 mm C-sections Thicknesses 1.4 mm to 2.0 mm	Autodesk Revit - Metek Building System
	Oval Quarter [11] London, UK	6	£110 mil.	Cassette floor and roof joists thickness 1.2 to 2.4 mm Load bearing structure: 100mm C-sections in double leaf	
	Harbour Court [12] Bristol, UK	7		LGS load-bearing walls 100mm x 1.6mm C-sections	
Sigmat	iQ Bristol [13] Bristol, UK	11	£2.6 mil.	LGS load-bearing walls	Tekla structure
Prescient Co	Generation Atlanta [14] Georgia, US	17		12 upper storeys of LGS walls, frames with SHS post	Autodesk Revit with Prescient extension
Wall-tech	Metreau Apartments [15] Wisconsin, US	8		7 upper storeys of LGS walls, floor joists and roof trusses.	BIM (Software unspecified)
	316 Madison [16] Iowa, US	7	\$12 mil.	5 upper storeys of LS load-bearing walls	BIM (Software unspecified)
Worthington Building Systems	Convent Hill [17] Wisconsin, US	10	\$9.9 mil.	LGS load-bearing walls of 8 upper storeys. LGS floor joist and roof joist	BIM (Software unspecified)

Intelligent Steel Solutions [18], a UK-based company working in the design, manufacturing and installation of LGS and HRS, employed Tekla Structures in several mid-rise projects for 3D BIM modelling. They used the Howick roll former extension for Tekla to automate the manufacturing process. The company used LGS to build load-bearing panels for buildings up to 10 storeys including the Vita Student Westgate project [7], the Brent House [8] and the Whiting Avenue [9]. In these projects, Tekla Structures serves as a BIM platform to store the majority of building information including 3D models, structural drawings, bill of quantities and so on.

Metek [19] is a leading company in the design, manufacturing and construction of light steel structures in the United Kingdom. Metek has been developing their BIM system since 2010 using Autodesk Revit, and recently achieved a 5D BIM process to assist design, pre-construction and scheduling, fabrication and construction. Autodesk Revit was used to create 3D models, manage all drawings, outline construction sequences, and output bills of materials and costs. Metek employed LGS in load-bearing walls for low- to mid-rise buildings including the Streatham Regeneration [10], the Oval Quarter [11] and the Harbour Court [12]. In these projects, LGS was used in both load-bearing and non-load wall panels together with rectangular hollow sections and square hollow sections for areas with a high loading demand.

Sigmat [20] is another UK based company working in off-site manufacturing and construction of LGS framing systems. The company employs Tekla BIM software to design superstructures using LGS. Sigmat is the LGS contractor working on the iQ Bristol project [13], which is considered the highest LGS building in the UK. The 11-storey building comprises LGS frames and floor systems sitting on a podium base. The project was completed in only 17 weeks using off-site manufacturing

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

of LGS walls, frames and floor systems. Tekla Structures was used for the project to create the 3D model and manage project information such as drawings and bill of quantities.

Prescient Co [21] is a US-based company working on LGS structural systems. Prescient developed a plug-in for Autodesk Revit to work with their LGS system for design, manufacturing, and onsite assembly. According to the company, the Prescient LGS system is suitable for building up to 54 meters. The system comprises hollow section steel posts, and LGS frames and wall panels. Their currently highest building is the Generation Atlanta [14] comprising 12 Prescient storeys built over 5 storeys of concrete podiums.

Metreau Apartments [15] is an 8-storey residential building comprising 107 units. This project was constructed using 7 storeys from a LGS framing system. Wall-tech, a US-based company, was in charge of manufacturing and carrying out onsite assembly of the LGS framing system including LGS walls, floor joists and roof trusses with thicknesses from 1.1 mm to 2.5 mm. Wall-tech is also the LGS contractor of 316 Madison building [16], a 7-storey student accommodation. Wall-tech constructed the Tall Order project using LGS load-bearing walls on 5 upper storeys sitting on a two-storey concrete podium. In these projects, Wall-tech also developed BIM models to manage building information. However, they did not specify the software.

Convent Hill [17] is also a mid-rise building constructed using LGS. The project is a residential building consisting of 120 units over 10 storeys. The LGS system was manufactured and assembled by Worthington Building Systems using cold-formed steel C-sections with thicknesses from 1.1 mm to 1.7 mm for wall panels, and up to 2.5 mm in floor joists.

In summary, LGS structural systems have recently been adopted in mid-rise buildings in Europe and America. All activities related to a LGS structural system such as design, manufacturing and onsite assembly are usually conducted by a LGS contractor since the design and manufacturing processes are highly dependent on specific machinery and related software. Due to the limitation of the thickness and size of a LGS member, the load-bearing capacity of a mid-rise building is usually enhanced by concrete cores and hot-rolled steel posts, and beams at critical positions to increase the resistance capacity against lateral and/or gravity loads. Furthermore, due to the complexity of design, manufacturing and onsite assembly of LGS systems, Building Modelling Information (BIM) is employed by almost all companies mentioned above (see Table 4). The application of BIM enables real-time coordination between stakeholders during design, construction and maintenance phases, thereby saving time and costs arising from changes and adjustments during these phases. It can also be noted from Table 4 that the US and UK are the leading countries in developing LGS systems for mid-rise buildings. Therefore, developing LGS systems for mid-rise buildings in Australia is imperative considering the advantages of LGS systems over traditional structural systems outlined above.

The adoption of LGS in mid-rise buildings in Australia has been hindered by several factors outlined by Franklin [1] from the Steel Research Hub:

- Firstly, LGS is currently used in low-rise buildings that do not require a high production capacity. In order to adopt LGS in mid-rise buildings, a high production capacity is required, which incurs significant set-up costs for a new production line.
- Secondly, the adoption of LGS in mid-rise buildings requires a shift in the Australian construction process. More logistics and planning are required to adapt current construction processes for reinforced concrete and hot rolled steel to LGS.
- Thirdly, due to the nature of LGS structures, which are mainly manufactured in factories, design for transportation must be considered in the early phase of a project.

These challenges need to be tackled in order to increase the speed of adopting LGS in mid-rise buildings. The adoption of LGS in mid-rise buildings can be accelerated through current developments in prefabrication and modular construction in Australia, which can resolve the challenges related to logistics and transportation. As a result, proving the cost-effectiveness of

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

LGS against other materials will be the key barrier to the success of adopting LGS in mid-rise buildings.

1.4. Breakdown of this scoping study

This scoping study report, which lays the foundation for the subsequent phases of the project, covers the following key areas:

- Evaluation of industry-accepted generative design and rapid engineering tools (Section 2)
- Leading research on generative design (GD) and rapid engineering (RE) tools for structural systems (Section 3)
- Critical tools for the rapid evaluation of structural systems for low- to mid-rise commercial projects (Section 4)
- Inputs required by GD tools to access structural systems (Section 5)
- Interoperability of GD tools with detailed LGS design and engineering software (Section 6).

2. EVALUATION OF INDUSTRY ACCEPTED GENERATIVE DESIGN AND RAPID ENGINEERING TOOLS

2.1. Traditional GD methods and systems

Generative design (GD) is a process by which designers or engineers employ a software that explores all possible permutations of a solution. The software performs numerous iterations and provides several design options based on a set of objectives (e.g., structural performance, energy consumption and daylighting/glare) whilst satisfying a set of constraints (e.g., maximum cost, minimum section thickness and maximum span length). In the context of buildings, GD may be employed to generate various architectural shapes and forms, and optimise the structural performance [22, 23]. GD can automate repetitive, tedious and time-consuming tasks and procedures, which is particularly advantageous for mid- to high-rise buildings. A designer can thereby rapidly evaluate and explore numerous design options [24].

The common existing GD tools are those that enhance interoperability between software applications (e.g., structural and BIM) thereby exploiting their existing powerful functionality and integrating them together in a workflow. This workflow can effectively be used, for example, to expedite the generation of BIM models, conduct structural analysis simulations and run optimisation studies, which can lead to significant time and cost savings. The common industry accepted GD tools, which can be particularly useful for automating the evaluation of LGS against other structural systems in the planning phase of a project, are Grasshopper and Autodesk Dynamo. These central visual scripting tools contain many plugins (implemented by architects, engineers and so on) that provide connectivity between the various existing planning, analysis (structural, energy/thermal, daylighting), design (members, components and connections), and BIM and production management software packages. A high-level snapshot of an example GD framework is illustrated in Figure 2, which highlights the strong industry acceptance of Dynamo and Grasshopper, given the extensive development of plugins that interface with some of the software tools shown.

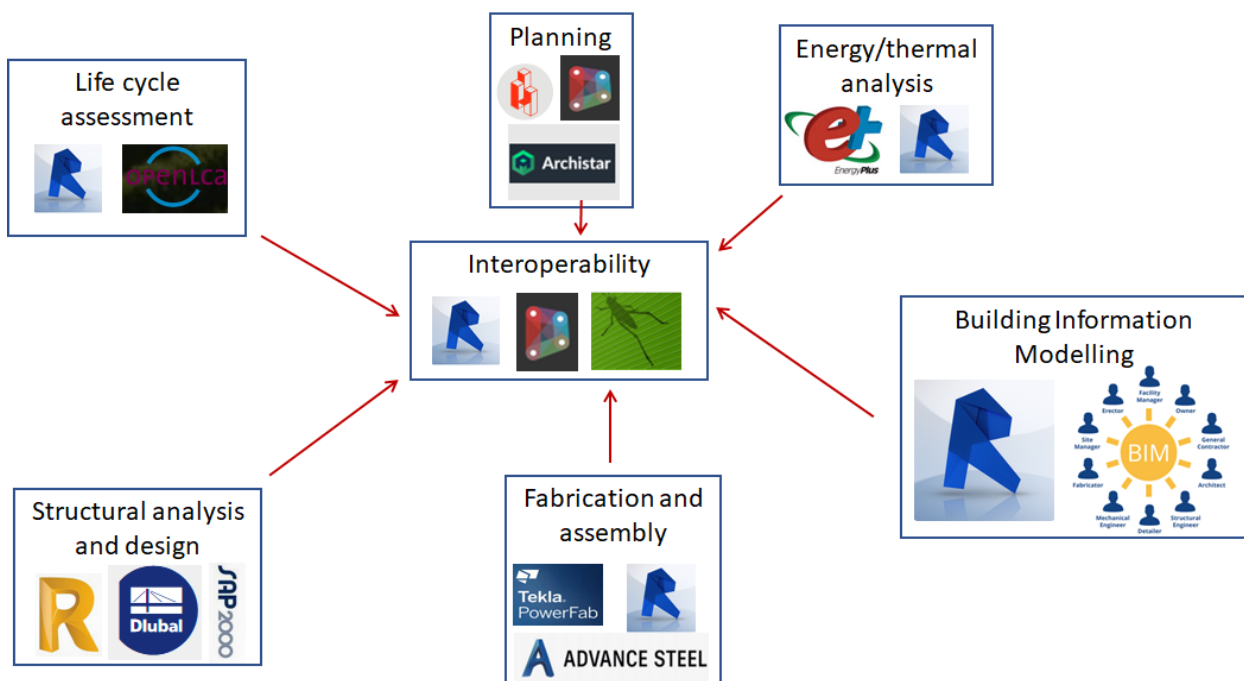


Figure 2: GD tools enhancing interoperability between several software packages. Revit possesses numerous functions and thereby appears in several categories.

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

2.1.1. Grasshopper

Grasshopper is a visual programming language and environment that runs within the Rhinoceros 3D computer-aided design (CAD) application [25]. Grasshopper is primarily used to build generative algorithms. Many of Grasshopper's components create 3D geometry. Advanced uses of Grasshopper include parametric modelling for structural engineering, architecture and fabrication, lighting performance analysis for eco-friendly architecture, and building energy consumption [26]. Figure 3 illustrates an example where building design options were generated using Rhino-Grasshopper.

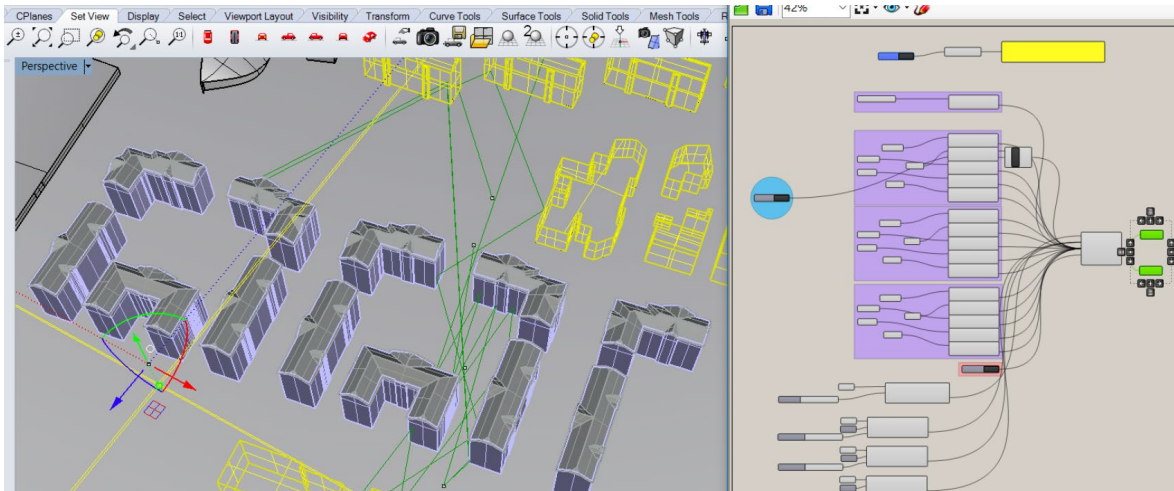


Figure 3: An example of building design options generated using Rhino-Grasshopper [27].

Revit-Grasshopper tool: The latest version of Rhino (Rhino7) includes a new technology that allows the user to work with Rhino and Grasshopper inside Revit's environment. Rhino.Inside.Revit allows the user to link both platforms and avoid the need to import or export geometry. This creates an unprecedented integration between these applications and enables Rhino to run as a plugin inside other host applications. This can simplify the process for exchanging models as the user can directly access the Revit Application Programming Interface (API).

An example of a computational design workflow using Revit-Grasshopper is shown in Figure 4. Grasshopper is used as the parametric design tool and a visual programming environment tightly integrated with Rhino's 3D modelling tools. Grasshopper requires no knowledge of programming or scripting, but still allows designers to build simple to awe-inspiring generative forms. Grasshopper also has a very rich add-on library.

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

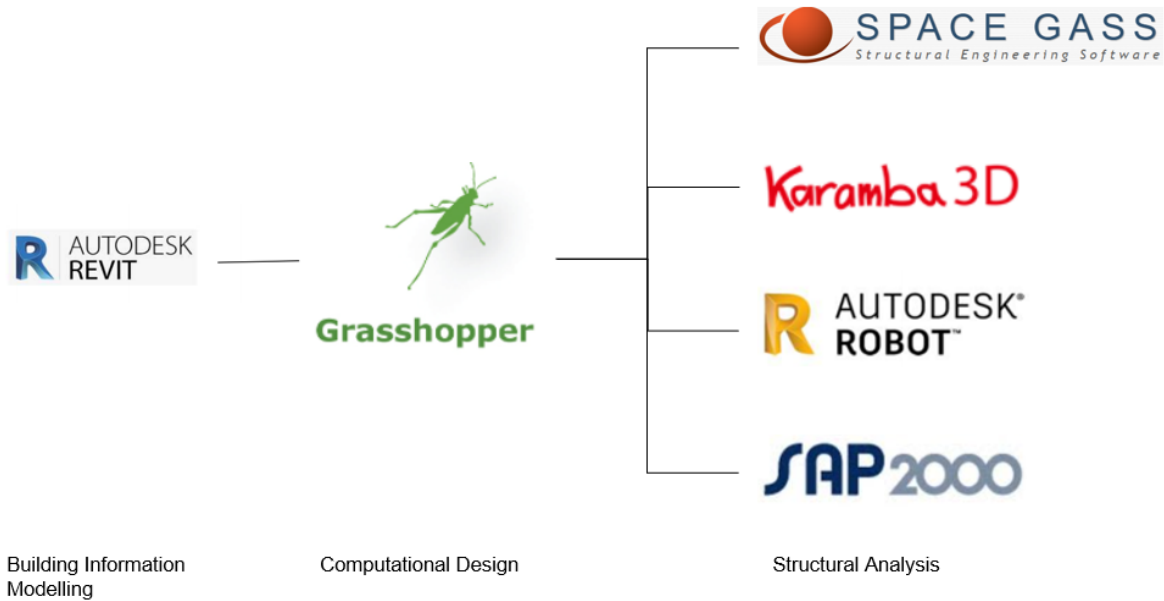


Figure 4: Computational design workflow using Revit-Grasshopper tool.

To explore the computational design workflow in Revit-Grasshopper, a parametric tool was developed for a multi-storey steel frame building. In this section, Karamba 3D is used as a parametric structural engineering tool in Grasshopper which provides accurate analysis of spatial trusses, frames and shells. Figure 5 shows an example of a parametric model of a multi-storey steel building using the Revit-Grasshopper workflow, with the 3D visual model generated in Revit and the analytical model generated in Autodesk Robot Structural Analysis.

In addition to the strength of the Autodesk Revit tool mentioned in the previous section, additional advancements of the design workflow using the Revit-Dynamo tool are summarised below:

- Karamba3D is fully embedded in the parametric design environment of Grasshopper, a plug-in for the 3D modelling tool Rhinoceros. This makes it easy to combine parameterised geometric models, finite element calculations and optimisation algorithms like Galapagos.
- Rhino-Grasshopper is also much lighter and faster than Revit-Dynamo.

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

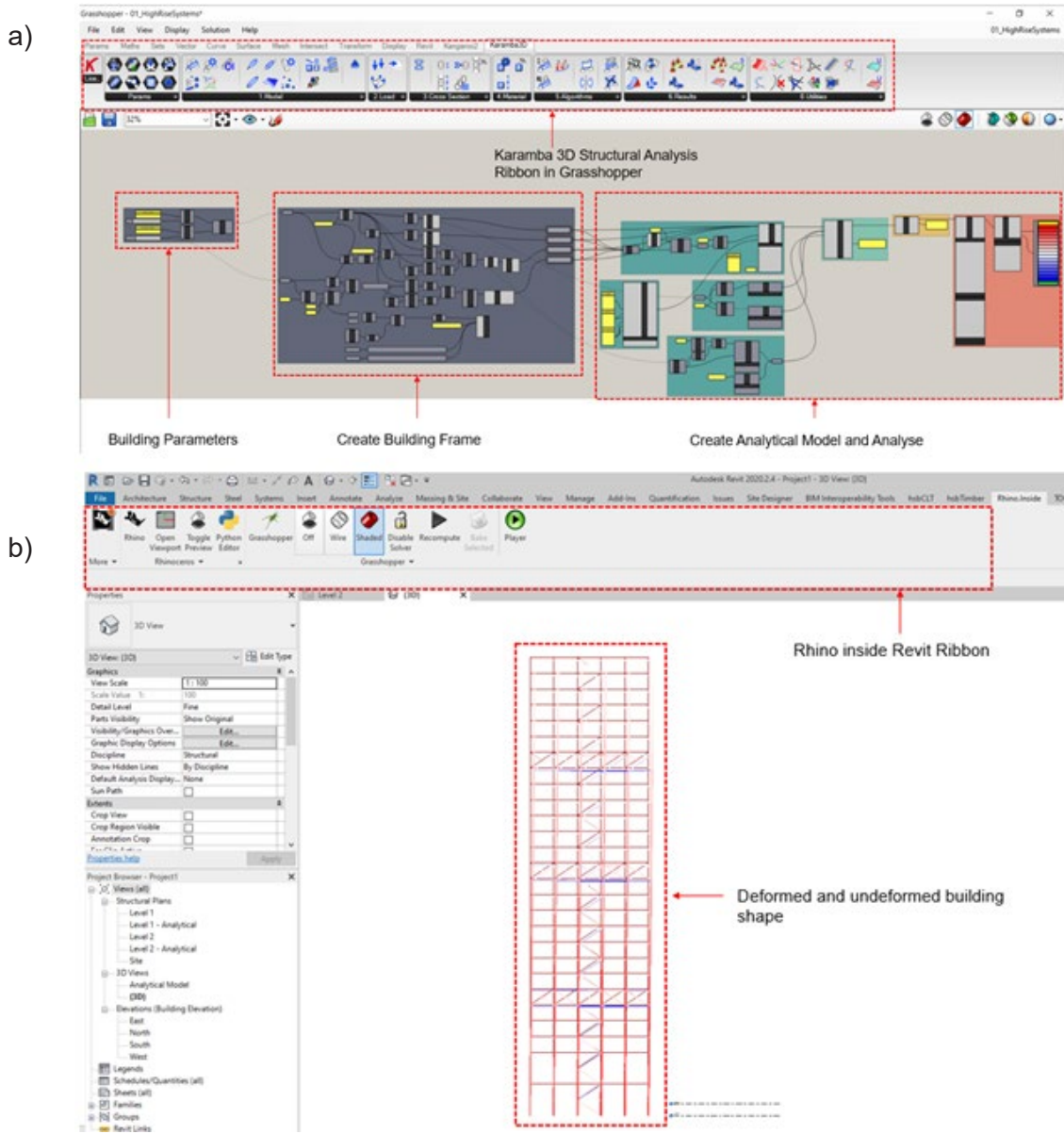


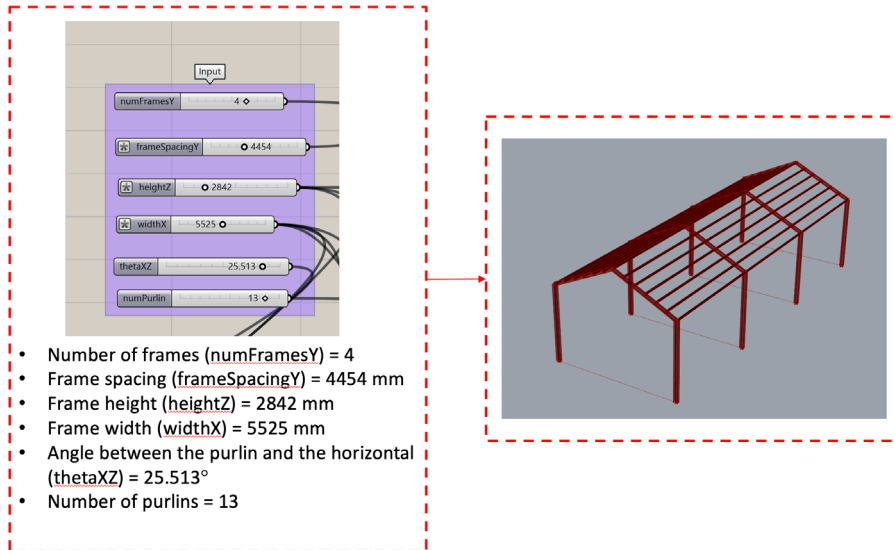
Figure 5: Parametric model development using Revit-Grasshopper tool: a) parametric model in Grasshopper; and b) generated building model in Revit.

Rhino and Grasshopper: Similar to Revit-Dynamo, Rhino and Grasshopper provide new methods for extending and controlling 3D design and modelling processes. These include automating repetitive processes, generating geometry through mathematical functions, quickly making changes to complex models, and creating complex forms through repetitions of simple geometry. As discussed in the previous section, Rhino/Grasshopper is more cost-competitive than the Autodesk family i.e., the development community around Grasshopper is stronger. There are other differences between the two platforms. For example, trees are used in Grasshopper to store data whereas nested lists are used in Dynamo. However, many users report that their computational speed is slightly different. A simple example of a frame prototype developed in Rhino and Grasshopper, and Autodesk Robot Structural Analysis (RSA) is provided to demonstrate the interoperable software capabilities. The prototype includes the following considerations:

- The variables are parametrised, e.g., frame spacing, frame height and roof pitch as shown in Figure 6
- The geometries are generated to input into structural analysis
- Some of the surfaces are generated (floor and wall) to input for energy analysis.

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

Several plugins that are available in food4rhino.com can link structural analysis programs and Rhino/Grasshopper. Modelling, setting load and load combination data, performing remote analysis operations, extracting results, and automating the overall design process of structures are all made easier with plugins. Geometry Gym plugin was chosen in this report. The plugin links many commercial structural analysis software packages such as GSA, ETABS, SAP2000, Autodesk RSA, Strand7, Spacegass, Bentley ISM, Microstran and Karamba3d. The link to Robot Structural Analysis (Robot) is demonstrated through a simple example herein.



Input: User-defined parameters:

Output: Desired geometry

Figure 6: Parametrised geometry of a portal frame with a gable roof in Rhino/Grasshopper.

In addition to geometry, materials and section properties, member restraints and releases can be defined and automatically updated in RSA. Figure 7 shows an example where the user can easily update the footing restraint in their Robot model using a toggle switch in Grasshopper.

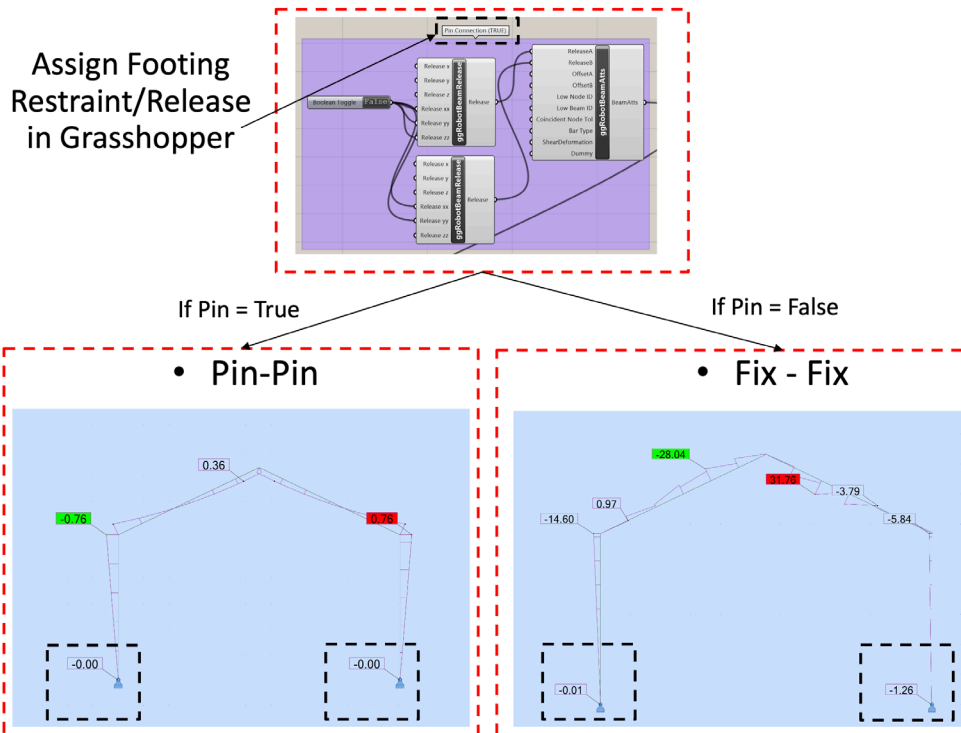


Figure 7: Linking member restraints and releases between Grasshopper and Robot Structural Analysis.

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

In terms of loading, different load combinations and assumptions can also be made in the model. For example, the closed frame is subjected to a dead load, superimposed dead load, live load and wind load. The load values and factors in load combination 1 are shown in Table 5. With this load combination, the most outer purlins (green purlins in Figure 8) are modelled to carry only half of the load carried by the inner purlin. The vertical load (Pz) of 0.74kN is applied to the outer purlins compared with 1.48 kN for the inner purlins (Figure 8).

Table 5: Load acting on the portal frame.

Type	Assumption	Factor
Dead Load	Based on material and section of the member	1.2G
Live Load (roof)	0.25 kPa	1.0Q
Wind Load (upward)	0.75 kPa	0.7W
Superimposed Dead Load	0.35 kPa	1.2G

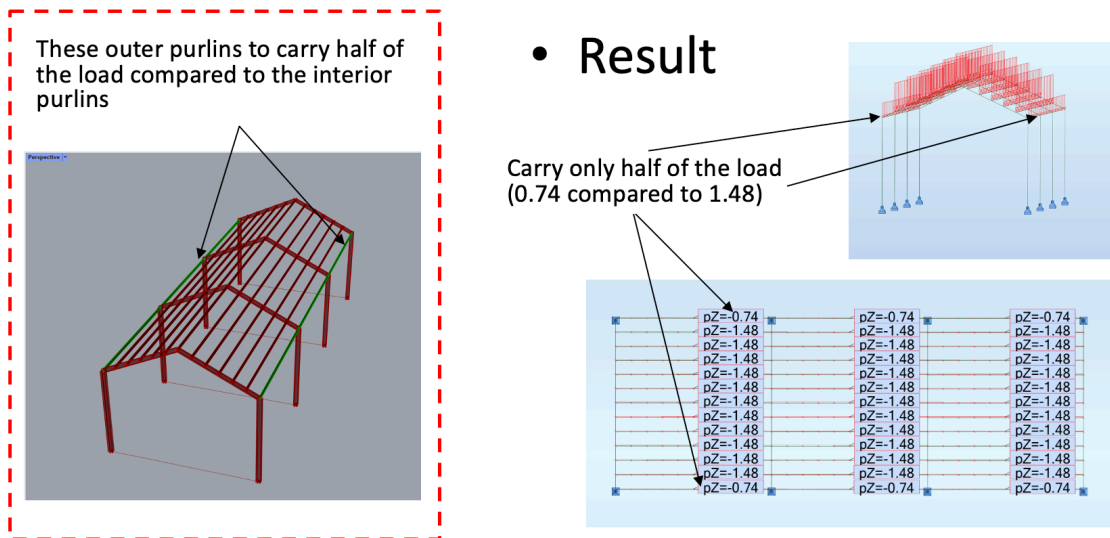


Figure 8: Different assumptions can be made by the user with Grasshopper, which are automatically updated in the RSA model.

Figure 9 shows that the result can be quickly extracted from Robot Structural Analysis to Grasshopper. With this capability, a simple parametric study was also conducted to determine the impact of the angle θ on the reaction of the footing. The results are shown in Figure 10.

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

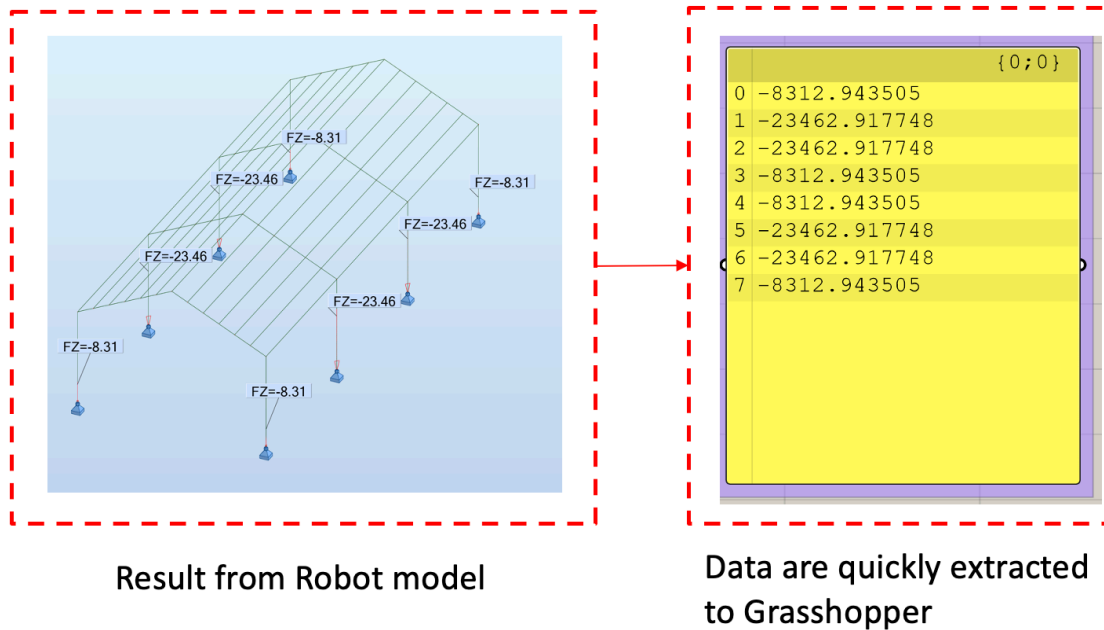


Figure 9: Extracting the results directly from Robot to Grasshopper for design calculations.

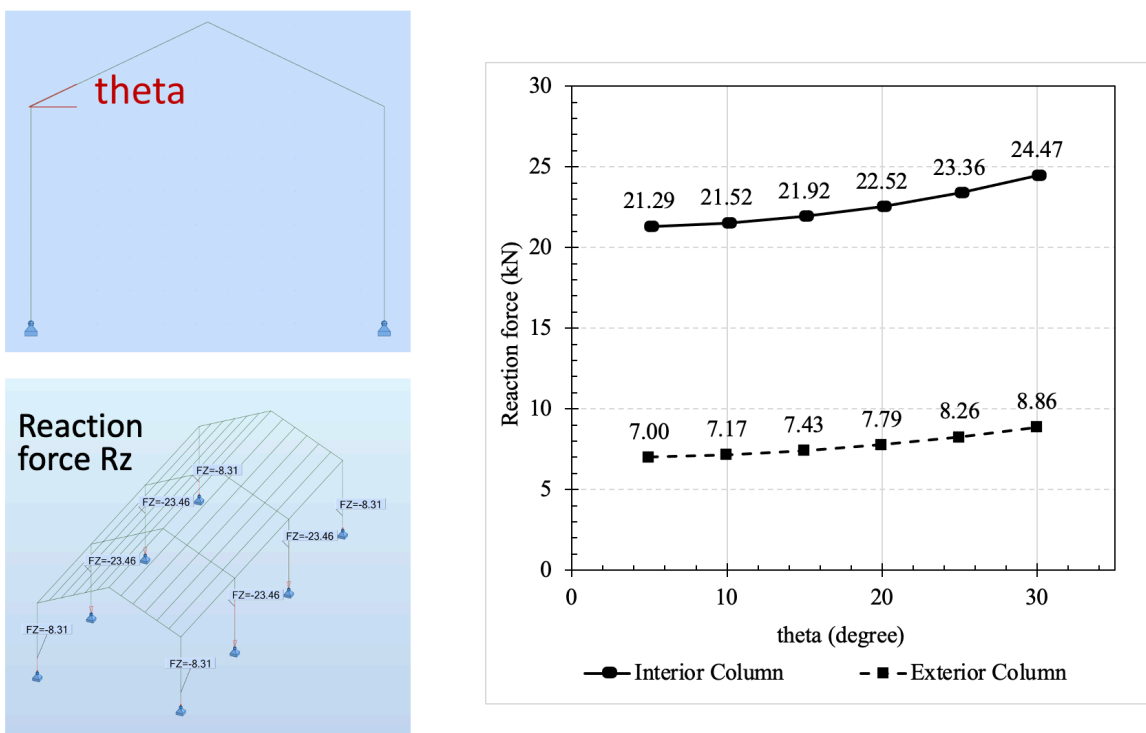


Figure 10: A simple parametric study assessing the effects of the roof pitch angle on the reaction at the footing.

2.1.2. Autodesk Dynamo

Autodesk Dynamo is a graphical programming interface that allows the user to customise their building information workflow. Dynamo is an open-source visual programming tool that is installed as part of Autodesk Revit. Dynamo extends the power of Revit by providing access to the Revit Application Programming Interface (API) in a more accessible manner, rather than through typing code. With Dynamo, the user can create programs by manipulating graphical elements called

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

nodes. It is an approach to programming better suited for visually oriented people e.g., architects, designers and engineers [28]. An example demonstrating generative design using Dynamo is shown in Figure 11.

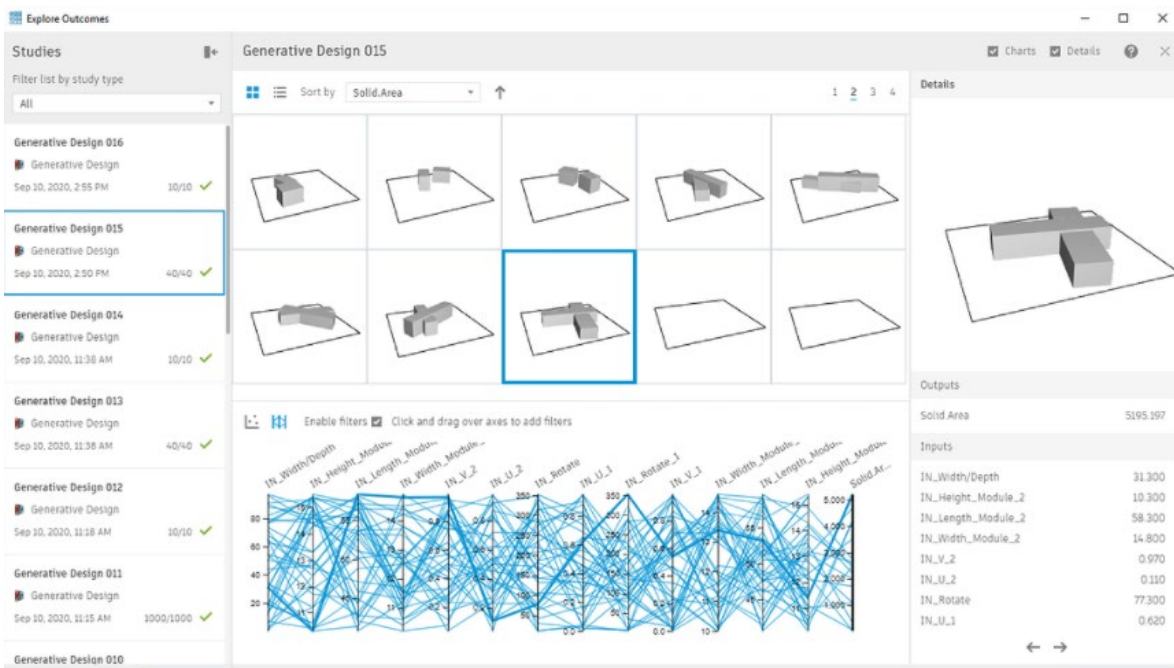


Figure 11: An example of generative design using Autodesk Dynamo [29].

In this section, Revit-Dynamo tools will be investigated to explore their capabilities in creating an automated computational design process from geometric design to the structural analysis stage. The computational design workflow using Revit-Dynamo is shown in Figure 12. The computational design workflow will create the model parametrically using Dynamo with Revit, the host BIM platform for 3D visualisation of the building system. The building model will be automatically generated into structural analysis software for analysis in Autodesk Robot or SAP2000.

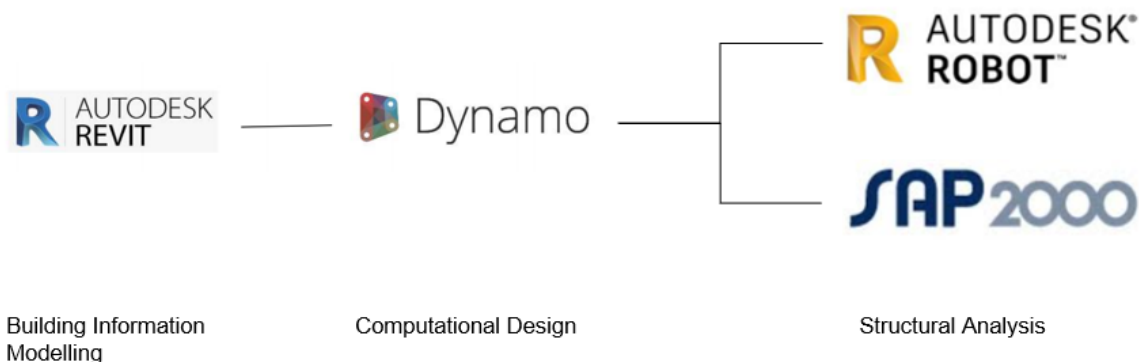


Figure 12: Computational design workflow using the Revit-Dynamo tool.

In Dynamo, each node performs a specific task. Nodes have inputs and outputs as shown in Figure 13. The outputs from one node are connected to inputs on another using wires. The program or graph flows from node to node through the network of wires. The result is a graphical representation of the steps required to achieve the end design.

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

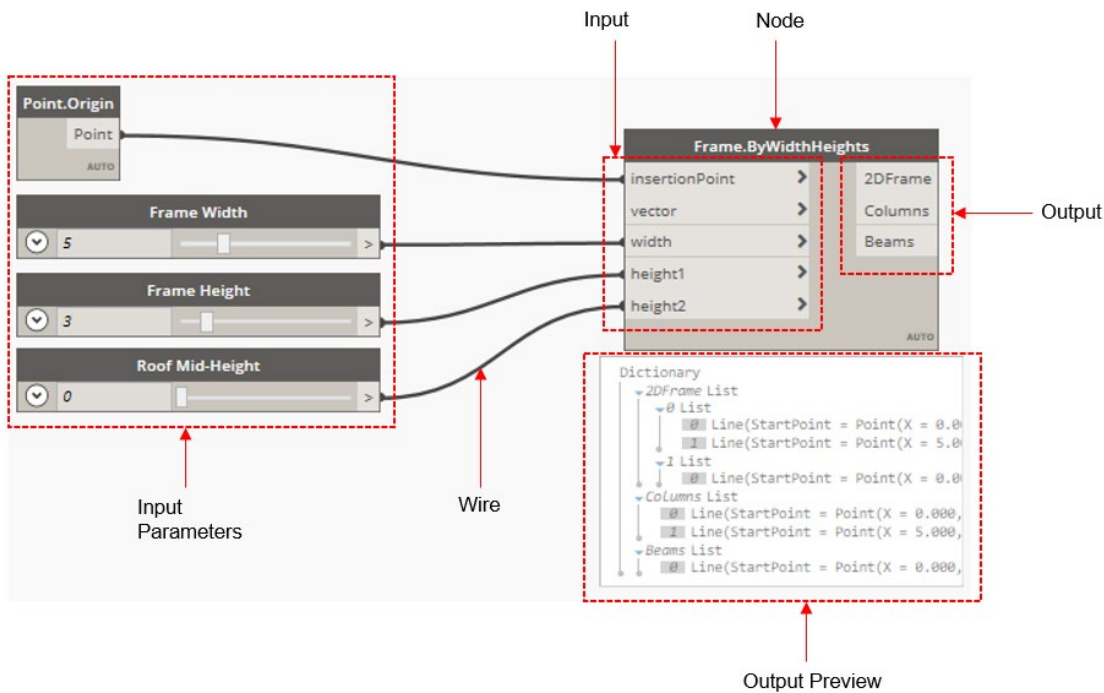


Figure 13: Overview of an Autodesk Dynamo process.

Dynamo users can also create node libraries or packages and upload them to a central repository. This repository can be searched directly and installed from within Dynamo. For example, the Structural Design (SD) package was developed and published by Tomasz Fudala [30] to assist structural engineering users in creating an analytical model for a parametric 2D portal frame with input parameters such as insertion point, width, eave height and ridge height as shown in Figure 14. The author used Python/Microsoft Visual Studio to develop the script for nodes in the SD package.

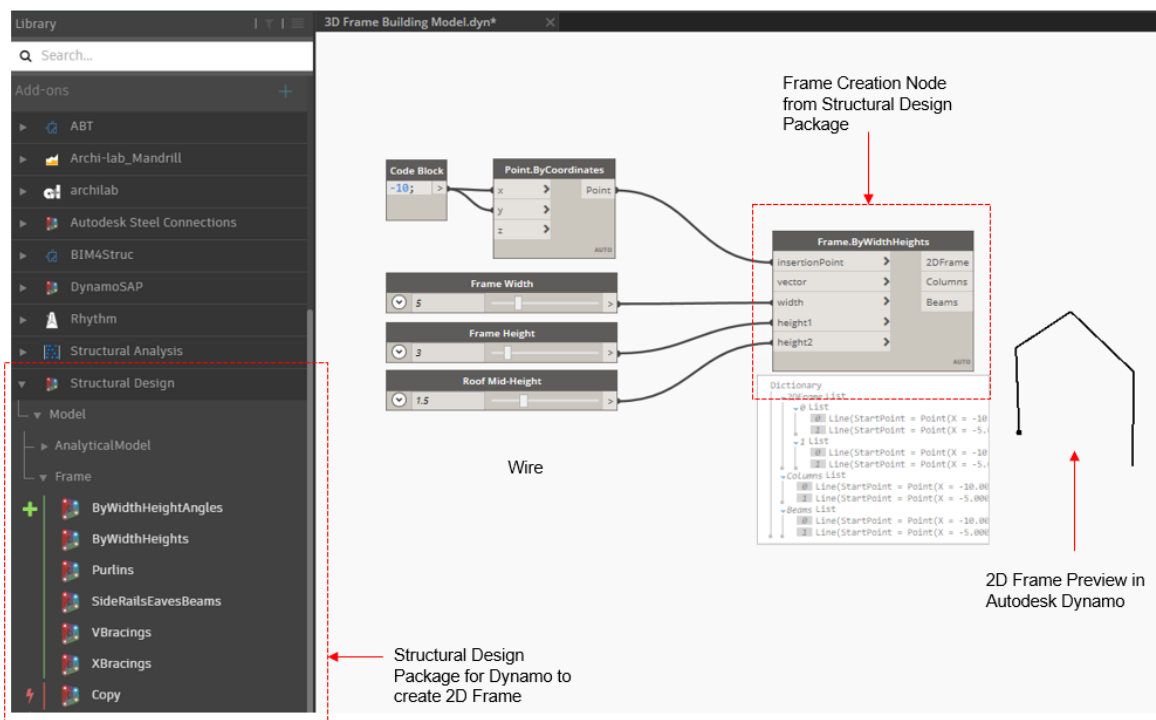


Figure 14: Example employing the Dynamo Structural Design package to create a 2D portal frame.

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

To explore the computational design workflow in Revit-Dynamo, a parametric tool was developed for a multi-storey steel frame building. SD package was used to generate the 3D frame model in Revit and the analytical model in Autodesk Robot for structural analysis. Figure 15 shows the parametric process for creating a multi-storey steel building, the 3D visual model generated in Revit and the analytical model generated in Autodesk Robot.

The Structural Analysis (SA) package enables the analysis of more design options, and more complex and resilient structures. Based on the Dynamo geometry, structural engineers can create an analytical model, and apply section shapes and boundary conditions, such as supports and releases. Engineers can also create structural load cases and automatically apply loads, which can be recalculated every time the structural geometry is changed. Once the analysis is done, structural engineers can review the results of the analysis in Robot Structural Analysis, or they can retrieve the results within Dynamo.

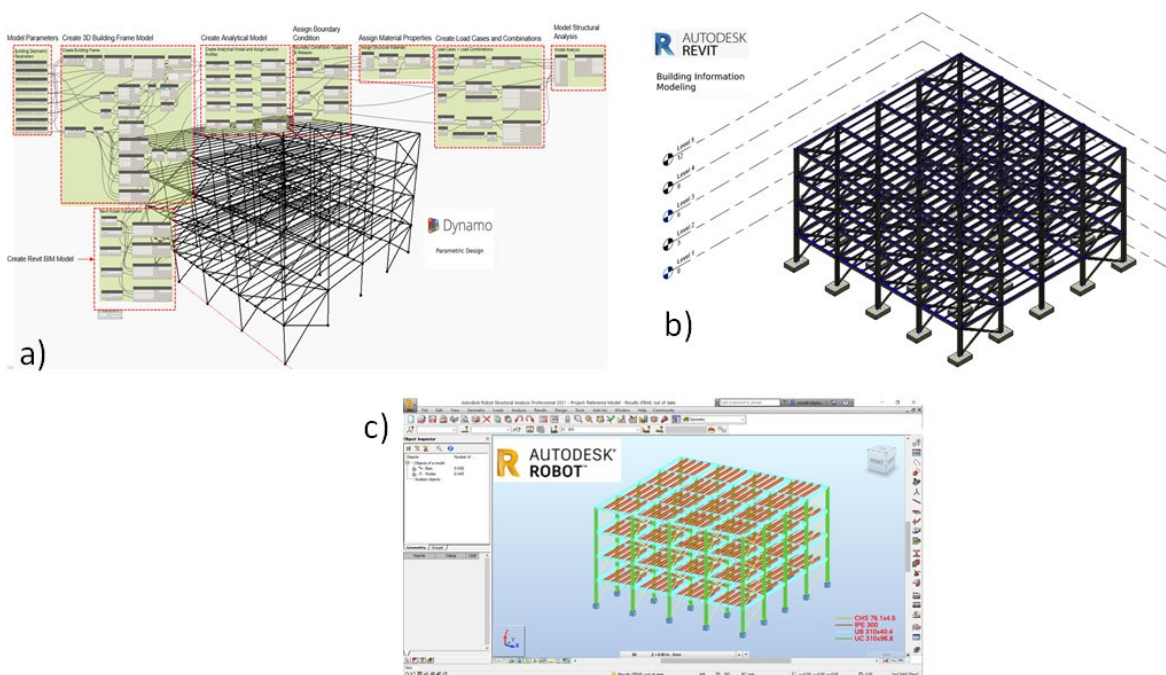


Figure 15: Parametric design workflow of a multi-storey steel frame building: (a) parametric process in Autodesk Dynamo; (b) 3D BIM model generated in Revit; and (c) analytical model generated in Autodesk Robot for structural analysis.

Another package exists for structural analysis of the parametric model in Dynamo, which allows for building model analysis in SAP2000. This package is DynamoSAP which is a parametric interface for SAP2000 developed in C Sharp using Visual Studio, and tested with Dynamo 0.7.5 and SAP2000 version 16 by Core Studio from Thornton Tomasetti Team. The package enables designers and engineers to generatively author and analyse structural systems in SAP, using Dynamo to drive the SAP model. A sample workflow process is shown in Figure 16.

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

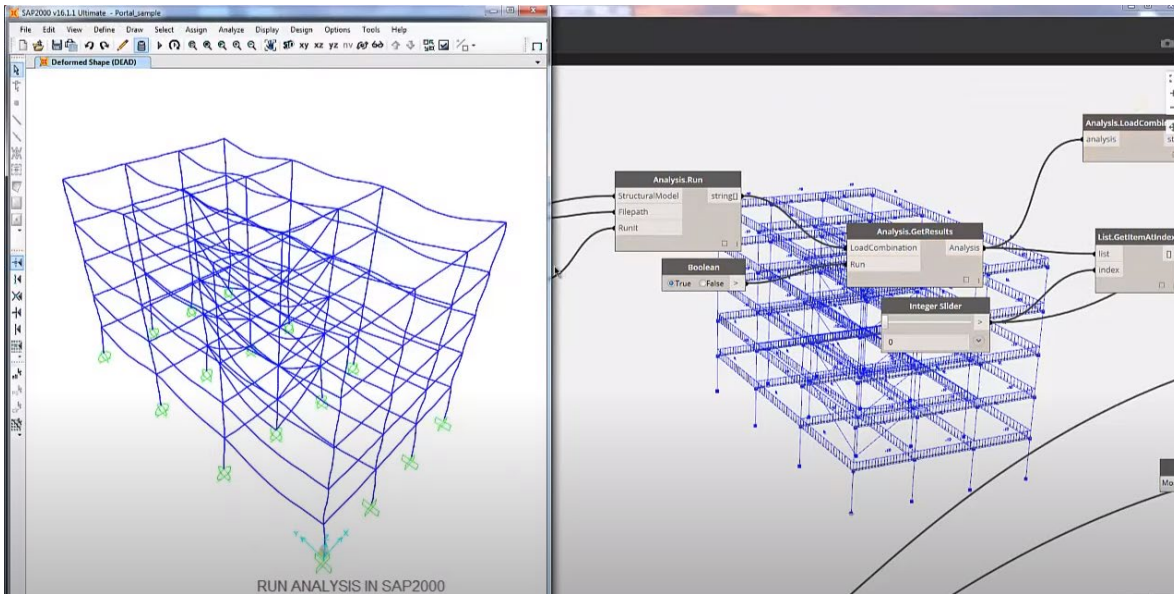


Figure 16: Example of structural analysis on a steel frame building using DynamoSAP library.

Figure 17 shows a parametric design workflow developed for a 3D steel frame building with the steel deck floor system included as part of a tool developed in the Revit-Dynamo workflow. The tool is capable of generating the steel deck into Autodesk Revit for 3D modelling and the analytical model into Autodesk Robot for structural analysis in real time.

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

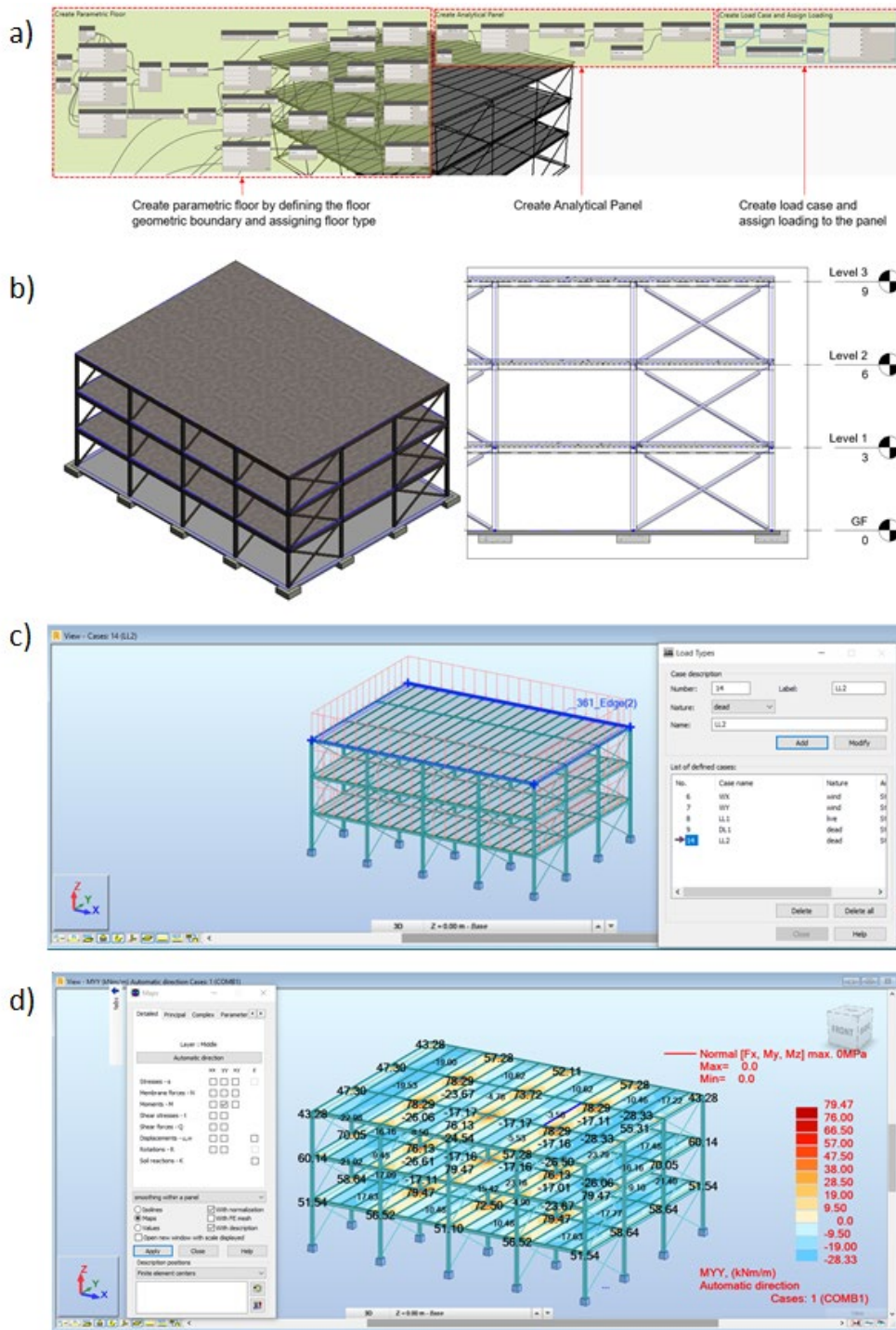


Figure 17: Parametric modelling workflow of a multi-storey steel frame building with the steel deck floor system: (a) parametric process in Autodesk Dynamo; (b) 3D and elevation views of the BIM model generated in Revit; (c) analytical model generated in Autodesk Robot for structural analysis with the applied loading; and (d) moment distribution of the panel resulting from load combination 1.2DL+1.6LL.

2.2. Building information modelling software

Building Information Modelling (BIM) is the holistic process of creating and managing information for a built asset. BIM integrates structured, multi-disciplinary data to produce a digital representation of an asset across its lifecycle, from planning and design to construction and operations based on an intelligent model. The model can be enabled by a cloud platform. BIM is used for creating and managing data during design, construction and operations processes. BIM integrates multi-disciplinary data to create detailed digital

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

representations that are managed in an open cloud platform for real-time collaboration. Using BIM provides greater visibility, better decision-making, more sustainable options, and cost-savings on Architecture, Engineering and Construction (AEC) projects. There are many BIM software packages available. Some of the most commonly used BIM software that have the most potential to enable the adoption of LGS for mid-rise buildings in the construction industry are reviewed hereafter, with Revit and Tekla Structures being the most widely adopted as per the case studies visited in Section 1.3.

2.2.1. Autodesk products

Autodesk Revit [31] is one of the most commonly used BIM software packages that centralises architecture, engineering and construction disciplines into a unified modelling environment, thereby driving more efficient and cost-effective projects. The software can be employed to drive efficiency and accuracy across the project lifecycle, from conceptual design, visualisation and analysis to fabrication and construction. Revit enables the user to model buildings with accuracy and high precision, automatically update floor plans, elevations and sections, and generally automates repetitive tasks. The key aspects of Revit are architectural design, structural engineering, Mechanical, Electrical and Plumbing (MEP) engineering and construction. Revit is capable of coordination and planning i.e., 4D BIM for project life cycle, maintenance and even demolition procedures for various structural systems including LGS can be executed. Moreover, 5D BIM can be carried out for budgeting of the various projects. The key functionalities of Revit are listed as follows:

- Architectural design (conceptual, building energy optimisation, 3D design visualisation etc.)
- Structural engineering and fabrication (physical and analytical model, reinforcement detailing, structural steel modelling with high level of detail using a variety of parametric steel connections in Revit or by creating customised steel connections)
- Mechanical, electrical and plumbing (HVAC, electrical and plumbing design and documentation, MEP fabrication detailing)
- Fabrication service conversion and documentation
- Work-sharing whereby stakeholders from multiple disciplines can work on the same files
- Create schedules, quantities, and material take-offs to quantify and analyse the components and materials used in a project
- Provide a tabular display of model information from the properties of elements in a project
- Interoperability and modelling LGS systems through plugins, and exports to specialised LGS packages (e.g., ENDUROCAD) in commonly used formats such as Industry Foundation Classes (IFC).

The key automation capabilities of Revit are listed as follows:

- Specialised plugins for LGS systems have been developed, which are discussed in Section 2.4, namely AGACAD, StructSoft, FRAMECAD and SteelSmart Framer
- New generative design module to quickly produce design alternatives based on objectives and constraints
- Expand and optimise BIM workflows with an open-source graphical programming interface (Dynamo)
- Allows user to extend Revit functionality with API access, third-party solutions, add-ins and a content library on the Autodesk App Store
- Interface with analysis tools e.g., Robot Structural Analysis
- Link with LGS fabrication tools (e.g., CNC machine and roll former) through the aforementioned plugins
- Interface with Grasshopper through Rhino.Inside.Revit.

Revit Generative Design [32, 33], formerly Autodesk Project Refinery, allows the user to rapidly generate design alternatives based on their goals, constraints and inputs. The user can then explore, optimise and make informed decisions to address design problems. In Dynamo for Revit,

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

a new set of tools streamlines and simplifies the creation and update process for graphs that will be used as Generative Design (GD) study types. As a generative design tool for the architecture, engineering and construction industry, the GD tool provides users the power to quickly explore and optimise their Dynamo designs. It employs genetic algorithms to perform multi-objective optimisation studies and presents different design permutations in a user-friendly interface. Figure 18 shows an example of the optimisation process for a spatial steel truss structure using Refinery in Autodesk Dynamo. The optimisation problem consists of finding the best truss configuration based on several objectives, namely maximising the platform area, minimising deformation and minimising weight. Based on these objectives, Refinery provides various configurations of the truss by varying the heights at the start and end of the truss, and its divisions (number of panels/squares along the width).

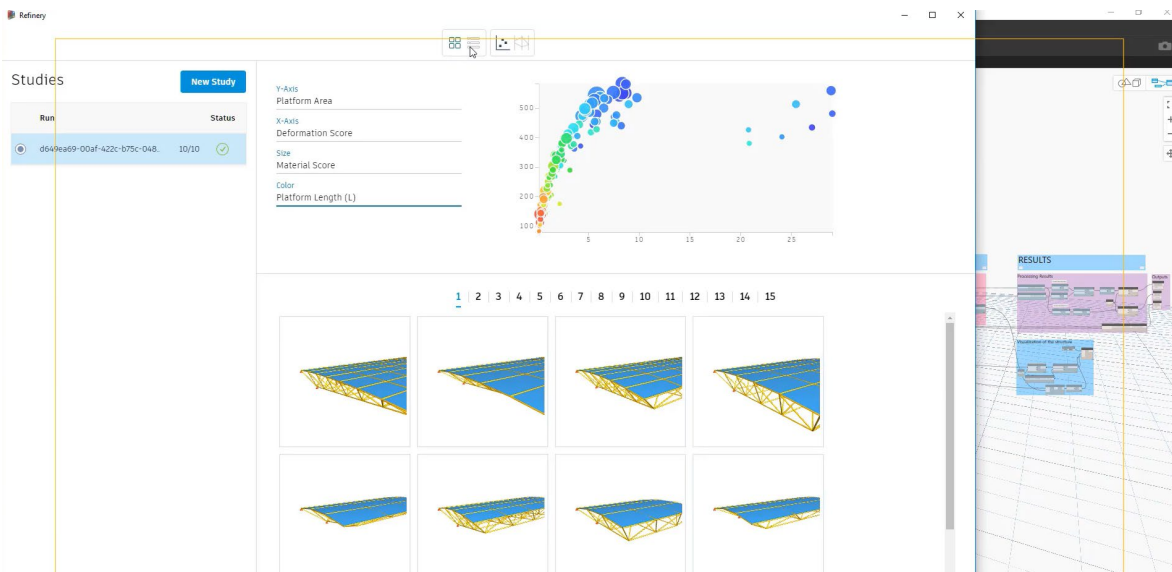


Figure 18: Various design options for spatial steel truss using Revit Generative Design.

Autodesk BIM 360 is a cloud-based platform that enables interactions between various stakeholders of the project. It provides BIM coordination, data management, documentation, project review, optimisation, reduction of risk and budgeting functionalities. The use of BIM 360 can prevent rework and detect clashes between LGS building components as it allows coordination between engineers, architects, contractors, builders and owner in the early planning to the final design stage [34]. Moreover, prediction of safety hazards, decision making, automation of tasks and maintaining schedules by minimising reworks can be achieved using BIM 360.

Autodesk Fusion 360 can be employed with BIM 360 to execute generative design on the cloud [35]. The GD algorithms in Fusion 360 use an approach called form synthesis [36]. The GD for LGS products can be performed using the following key steps:

1. The input of parameters i.e., material, strength, volume, weight and cost by the designer
2. Numerous designs are generated using algorithms (including AI) and performance analysis of each design is conducted
3. The designer can intervene and modify the objectives and constraints
4. The design prototype is produced in the final step. The third step can be repeated by designers and engineers if the design option is not satisfactory.

Autodesk Navisworks [37] is a BIM package available in two versions, namely Navisworks manage and Navisworks simulate, which enables greater co-ordination, construction simulation and whole-project analysis for integrated project review. Navisworks Manage implements advanced clash detection and interference management tools. Navisworks has been shown to

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

minimise design errors by 30% on a complex project in China [38]. The Navisworks manage and simulate packages can be used for review to minimise errors and reduce rework for LGS building projects. The key features of Navisworks are listed as follows:

- BIM 360 model coordination: integration whereby costly constructability issues can be rapidly identified and resolved; updated IFC file reader that enables the same open-source code in Revit to be used to manage interoperable IFC files; clash detection to assist with finding and resolving conflicts; and BIM coordination with other Autodesk products including AutoCAD and Revit.
- Model review: combine design and construction data in a single model; link animated model objects to construction schedules for high-quality project simulations; centralise data created by multi-disciplinary teams to explore and review complex models in real time; and publish models in distributed file formats that capture detailed design information
- Quantification: integrated quantification take-off, whereby lines, areas and counts with 2D and 3D take-off can be measured as opposed to conducting manual calculations; tracing existing geometry on a 2D PDF worksheet, such as a floor plan, to create take-offs automatically; export models from Navisworks into Assemble for use in estimating, scheduling or other workflows
- Model simulations: generate 5D construction schedules and logistics; render photo-realistic models; reality capture with enhanced point cloud integration; create renders for entire project models that can be stored on the cloud.

2.2.2. Tekla Structures

Tekla Structures (TS) [39] is a comprehensive BIM program that enables the user to create, combine, manage and share multi-material 3D models, which are packaged with comprehensive construction information. The software can thereby be employed throughout the phases of a project, including conceptual planning for buildings and infrastructure, construction and maintenance, as well as design, detailing and information management. TS has advanced computer-aided design (CAD) functionalities to create accurate and detailed structural 3D models. The software can achieve a Level of Development (LOD) of 500, which is the highest level that is categorised as truly constructible, and ensures that the value and reliability of the model is evident to all project stakeholders.

TS promotes an open approach to BIM by allowing interoperability with other software packages, digital construction tools and fabrication machinery [40]. Specifically, it can interface with analysis and design packages through an Application Programming Interface (API), namely Tekla Open API. In addition, the software links with these packages by file transfer (exports in common formats such as IFC) and to in-house analysis and design calculation spreadsheets. A comprehensive list of these packages is provided at [41], including analysis and design, connection design, manufacturing and management information system (MIS) in steel and rebar fabrication, manufacturing execution systems (MES) and production planning solutions (PPS) for precast concrete production, production machines (CNC steel machines, light metal framing machines, precast concrete machinery), project management, and general contracting, surveying and scanning. The benefits of linking with analysis and design packages are listed as follows:

- Coordination and visualisation of the model, drawings and reports.
- Both engineers and modellers can work on the same project model.
- Efficient change management keeps project information up to date.

Through the well-documented TS Open API [42], TS integrates into processes, workflows and software. It provides an interface for different types of applications to interact with the model and drawing objects in TS. The API thereby automates routine tasks by replicating the functions of the user interface such as creating drawings, connections, service penetrations in members and so on. Through the API, TS interfaces with other solutions, digital construction tools and

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

manufacturing machinery. Information can be transferred between a TS model and drawing database and other software used in a workflow, such as:

- Analysis and Design: Interface with analysis and design packages through Tekla Open API.
- MIS software solutions: In steel fabrication and precast concrete manufacturing.
- Production machines: In steel, any CNC software that imports Deutsche Stahlbau-Verband (DSTV) files can be integrated. The DSTV format has become an international standard for communicating with beam lines, drill lines, coping machines and plate cutting. For precast concrete production, information from a TS model can be transferred to communicate reinforcement, embedded materials and concrete geometry.
- Project management: Communication and time-based management data can be integrated, and dynamic dashboard views of project status can be created.
- Architectural integration: TS model and drawing information can be shared with architectural modelling programs.
- Industrial collaboration: Interfacing with the process and plant layout planning and piping design products.

TS provides constructability, different design solutions, precise detailing and cost estimation in the early project planning phase with automated built-in processes. Considerable time and money savings can thereby be achieved by using TS for modelling LGS and other building materials [43]. The workflows, including data driven design, parametric modelling and parametric design can be facilitated by adopting a live link between Grasshopper and TS. In addition, TS interfaces with structural software which makes it an excellent tool for GD of LGS and other conventional building systems. Moreover, the LGS framing from TS BIM model can be sent to CNC machinery and roll formers for fabrication. The inbuilt API and external plugins for framing tools link the model to light metal machinery including FrameCad, Howick, Pinnacle, Arkitech and Samesor. An example of a LGS wall component generated using the Howick plugin is shown in Figure 19. Furthermore, the correct installation of LGS components can be conducted on site and thereby minimise rework[43].

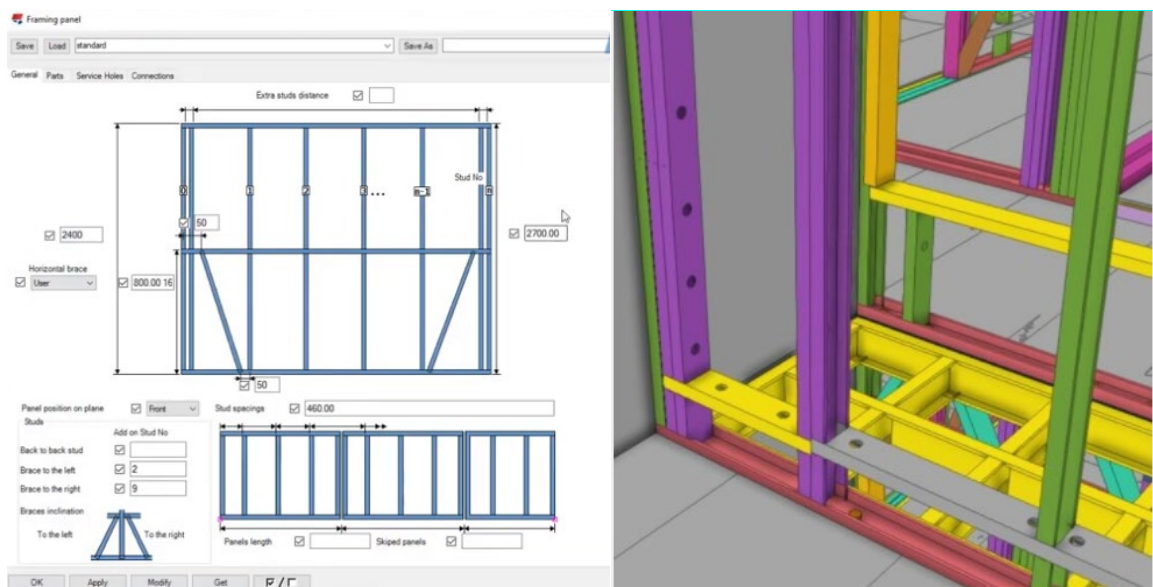


Figure 19: Model of a LGS system in Tekla Structures [43]. The LGS framing components are generated using the built-in Howick LGS plugin.

2.2.3. Archicad

Archicad is another commonly used BIM software having the capabilities of GD. The built-in tools in the software and user-friendly interface enables the design, visualisation, documentation, and delivery of projects, which makes it the most efficient and intuitive BIM software on the market. ArchiCAD is capable of enhancing real-time collaboration between stakeholders via their BIM cloud system, assisting design of architecture, structure and MEP, and exporting drawings that satisfy local standards. Furthermore, Archicad also offers a design automation tool and allows users to

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

carry out GD using Grasshopper and Rhinoceros [31, 44]. In terms of workflow automation, Archicad allows users to develop automation scripts using the Python programming language to collect and exchange data with other systems [45]. The key features are listed as follows:

- Collaboration: Teams can work together locally and around the world on projects with varying size and complexity. The software utilises open standards and workflows to guarantee effective collaboration between team members which employ different software packages.
- Design: The BIM model of the entire building can be created with Archicad’s powerful toolkit. The structural model and architectural model can be integrated in one shared design hub, resulting in a powerful, collaborative environment. Archicad have recently developed tools to integrate the structural analytical model.
- Visualisation: The 3D model can be presented as an image by producing non-photorealistic renderings with Sketch Render, which is best suited for early project phases. Design intent and other aspects of the building typically discussed in the early phases communicated effectively for rapid client feedback and coordination.
- Documentation: ‘Out of the box’ documentation sets can be obtained directly from the BIM model. Design services can be extended with quantity take-offs with no additional effort. Schedules and sheets can be created with accurate information obtained from the BIM model, which reduces errors or miscalculations.

2.2.4. Other BIM Packages

From Section 1.3, it is evident that Revit and Tekla Structures are the main BIM tools adopted in the case studies of mid-rise LGS buildings in the US, UK and Canada. Some other packages with BIM capabilities are briefly summarised in Table 6.

Table 6: Other BIM software packages.

BIM software	Capabilities
Revizto	Revizto provides a collaborative, 2D and 3D BIM modelling platform for engineers, architects, contractors and owners [46]. From early design to various construction stages, clashes are mitigated in this software. Design, construction, MEP and facility managements are the key workflows in Revizto. However, the use of this software for LGS buildings and projects is not established.
Vectorworks	Vectorworks has BIM and CAD capabilities, and is mainly used in research [47]. The software can be used for 2D and 3D BIM, as well as conceptual design. Vectorworks is a fully integrated BIM software with provisions for structural framing, electrical, plumbing, site service, documentation, augmented reality, GIS, selection of various types of materials tools, and so on. The models from this software can be imported into Revit.
SketchUp	SketchUp is a 3D modelling software. A 3D model can be built and visualised in SketchUp with a high level of detail. A SketchUp model can be imported to Revit and Tekla Structures [48]. SketchUp also allows add-ins and extensions to be implemented to conduct automated design. Most importantly, SketchUp can be used with Trimble Connect, a cloud platform, to increase interoperability between different partners.
Sefaira	Sefaira is employed for energy efficient building design [49]. The software can execute ventilation, HVAC and energy consumption computations. Sefaira can thereby evaluate the performance of a building at the early planning stage. The software can interact with Revit, which makes it useful for LGS buildings. The energy performance models built in Sefaira can be exported to Revit.

2.3. Common stakeholder problems with existing GD/BIM tools

The common stakeholder problems with the existing GD and BIM tools in Australia, which were deduced from Sections 1 and 2 of this report, are listed as follows:

- Lack of studies on the efficacy of GD within BIM tools, especially in Australia, which is hindering industry acceptance. Although built-in LGS plugins have been developed for BIM packages in industry accepted software packages, such as Autodesk Revit and Tekla Structures, there is a lack of reporting on the utilisation of GD automation capabilities.
- Lack of support for Australian LGS sections and design codes (AS 4600) in GD tools (e.g., from BlueScope), which need to be implemented as libraries in BIM packages such as Revit, or plugins in structural analysis and design packages. In contrast, most of the commonly used software tools have comprehensive design provisions for RC, hot-rolled steel and timber structural systems.
- Although BIM and structural analysis and design software is well-established in the construction industry (e.g., Revit, Tekla Structures, Spacegass, Robot Structural Analysis etc.), the interoperability between these tools is not being exploited and the project phases (from planning to detailed design) are thereby disjointed. For example, a costly bottleneck can occur where a connection or component is modified in the detailed design phase, which requires manual time-consuming updates of the BIM model.
- Fire design considerations for LGS are not generally accounted for in GD tools i.e., GD tools are mainly focused on architectural, structural and energy analysis aspects [50].
- Current plugins do not offer fully automated control over the entire BIM modelling and structural analysis process e.g., specialised functionality such as inserting HRS systems where the loading demand is exceeded in a LGS component requires logic to be implemented using programming or visual scripting.
- Generally, plugins like Lyrebird and Hummingbird, Dynamo, Rhino.Inside.Revit, Generative component, Archicad API, Geometric descriptive language (GDL), Revit python shell, and so on, have been developed to integrate GD tools in Revit quite well [51]. However, these components have some limitations in terms of geometric and BIM operations. A comparison between these tools is provided in Table 7.

In general, overcoming these problems require that the software has a built-in Application Programming Interface (API) to be able to exploit the full automation capability from outside the software. For example, Tekla structures offers a powerful API that can be accessed from an external interoperability tool such as Grasshopper, to automatically generate any type of structural system, specialised connections, structural drawings and so on. In contrast, Revit requires that these tools (e.g., Grasshopper through Rhino.Inside.Revit or Dynamo) run from within the software. The interoperability between these tools and existing LGS specialised software such as ENDUROCAD should also be considered to accelerated industry acceptance.

Table 7: The comparison of various GD tools and their limitations [49].

Application	Visual scripting	Programming (e.g., Python and C#)	Geometric operations	BIM operation
RPS	No	Yes	Yes	Yes
Grasshopper	Yes	Yes	Yes	No
Lyrebird	Yes	No	No	Yes
Hummingbird	Yes	No	Yes	Yes
Dynamo	Yes	No	Yes	Yes
GC	Yes	Yes	Yes	Yes
GDL	No	Yes	Yes	Yes
ArchiCAD API	No	Yes	Yes	Yes

2.4. Methods/plugins to address these problems to increase the adoption of LGS

Advanced automation and built-in best practices help BIM professionals make optimal choices, move much faster, and avoid errors at every stage – from design and documentation to fabrication and construction [52]. The utilisation of a third-party plug-in in a BIM environment has allowed for rapid growth in the overseas building industries [53]. However, the effects of such advancements have not been fully realised in the construction industry in Australia. Even in the case of automated solutions, there are relatively few studies available in the literature which describe the use of these tools in the BIM environment [54].

The design workflow of light gauge steel (LGS) framing consists of using a BIM model authoring software, Autodesk Revit, as well as a third party plug-in to automatically generate light gauge steel framing and create the shop drawings [55]. In this section, an overview of commonly used third-party plug-ins for Revit will be introduced. These tools are instrumental in populating the architectural model with standard framing sizes, spacing and connection details. The automated functionality of these tools will be a great start for BIM professionals and engineers to gain a sense of the initial global model at the early project planning phase. The main capabilities of these tools are summarised in Table 8.

Table 8. Comparison summary of different third-party software for light-gauge steel framing.

Software	AGACAD Metal Framing	MWF Pro Metal	FRAMECAD	SteelSmart Framer
Revit Interoperability	Third-party plug-in inside Revit	Third-party plug-in inside Revit	External software with Export/Import link	Third-party plug-in inside Revit
Automatic Clash Detection of MEP Services	Yes	Yes	No	No
Customers	Widely spread among different design institutions	Widely spread among different design institutions	Limited to specialised customers	Limited to specialised customers
Compliance with Australian Standards	Yes	Yes	No	No
Availability of additional tools for other structural systems such as concrete, timber and hot rolled steel.	Yes	No	No	No

2.4.1. AGACAD add-ons for Revit: Tools 4 Revit (T4R)

AGACAD provides BIM solutions for Revit Professionals based on the needs and solved problems of the world’s most progressive BIM companies. They provide complete BIM software for prefabricated design, timber and metal-construction design, sustainable design, MEP engineering and BIM data management [56]. Selected BIM solutions for engineering professionals offered by AGACAD can be seen in Figure 20.

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

PRECAST CONCRETE

PRECAST CONCRETE

Model precast elements in Revit, get real-time full-project updates, element views with automatic dimensions, & shop tickets with BIM software. Prec...

METAL FRAMING SUITE

METAL FRAMING SUITE

Metal Framing Suite provides the easiest way to design the main structures of light-steel framed buildings. This powerful and flexible BIM software lets...

WOOD FRAMING SUITE

WOOD FRAMING SUITE

Wood Framing Suite gives a better way to design main structures of timber framed buildings. This powerful and flexible BIM software lets Revit® users de...

BEAM REINFORCEMENT

BEAM REINFORCEMENT

Beam Reinforcement is a feature of our Precast Concrete design software for Revit that lets you create, update and modify reinforcement for rectangular,...

COLUMN REINFORCEMENT

COLUMN REINFORCEMENT

Column Reinforcement is a feature of our Precast Concrete structural design software for Revit that lets you create, update, and modify reinforcement fo...

WALL REINFORCEMENT

WALL REINFORCEMENT

Wall Reinforcement is a feature of our Precast Concrete design software for Revit® that lets you create, update and modify reinforcement for solid, doub...

WOOD FRAMING CLT

WOOD FRAMING CLT

Wood Framing CLT lets Revit® users instantly create cross-laminated timber floor, roof slabs and wall panels of any shape or complexity. Functions are v...

WOOD FRAMING OAK

WOOD FRAMING OAK

Wood Framing OAK lets Revit® users instantly frame mass timber walls, floors, and roofs; create post-and-beam (also called post-and-lintel) framing stru...

WOOD FRAMING SIPS

WOOD FRAMING SIPS

Make wood framing with structural insulated panels – prefabricated building components for use as walls, floors and roofs – fast and easy with real-tim...

SANDWICH PANELS

SANDWICH PANELS

Sandwich Panel brings a collection of powerful features and top-notch automation for efficient modeling, data management, and output. Create coordinate...

VENTILATED FACADES

VENTILATED FACADES

Ventilated Facades software makes it quick and easy to design ventilated facades in Revit® with highly detailed elements and real-time full project upda...

CURTAIN WALLS & PANELS

CURTAIN WALLS

Curtain Walls & Panels enables quick and easy framing of architectural curtain walls or curtain panels in Revit® with real-time full project updates...

FRAMED PARTITIONS

FRAMED PARTITIONS

Framed Partitions makes it quick and easy to design various types of partition walls or ceilings in Revit®. The flexibility of the software allows users...

METAL FRAMING WALL

METAL FRAMING WALL

Metal Framing Wall makes metal framing of walls fast and easy with real-time full project updates in Revit®. Plus it generates views with automatic dime...

METAL FRAMING FLOOR

METAL FRAMING FLOOR

Metal Framing Floor makes metal framing of floors fast and easy with real-time full project updates in Revit®. Plus it generates views with automatic di...

METAL FRAMING ROOF

METAL FRAMING ROOF

Metal Framing Roof lets Revit® users instantly create metal truss and/or rafter systems of any shape or complexity, perform structural analysis, and gen...

WOOD FRAMING WALL

WOOD FRAMING WALL

Wood Framing Wall makes wood framing of walls fast and easy with real-time full project updates in Revit. Plus it generates views with automatic dimensi...

WOOD FRAMING FLOOR

WOOD FRAMING FLOOR

Wood Framing Floor makes framing timber floors fast and easy with real-time full project updates in Revit. Whether you need to frame multi-layer floors...

WOOD FRAMING ROOF

WOOD FRAMING ROOF

Wood Framing Roof lets Revit® users instantly create prefabricated wood frame roof panels, wooden truss and/or rafter systems of any shape or complexity...

WOOD FRAMING CNC EXPORTERS

WOOD FRAMING CNC EXPORTERS

AGACAD CNC Exporters automatically assemble all framing members per user definitions and send all necessary data to various CNC machines and CAD/CAM pro...

METAL FRAMING CNC EXPORTERS

METAL FRAMING CNC EXPORTERS

AGACAD's CNC Metal Exporter allows for direct export of light-gauge steel frames modeled in Autodesk Revit to CNC machines manufactured by Metroll, Roya...

Figure 20: Selected AGACAD BIM Solutions for Engineering Professionals [57].

For LGS framing, AGACAD offers Metal Framing Wall+ which automates light gauge steel wall framing work in Revit. It is a powerful, flexible, and easy to use tool. It helps you make optimal choices, move much faster, and avoid errors at every BIM stage – from design and documentation to wall panel fabrication and construction. It generates views with automatic dimensions for wall panels or segments, as well as accurate bills of materials and shop drawings. Therefore, quality production and accurate assembly on site are ensured [58].

Connectors, cuts, supports and other details can be distributed based on predefined rules or connection types. They can then be modified or updated to suit the project design stage and the level of detail required. Wall frames, and the layout of frame elements and details can be modified

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

and updated whenever the project is modified. Dynamic update functionality can make changes to all wall frames of the same type at once [58].

Using this tool, wall frame elements in the project can be easily marked based on their properties and locations in the wall layer. Information for fabrication can be automatically generated with all desired views, schedules and drawings for each wall panel [58].

Metal Framing Wall+ tool developed by AGACAD offers the following key features [59]:

- Flexible modelling of metal studs, deflection tracks, bracings, bridgings, noggings, straps, equipment supports and more
- Fully scalable: from simple structures to complex multi-level buildings; and irregular wall shapes
- Easy to transfer framing elements between the same groups or identical walls in different levels of buildings by predefining the elements that a building designer is going to affect i.e., all walls from the same model group, from the instance model group, or selected wall should be unique in the building
- Framing types are easily linked with wall types, which can be pre-set for bearing or non-bearing walls
- Precise framing of curtain walls and curtain wall panels using an additional feature
- Complex multi-layer wall framing: unlimited number of layers; layer-specific settings for connections (L, T, V, and End); recognition of inner/outer corners
- Complex headers and sills for windows, doors and other wall openings; settings can be pre-set for different opening sizes
- Automated details (anchors and bolts, clip angles, service holes, and so on) on studs and plates
- Quick alignment of metal studs or opening cripples with trusses or other frames
- Support for curved walls
- The wall frame can be modified any time and supplemented with additional members
- Built-in clash detection between structural and engineering objects; automated wall openings and flexible framing around it
- Sheathing layouts can be easily generated and split by existing studs
- Library of all main types of wall framing can be edited and expanded
- Automatic sorting, tagging, dimensioning, and scheduling (including mass) of all frames and sheathing layouts
- Shop drawing views and schedules are added automatically to the sheets according to a predefined user template
- All templates and rules are fully customisable; framing, sheathing, and shop drawing configurations can be saved for future projects and shared between company team members
- Easy setup, user-friendly interface with intuitive mouse-driven menus and options
- Optional CNC fabrication output enables the model data to be automatically exported for manufacturing.

Metal Framing Wall+ tool developed by AGACAD provides the below key benefits to the user [58]:

- Effective design: Few easy steps are required to configure wall framing for one-click metal wall framing
- Smart Modification: After framing a wall, changes and tweaks can be made very handily
- Design Evaluation: Fast wall framing made in early project stage helps the user to make better decisions. evaluate every detail of the project, and find the best alternative for the project. Material take-off, shop drawings, views are generated real-time so there is minimum risk of errors

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

- Speed: Easy setup, templates, user friendly interface, and fast framing generation make user-built framing in a fraction of the time required using manual methods. The system is very scalable so there is no difference if the user generates 10 or 100 walls, only the computational/analysis time is affected
- Completeness: the modelling of framing, tagging of elements, dimensioning, and scheduling are completed within a single solution. The process is completed in one place
- Time savings: Metal Framing Wall+ is built for quick project development. Standardised and automated wall framing, and shop drawing generation enable users to jump a few major steps in building design
- Shop drawings are produced, almost at the same time, as you frame your first wall. Easy to make templates allow the user to streamline this process. The user can check if the model is correct in the end, adjust a few issues and the project is ready for delivery
- Easy-to-use user interface: All user functions in Metal Framing Wall+ are typically performed with a few mouse clicks. The user may choose what must be modified and click the function, which is comfortably listed in a handy menu.

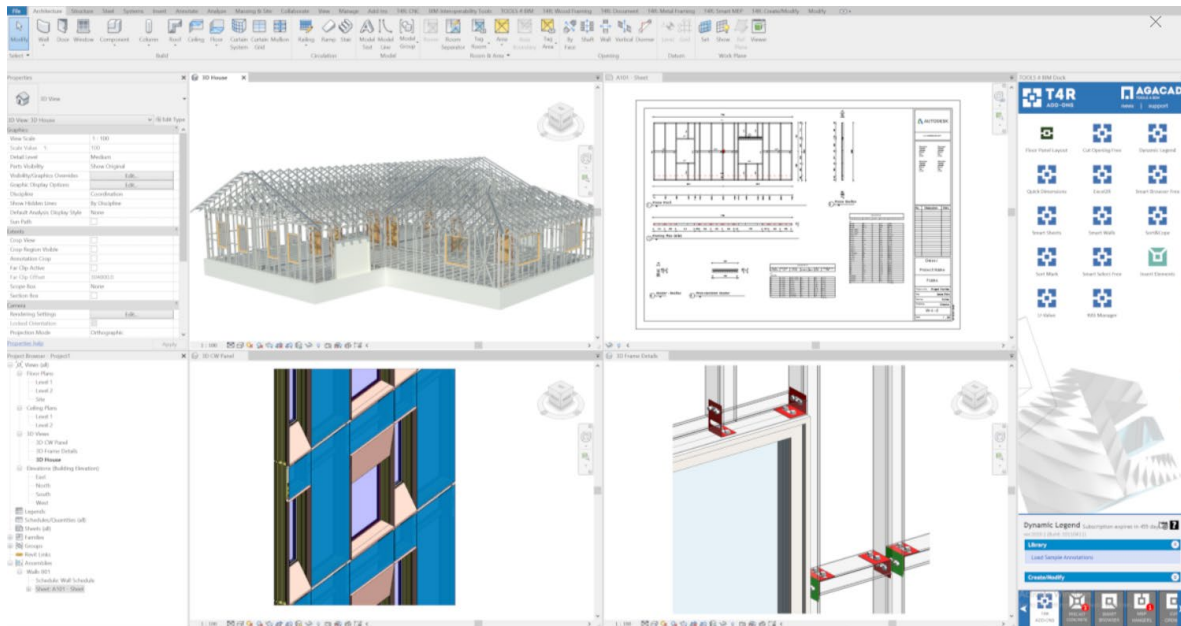
Metal Framing Wall+ tool is developed in compliance with the following standards and guidelines [58]:

- AISI S100-07/S2-10 – North American Specification for the Design of Cold-Formed Steel Structural Members with Supplement 2. American Iron and Steel Institute, Washington, DC
- AISI S200-07, 2007 – North American Standard for Cold-Formed Steel Framing – General Provisions. American Iron and Steel Institute, Washington, DC.
- NASH Standard – Residential and Low-rise Steel Framing, Part 1: Design Criteria. 2010.
- NASH Standard – Residential and Low-rise Steel Framing, Part 2: Design Solutions. 2010.
- Building Enclosure Design Guide – Wood Frame Multi-Unit Residential Buildings. Homeowner Protection Office (HPO), Vancouver, Canada, 2011.
- AISI D110-07 – Cold-Formed Steel Framing Design Guide, 2nd Edition. American Iron and Steel Institute, Washington, DC.
- AISI D100-08 – AISI Manual, Cold-Formed Steel Design. American Iron and Steel Institute, Washington, DC.

More than 13,000 commercial licenses are currently being used by small- and medium-sized architectural, MEP and construction companies, as well as notable large-scale international design companies. Selected customers are ARUP, AECOM, SMEC Australia and WSP. Other customers can be found in [60]. Metal Framing Wall+ tool developed by AGACAD is mainly capable of generating light gauge steel framing for a single storey home to a mid-rise building structure as shown in Figure 21.

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

(a)



(b)

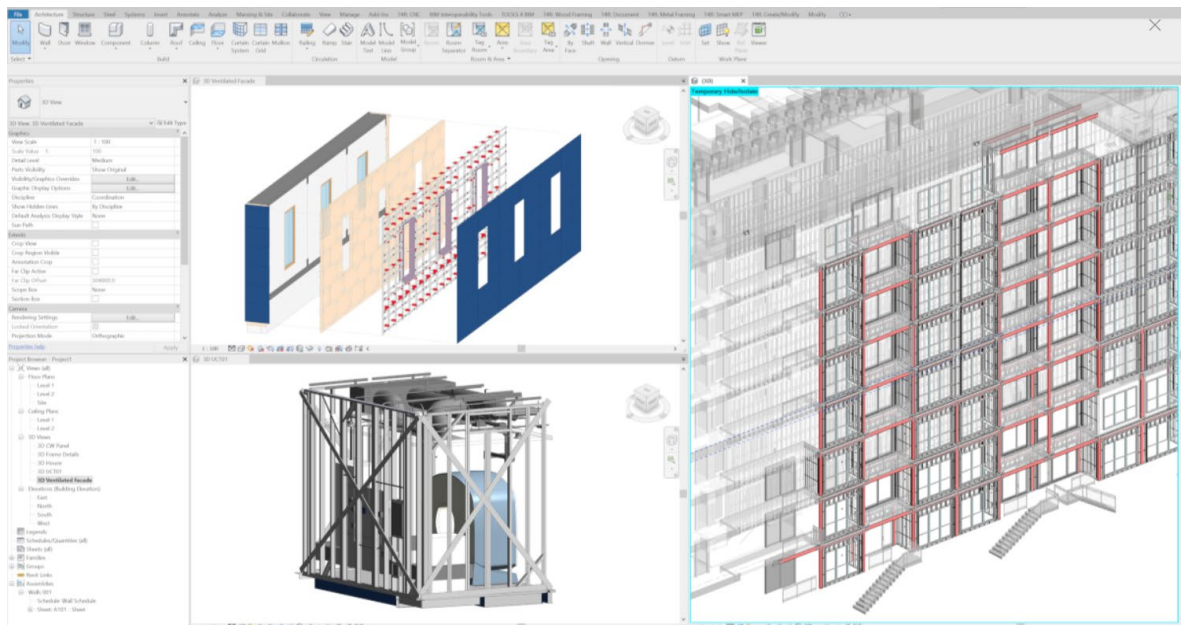


Figure 21: Metal Framing Wall+ tool capability in Revit for (a) house light gauge steel framing and (b) mid-rise building framing [58].

2.4.2. StructSoft plug-in for Revit: MWF Pro and Advanced Metal

Metal Wood Framer (MWF) by StructSoft simplifies complex Revit framing with a powerful range of tools for modelling, clash detection, construction documentation and optional output to CNC fabrication machines [61]. MWF is available for wood or light gauge steel (LGS), and includes multiple modules. The core modules are the steel (MWF Pro Metal and MWF Advanced Metal) and wood (MWF Pro Wood) solutions. There are also several specialised modules: MWF Panel Stacker, MWF CNC, MWF SIPS and MWF Post Frame as shown in Figure 22.

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

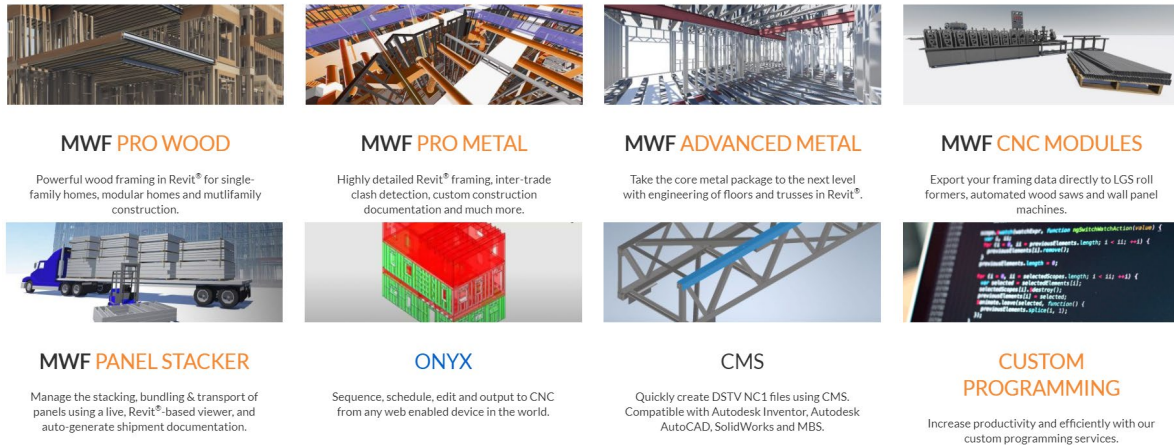


Figure 22: StructSoft BIM products for Revit [62].

MWF Pro Metal for Revit is an add-in for LGS framing using existing architectural model elements. It takes walls, floors, ceiling, roofs, trusses and converts them into panels. The user can employ MWF Pro Metal to run clash detection, and create complete construction documentation, such as shop drawings and bill of materials. The user can also export the geometry to a variety of different CNC fabrication machines.

Developed in conjunction with industry experts, MWF Pro Metal's automated tools allow users to easily frame entire projects while simultaneously creating schedules, material cut lists, framing elevations, and fully dimensioned 2D shop drawings. MWF is the tool of choice for professionals for framing many components, ranging from bathroom pods up to billion-dollar healthcare projects.

MWF tool developed by StructSoft provides the below key benefits to the user [61]:

- **MWF Built in intelligence:** MWF's intuitive template manager recognises Revit elements and allows for the quick creation of multiple panels in the Revit model at once
- **Pre-loaded libraries** from top building component manufacturers including ClarkDietrich, CEMCO, iSPAN, Marino/WARE, SCAFCO and more
- **Modelling connection members:** automatic modelling of accurate connection members such as kickers, bracing, straps, hangers, hold downs, equipment supports and more
- **Easily create openings:** detect clashes between thousands of structural intersections, and MEP within walls and floors in seconds
- **Quickly create layouts:** create ceiling and roof layouts, frame trusses, soffits and floors
- **Truss designer:** MWF's truss designer engine gives the user complete control over the truss shape, individual member size, types of gauges and so on.

StructSoft tools are developed with pre-loaded libraries from top building component manufacturers including ClarkDietrich, CEMCO, iSPAN, Marino/WARE, SCAFCO and more with the ability to add other manufacturers as necessary. The tools are compliant with Canadian and American standards [61]. Selected Customers of StructSoft tools include HOAR Construction, Swindale Associates, DPR Construction, KPFF Consulting Engineers, Howick and Habitat for Humanity. Other customers can be found in [63]. MWF Pro Metal tool developed by StructSoft has the capability to generate LGS framing in Revit considering as shown in Figure 23.

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

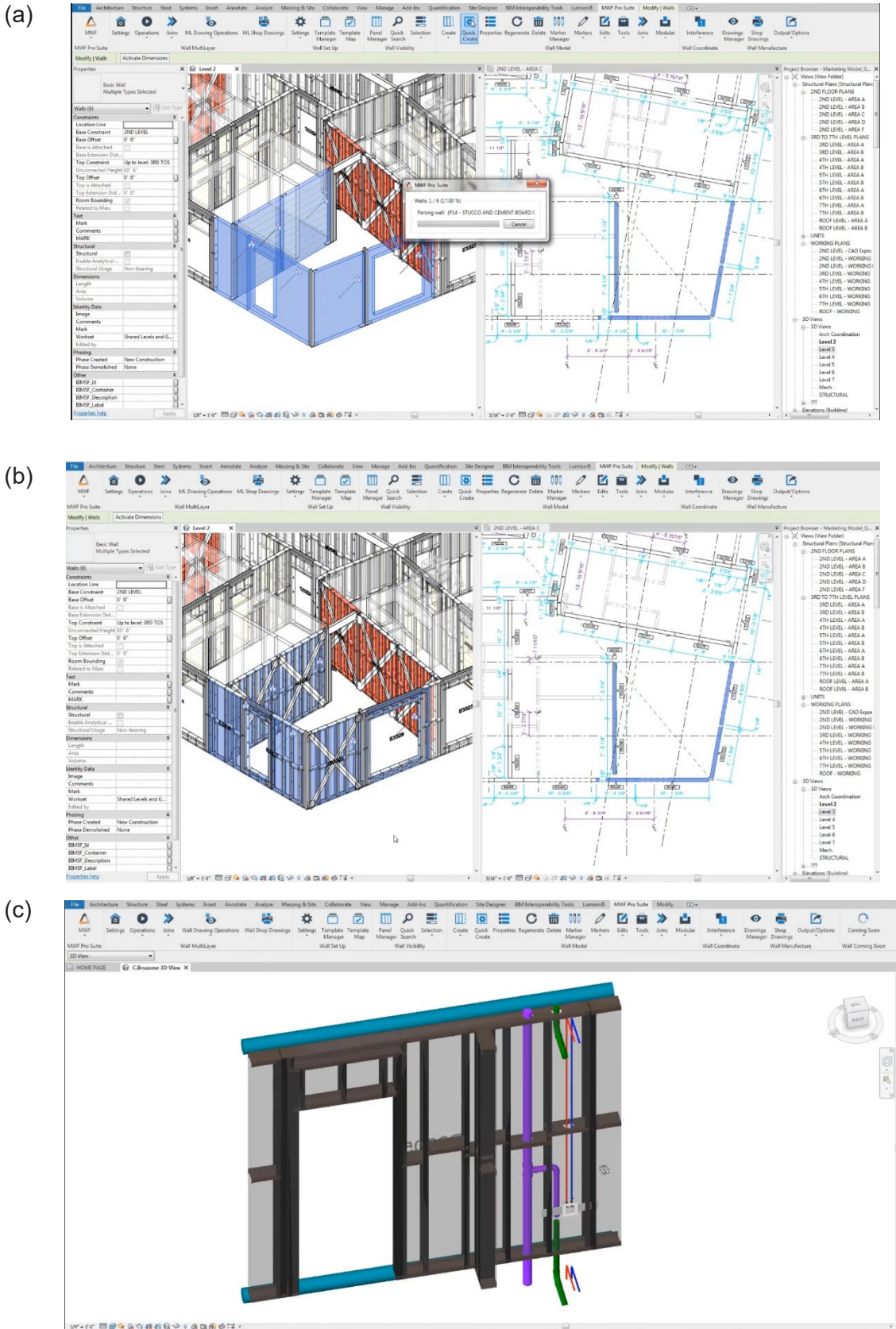


Figure 23: MWF Pro Metal capability in Revit: (a) selection of architectural walls, (b) automatic generation of light gauge steel framing system and (c) generating structural framing around services [61].

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

2.4.3. FRAMECAD Plugin for Revit: FRAMECAD Revlink

FRAMECAD LGS software packages integrate with the preferred architectural software already being used by design teams. Alternatively, all frame and truss design can occur within the FRAMECAD Structure software itself [64]. All of the big names in architectural software are compatible with FRAMECAD software, including Revit, Chief Architect and AutoCAD. As the name suggests, FRAMECAD is CAD-based, so the design-files created in other CAD-based programs are imported easily. Even if the software used by the architect is not CAD-based and not initially compatible with FRAMECAD Structure, the FRAMECAD team will take steps to create compatibility.

The FRAMECAD software suite offers streamlined Building Information Modelling (BIM) integration. Sharing the design and building information is easy, fast and efficient. The proprietary plug-in FRAMECAD Revlink allows the user to work seamlessly between Revit and FRAMECAD Detailer, or Revit and FRAMECAD Structure i.e., one complete model is available. The integration between platforms (Revit to Structure and Revit to Detailer) using FRAMECAD Revlink is bi-directional and very fast to run, thereby speeding up the engineering and design processes [64]. Summary FRAMECAD software BIM tools are shown in Figure 24.

FRAMECAD Structure is an integrated engineering software package that saves users time and money. Completing over 25,000 engineering calculations per square meter of roof and walls in just seconds, FRAMECAD Structure improves user engineering time by up to 80%. FRAMECAD Structure makes real-time engineering calculations as the designs are created (analysing loads, deflections and other forces), making it an easy process to optimise building code compliance whilst delivering best value engineering practices.

FRAMECAD Detailer is recognised as the most versatile LGS design software, which is incredibly easy to use, whilst being able to design almost anything the user needs. With the addition of FRAMECAD Revlink, customers can now use the powerful Detailer framing engine in conjunction with Revit to complete the building design.

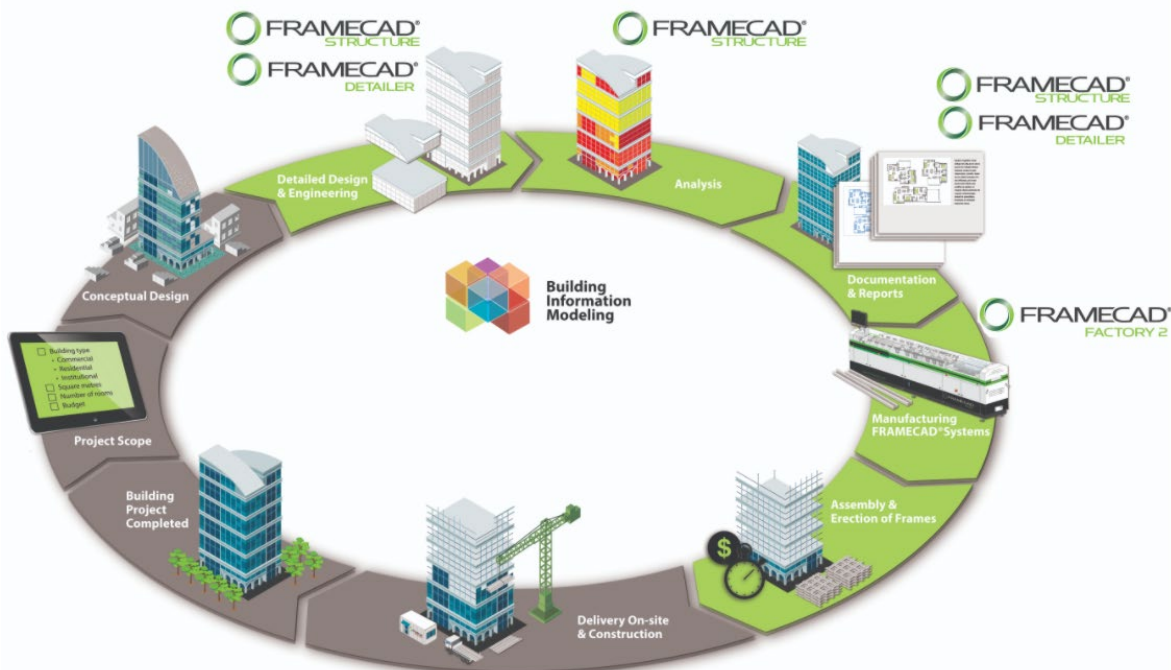


Figure 24: BIM software suite offered by FRAMECAD for LGS [64].

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

The key features of FRAMECAD solutions for light gauge steel framing are [65]:

- Fast: over 25,000 calculations per square meter of roof and walls in seconds; a task which would take days, or potentially weeks, if done manually
- Reduces engineering costs: real-time engineering as the building is designed; this reduces the engineering input and means that external engineering costs are greatly reduced
- Reduces material costs: using materials as efficiently as possible and reducing wastage. The material savings from using FRAMECAD Structure can be as much as 30% on roof truss designs by optimisation and value engineering
- Accurate: producing accurate calculations automatically, eliminating errors that may occur during manual calculations
- Straightforward: easy to use such that non-engineering designers can complete more of the design work
- Compliant: real-time engineering calculations as the designs are created, analysing loads, deflections and other forces, and making it an easy process to check for compliant engineering
- Optimises the design and manufacturing preparation: enables users to review the engineered design files in order to improve manufacturing details and onsite constructability; produces a manufacturing file that can be read by the LGS machine's system. Once a file has gone through FRAMECAD Detailer, it is ready for manufacture
- Visualisation: the 3D view means the framing can be shown in a virtual walk-through format to help customers visualise the design and allow designers to check for design errors, thereby eliminating on-site correction time
- Improves the construction process: the software covers the detailing of the component parts, as well as the generation of workshop drawings. With these drawings brought up on a screen or printed out, the production team can conduct the initial phase of fabrication and construction with ease
- Enables the use of unskilled labour: by ensuring that what is produced is easy to put together, local unskilled labour can be trained up quickly to support on-site activities and ensure quick delivery of projects
- Eliminates on-site correction time: the framing can be shown in a virtual walk-through format to help customers visualise the design and eliminate design errors prior to erection.

The key benefits of FRAMECAD solutions for light gauge steel framing are [66]:

- Speed: one of the biggest advantages of design-led LGS construction is the way in which it can significantly speed up the construction process
- Make the best use of people: taking a design-led approach to construction revolutionises the approach to human resources, changing the roles and tasks that specific people undertake dramatically
- Compliance made easy: with LGS construction, compliance is no longer such an immense pain point – LGS systems like FRAMECAD make the compliance process easy
- Material wastage reduced: reducing waste has both financial and environmental implications and LGS construction is extremely effective in doing so
- Return on investment (ROI) maximised: in all aspects of construction, maximising ROI is key. With LGS construction, time, human and material resources are all reduced, improving ROI significantly.

All commonly followed building codes are included instead of prebuilt into FRAMECAD, with the ability to add other codes as necessary. FRAMECAD software adheres to design building codes available in United States, Canada, Australia/New Zealand, China, Europe, Russia, Brazil and South Africa [67].

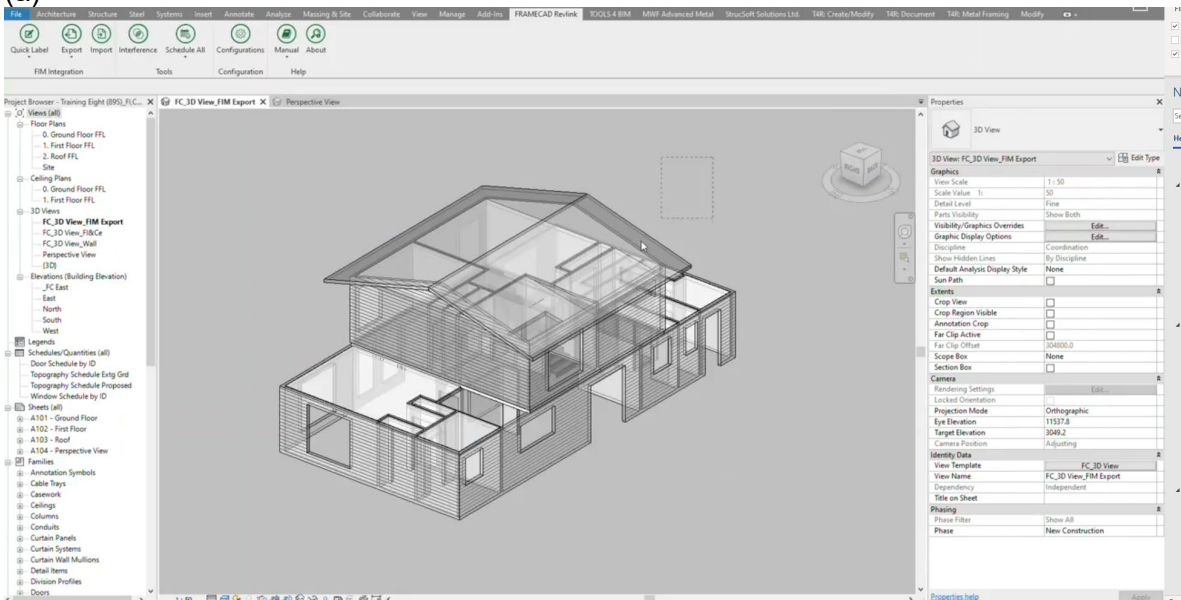
Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

Selected Customers of FRAMECAD tools include Dynamic Steel Frame, Combined Metal Industries, SBS Group, Steel Frame Solutions, CMG Frames, Castle Evolution, etc. A full list of customers can be found in [68].

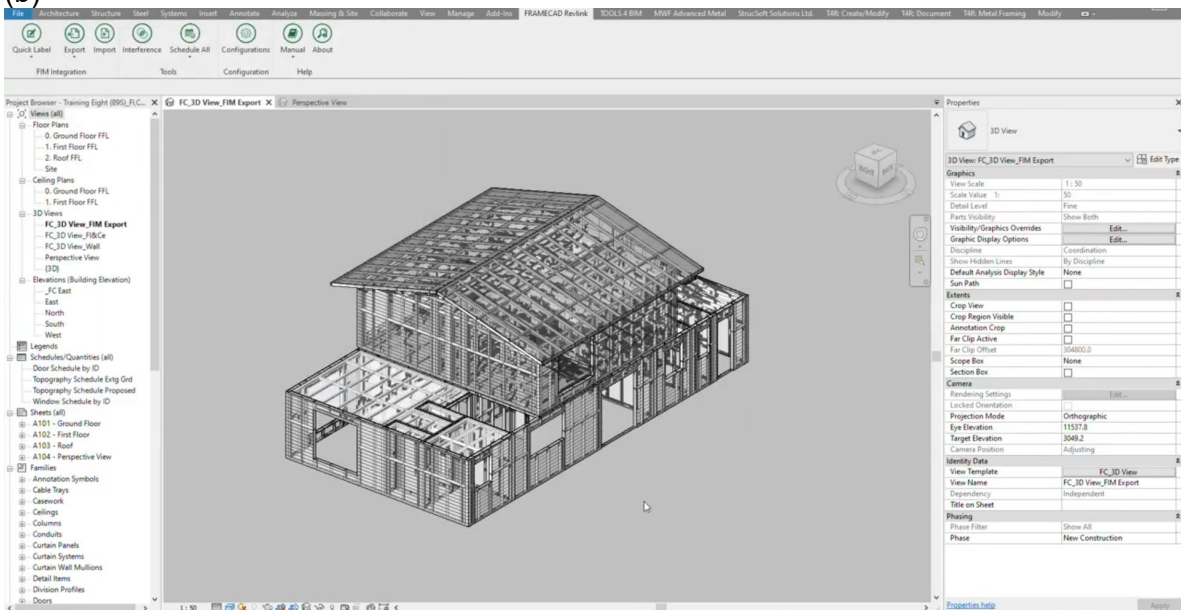
FRAMECAD Revlink offers the full journey (export/import/update) for walls, ceilings, floor and roof panels, including inclined panels, allowing a full model to be exported to Revit. The latest version of FRAMECAD Revlink includes a multiple layer configuration for export. This provides the option to select different wall layers and then apply them to the framing, such as double panels within an intertenancy wall, which offers even better design flexibility.

The integration between platforms (Revit to FRAMECAD Structure and Revit to FRAMECAD Detailer) is bi-directional and very fast to run, speeding up the engineering and design processes. FRAMECAD Revlink allows the complete framing design to be created in either Detailer or Structure, and then imported into Revit and merged with the architectural design. An example of generating of LGS framing system using FRAMECAD tools is shown in Figure 25.

(a)



(b)



Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

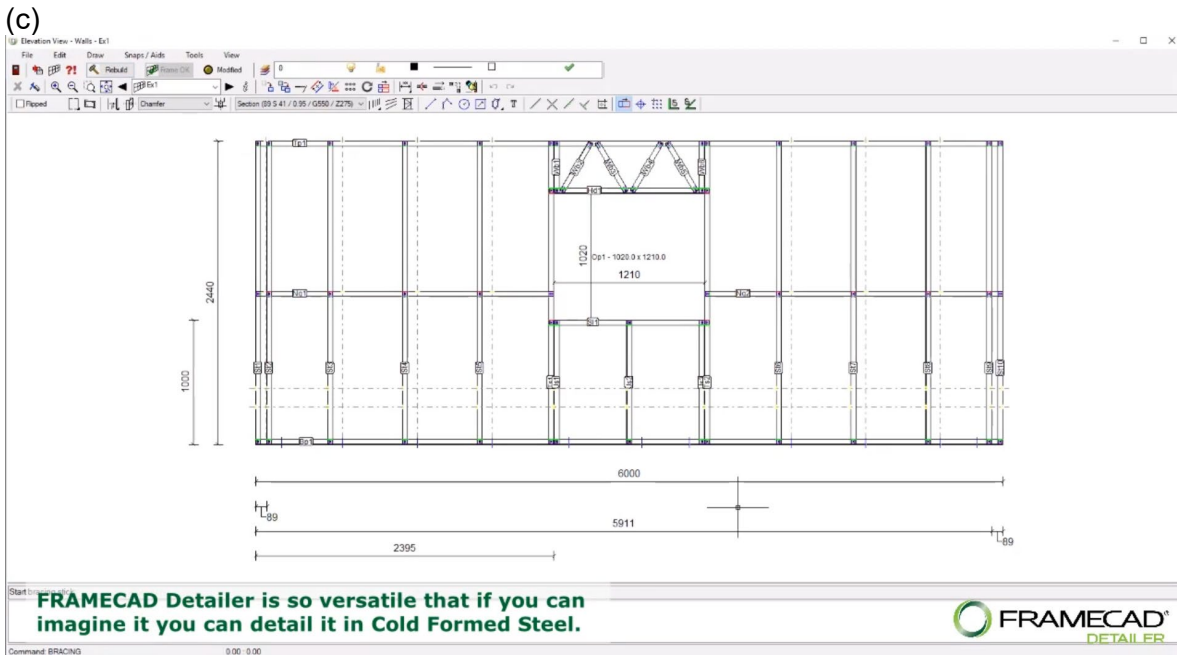


Figure 25: Generating a LGS system using FRAMECAD: (a) Export Revit model using FRAMECAD RevLink to FRAMECAD Structure, (b) Import LGS system from FRAMECAD Structure to Revit using FRAMECAD RevLink and (c) LGS detailing using FRAMECAD Detailer [66].

2.4.4. ASI Plugin for Revit: SteelSmart Frammer

ASI's SteelSmart Frammer was developed for The Steel Network, Inc. (TSN) to provide engineers and contractors with a powerful new tool to better design, estimate and communicate light steel framing on projects using Autodesk Revit Building Information Modelling (BIM) software [69].

The key features of SteelSmart Frammer for light gauge steel framing are [69]:

- Fully integrated 3D BIM modelling in Autodesk Revit (not compatible with Revit LT)
- Import wall styles and layouts from the SteelSmart System design software or create your own in SteelSmart Frammer for Loadbearing Walls, Curtain Walls, Interior Drywall, Shear Walls, Steel Joist Floors and Short Walls
- Easily model every stud, track, joist, shear wall and connector
- Know exact quantities and lengths for all light steel framing
- Export complete material take-off to Excel for the entire structure, plus separate panel lists
- Export panel drawings with panel material lists
- Export plan layouts.

The key benefits of SteelSmart Frammer for light gauge steel framing are [69]:

- Import steel framing designs: easily import design work done in SteelSmart System
- Automate take-offs are easily exported material lists by panel, and for the total structure with the click of a button
- Simplify estimation: once the model is built, request a quote from TSN with the click of a button
- Automate shop and drawing production: steel framing has the highest strength-to-weight ratio of any building system, results in no hidden construction costs related to fire safety for combustible framing systems, and results in lower insurance rates
- BIM clash detection: determines and addresses conflicts with light steel framing and other building components in Revit before attending the jobsite.

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

The following design codes are available within the SteelSmart System [70]:

- 2018 IBC with AISI S100-16 and ASCE 7-16
- 2015 IBC with AISI S100-12 and ASCE 7-10
- 2012 IBC with AISI S100-07/S2-10, and ASCE 7-10
- 2009 IBC with AISI S100-07 and ASCE 7-05
- 2006 IBC with AISI-NAS 2001/04 Supplement and ASCE 7-05
- Canadian NBC 2015 with AISI S136-12
- Canadian NBC 2010 with AISI S100-07/S2-10.

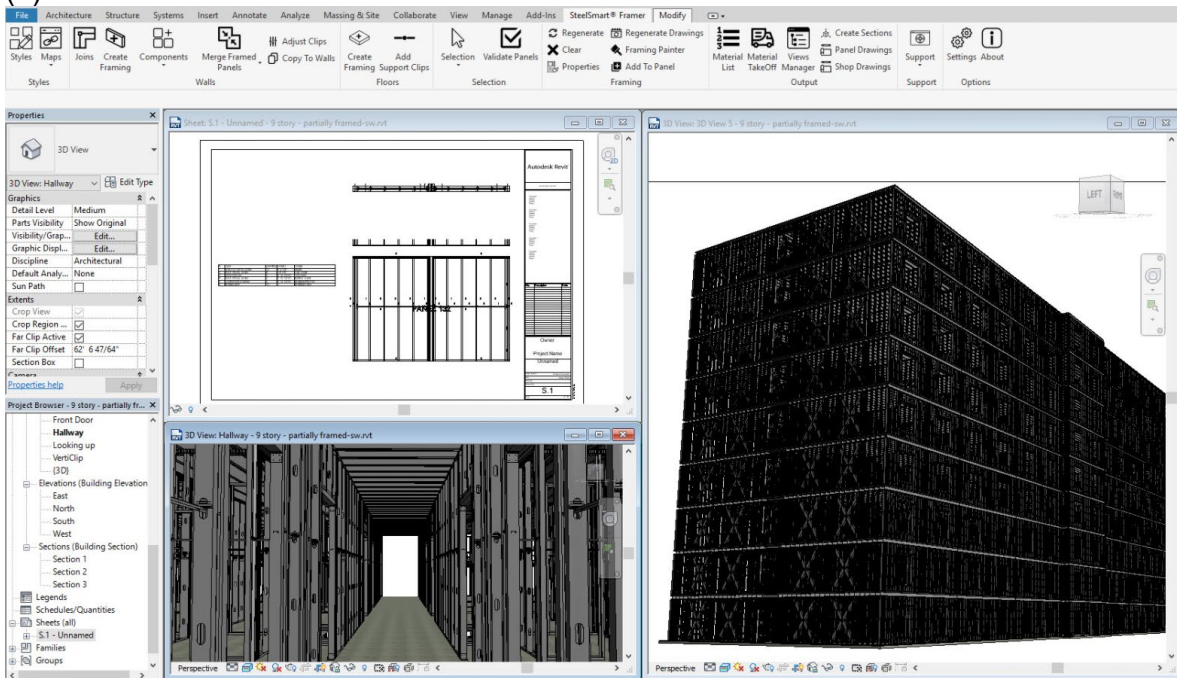
Selected Customers of FRAMECAD tools include FDR Engineers, BAM Consulting Engineers, The Steel Network, Titan Tire Company and Jacobs Technology. A full list of other clients which are using Applied Science International tools can be found in [71]. SteelSmart Frammer Plugin for Revit tool developed by Applied Science International (ASI) mainly has the capability to generate LGS framing in Revit as shown in Figure 26.

(a)



Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

(b)



(c)

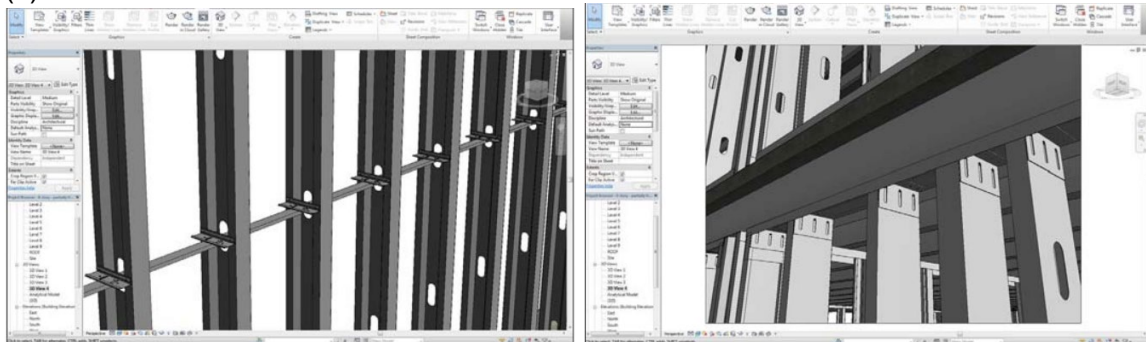


Figure 26: Generating a LGS system using SteelSmart Framer: (a) 3D rendered model, (b) generating LGS system and drawings inside Revit and (c) LGS connection details [69].

2.5. Common rapid structural engineering software

Structural analysis and design software packages, with an in-built Application Programming Interface (API) to enable interoperability with BIM packages, are the most prevalent for automating the early evaluation of LGS against other common structural systems for mid-rise building applications. Many structural analysis and design packages are adopted in the industry. Spacegass and ETABS are the most prevalent tools for the purpose of this project, as Spacegass implements LGS design checks according to AS 4600, and ETABS is used to evaluate LGS against other structural systems according to the studies by Franklin [1] at the Steel Research Hub. The automation features and limitations of several software packages are summarised in Table 9 and explored hereafter.

Table 9. Comparison summary of different rapid engineering tools with automation capabilities.

Software	Integration with Grasshopper or Dynamo	Automation Features through API	Support for AS4600 Design Code	In-built LGS Profiles
Spacegass	Yes	No	Yes (limited)	Yes
ETABS	Yes	Yes	No	Yes
SAP	Yes	Yes	No	Yes
Robot	Yes	Yes	No	Yes
STRAP	Yes	Yes	No	Yes
DLUBAL	Yes	Yes	No	Yes

2.5.1. Spacegass

Spacegass is a multi-purpose 3D analysis and design program for structural engineers. The software has an extensive range of features that make it suitable for modelling beams, trusses and frames to buildings, towers, tanks, cable structures and bridges. The main capabilities include a 64-bit multi-core solver, 3D rendered graphics, plate finite elements, frame elements, cable elements, tension/compression-only elements, moving loads and links to many CAD and building management programs [72].

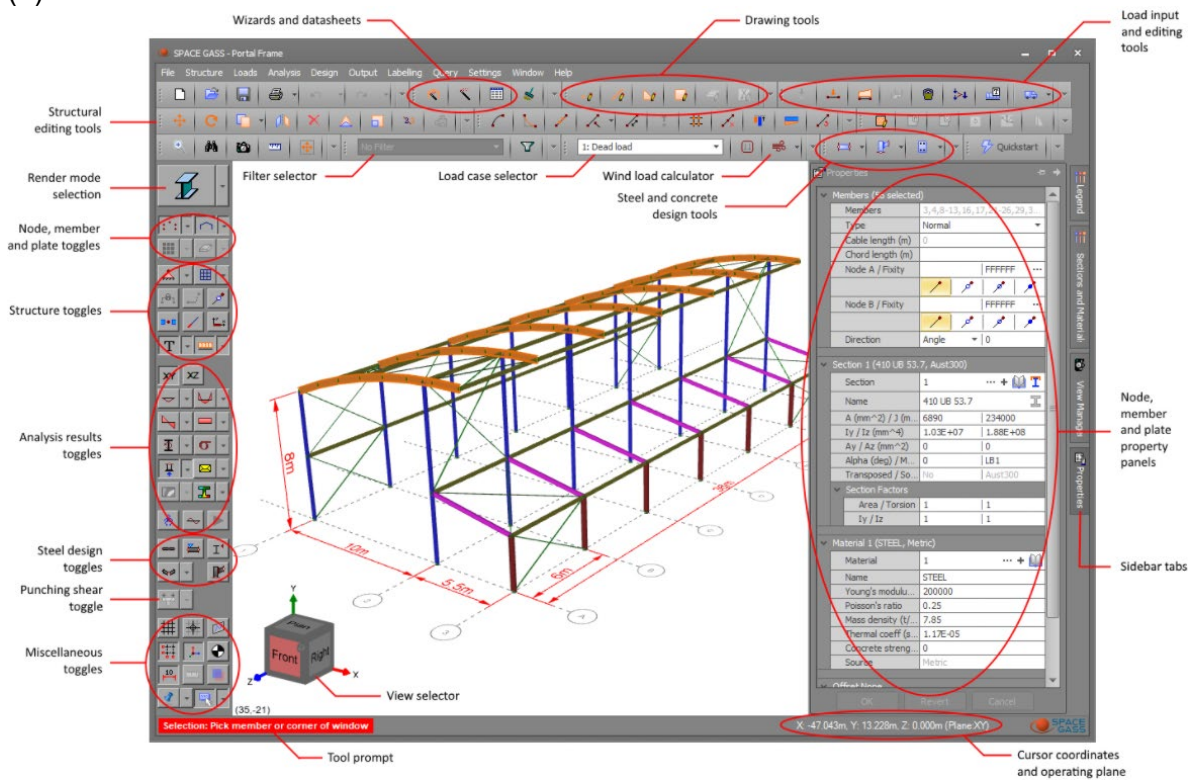
The most relevant features in Spacegass are listed as follows [72]:

- Metric, imperial or any mixed unit system
- A structure wizard that guides the user through the generation of standard structures
- Full data generation facilities for linear and curved structures
- Rigid, sliding and pin-ended members, semi-rigid joints, and rigid, sliding, pinned and elastic supports
- Standard section, material, spectral, vehicle, bolt, plate and weld libraries
- Shape builder for built-up shapes and non-standard sections
- All types of node and member loads (concentrated and distributed)
- Prescribed node translations and rotations
- Thermal, prestress, area and moving loads, as well as automatic self-weight generator
- Pattern loading tool
- Load combinations and load case enveloping
- Linear and non-linear analysis including small, finite and large displacements
- Analysis optimisation
- Floor and diaphragm generation tools
- Storey shear and storey drift calculations and charts
- Wind load generation for enclosed multi-storey buildings
- Direct link with Autodesk Revit (also links to Tekla, Prosteel, Microstation and others)
- IDEA StatiCa connection design link.

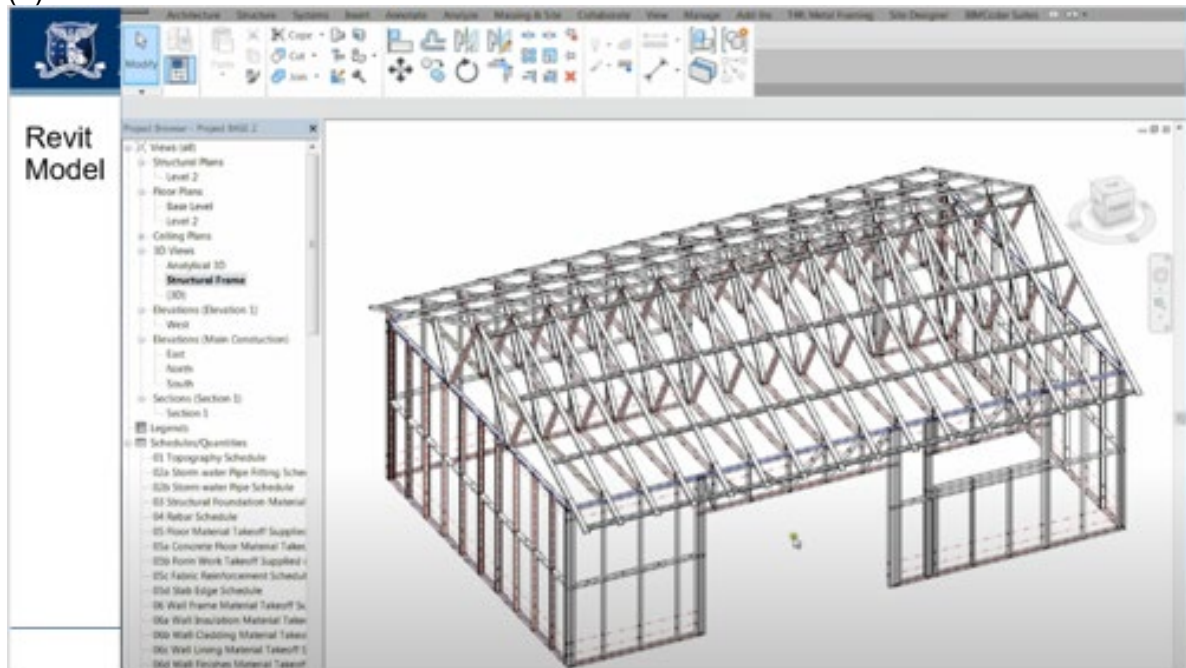
The Spacegass steel member design module can handle most types of steel members including beams, columns, ties, struts, braces, and members subjected to combinations of axial loads, shear forces and bending moments (uniaxial or biaxial) and check design adequacy in accordance with AISC-LRFD, EUROCODE 3, AS4100, AS4600, NZS3404, BS5950, IS800 and HK CP2011 [73]. Figure 27 shows an overview of SPACE GASS software for the design and analysis of a LGS frame building.

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

(a)

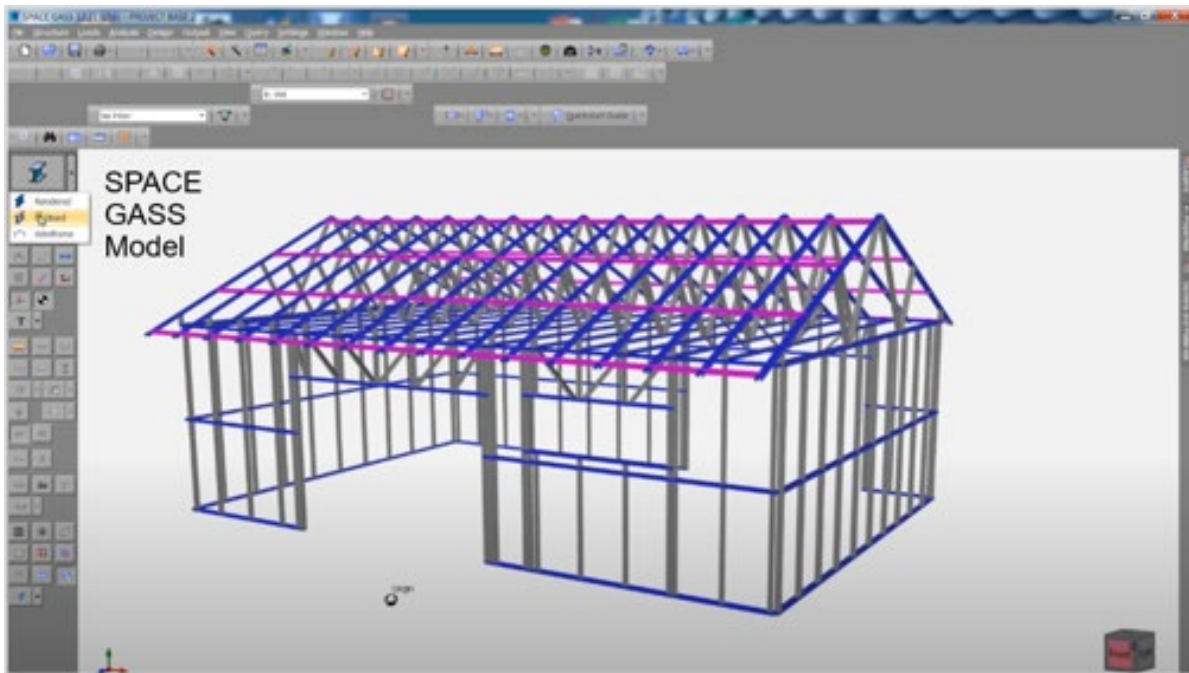


(b)



(c)

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1



(d)

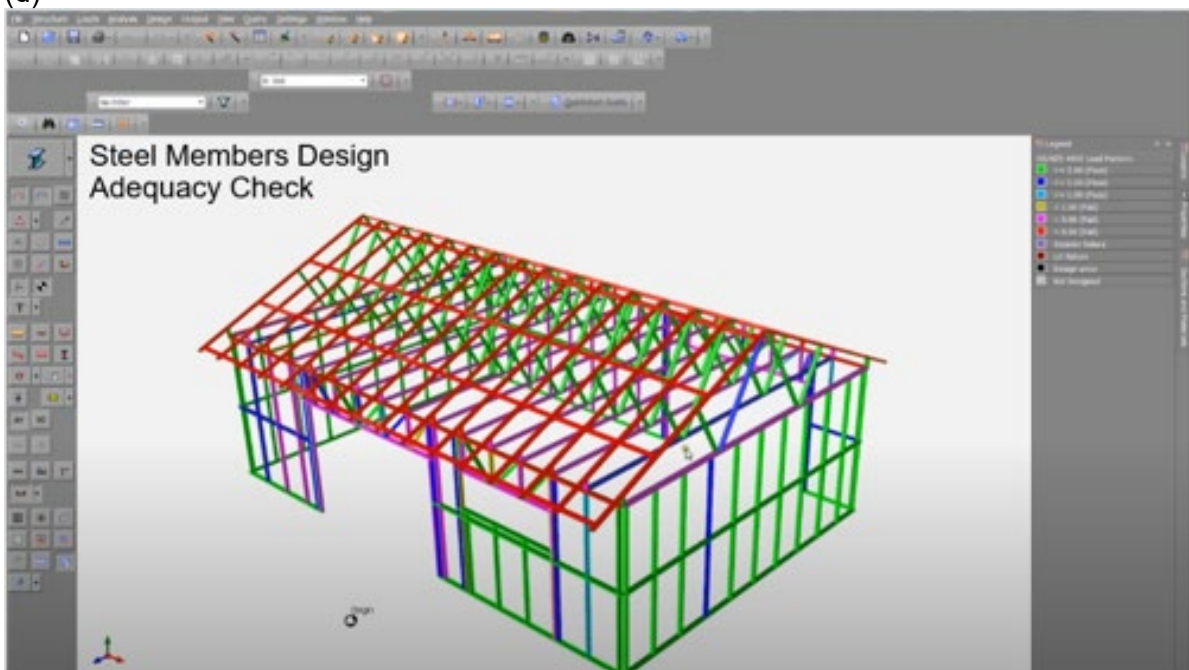


Figure 27: An overview of SPACEGASS capability for structural analysis of a LGS system. (a) Quickstart Guide, (b) Export Revit model to SPACEGASS, (c) Exported 3D model of LGS frame and (d) steel member design adequacy check.

2.5.2. ETABS

ETABS [74] is a structural software which can automate analysis and structural design. It is perhaps the most commonly used software for building systems in the world. Apart from high-rise buildings it can be used for low to mid rise buildings. ETABS has many of the structural analysis and design features of Spacegass, which will not be repeated herein. Other specialised features of this software and its interoperable capabilities are summarised as follows:

- Universally used for design of various building systems RCC, steel, hybrid, including LGS
- Automatically replicates similar stories, and applies changes to sections, loadings with a single click
- Mid- to high-rise buildings can be analysed and designed under gravity, seismic, dynamic and wind loads

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

- Built-in API which allows the user to implement custom plugins
- Currently the software supports limited Australian steel design and loading codes (AS 4100-1998 R2016, AS 1170, AS 1170.2)
- Bi-directional live link with Revit and Tekla Structures, which enables mutual data exchange and updates between the BIM and structural model
- The software is capable of analysing composite structures
- IFC drawings from ENDUROCAD can be imported and exported to ETABS
- Interoperability with the current industry BIM and other structural design software
- Initial evaluation of the LGS building can be performed using ETABS very quickly
- The software has limited support for the design of timber structures.

2.5.3. Other tools

Other structural analysis and design tools are briefly outlined herein.

SAP2000 [75] is a structural analysis and design software package with the following key functions and automation capabilities:

- Can model seismic and wind loading on structures, as well as moving loads on bridges
- Capable of modelling structures subjected to temperature and displacement loading
- Implements design modules for numerous materials, including steel, concrete, aluminium and LGS frames
- Conducts static, dynamic, response spectrum, and non-linear buckling and time history analysis
- Integration with Revit and Tekla Structures, as well as third party tools such as ENDUROCAD through plugins and Industry Foundation Classes (IFC)
- Automation capabilities are available through its well-documented API. For example, a package DynamoSAP has been developed for conducting structural analysis of parametric models developed in Dynamo. Another example is a plugin by GeometryGym, which enables interoperability between SAP2000 and Grasshopper.

Robot Structural Analysis (RSA) [76] is a structural analysis software package with the following key functionalities:

- BIM integrated workflows through data exchange with Revit
- Computational Fluid Dynamics (CFD) wind loading simulation
- Extensive analysis e.g., static, modal and nonlinear structures
- High-quality, advanced finite element mesh for more precise analysis results
- Wind and seismic loading assignment and simulation in accordance with AS1170.2 and AS 1170.4, respectively
- Advanced analysis of 3D frames using modal, response spectrum, sequential staged construction and P-delta effects
- Australian design standards e.g., AS 4100-1998 is employed for steel design.

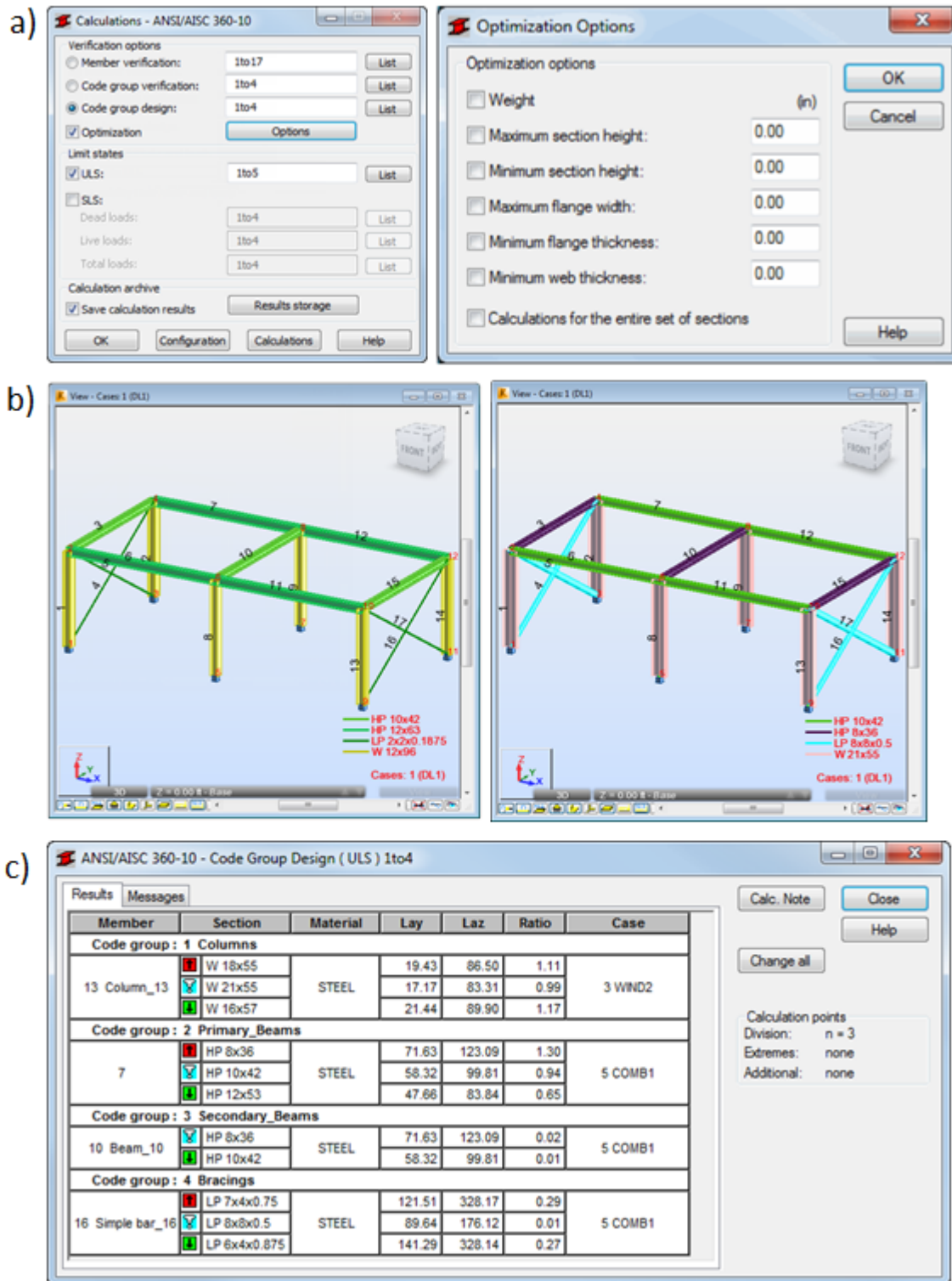
RSA also has several automation capabilities. These include an open and flexible API, which is well-documented, as well as in-built plugins available to establish a live link with Dynamo (through structural analysis package) and Grasshopper (through GeometryGym). RSA provides a module to determine the parameters of calculations performed on member groups with the optimisation options accounted for.

The following optimisation options are available, which are shown in Figure 28a:

- **Weight:** Selecting this option accounts for section weight in the optimisation i.e., the lightest section in the group amongst the sections that meet the code-defined criteria.
- **Maximum section height:** Selecting this option accounts for the maximum section height in the optimisation; the section height is defined in the edit field located to the right of the option.
- **Minimum section height:** Selecting this option accounts for the minimum section height in the optimisation; the section height is defined in the edit field located to the right of the option.
- **Minimum flange thickness:** Selecting this option accounts for the minimum flange thickness in the optimisation; the flange thickness is defined in the edit field located to the right of the option.
- **Minimum web thickness:** Selecting this option accounts for the minimum web thickness in the optimisation; the web thickness is defined in the edit field located to the right of the option.

The lower part of the dialog contains the calculations for the entire set of section options. Selecting this option results in activation (during the calculations) of the procedure that searches the entire section database for the optimal section. This is especially important when the database contains sections not arranged in ascending order i.e., each successive section is larger than the previous one. If the option 'calculations' for the entire set of sections is selected and the 'weight' option is cleared, then the optimal section is the one for which the value of the efficiency ratio is the greatest (but less than 1). An example of a 3D steel frame designed in accordance with ANSI/AISC 360-10 code and optimised based on weight is shown in Figure 28b-c.

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1



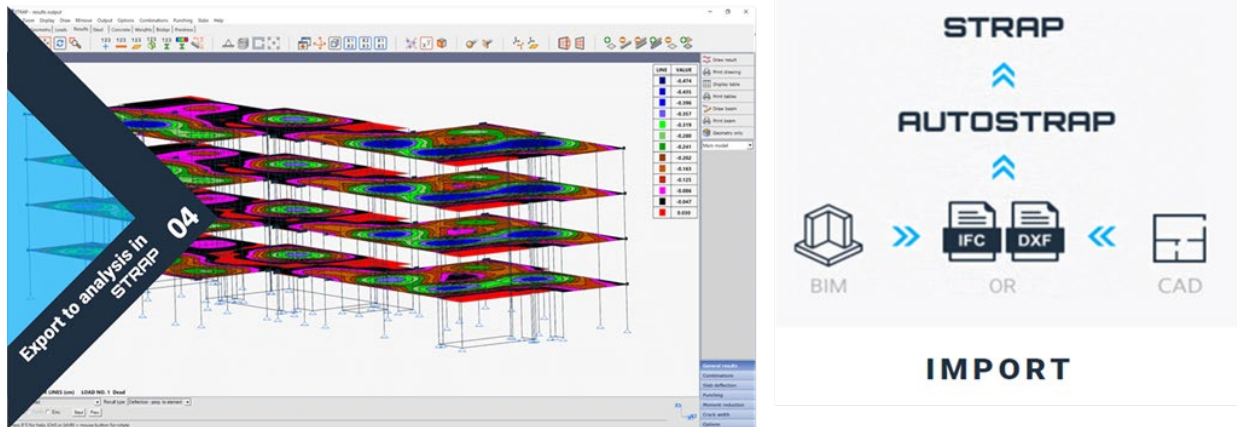
Note: The blue icon (🔍) indicates the optimum section, while the red and green arrows (⬆️ and ⬇️) indicate sections which do not meet the code requirements, or sections which meet the requirements with excessive reserves.

Figure 28: Robot Structural Analysis optimisation option: (a) calculation and optimisation dialog with optimisation options, (b) example of a steel frame before optimisation (left) and after optimisation based on the weight option (right), and (c) code group design dialog displaying the most significant information on the sections.

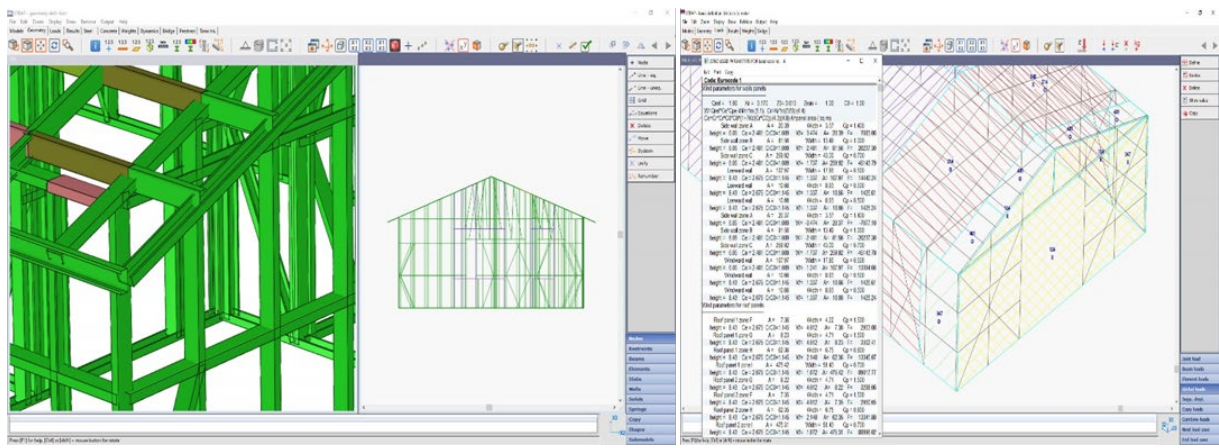
Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

STRAP [77] is another structural analysis software tool, which has the following capabilities:

- Structural design for LGS mid-rise buildings
- Simple shell structures can be modelled and designed
- Dynamic analysis, response spectrum, time history analysis and so on can be performed
- Import BIM, IFC, DXF files and convert them automatically into a structural model
- Loadings can be defined and applied and seismic design according to AS 4100 is supported
- IFC drawings can be imported and exported to and from ENDUROCAD.



(a) Interoperability



(b) Defining LGS

(c) Analysis output

Figure 29: STRAP feature for LGS [77].

Diubal [78] is a multi-purpose software for conducting structural, non-structural, hydraulic, electrical and mechanical analysis. The main features of this software are summarised below:

- Comprehensive software capable of structural analysis and design for various types of materials including steel, cross-laminated timber (CLT), timber, LGS, concrete, glass, aluminium and their connections
- Besides structural design, hydraulics, mechanical, industrial and piping systems can be analysed and designed

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

- Provision of various codes including AS 4100
- Capable of interacting with other structural and BIM software
- Integration with Tekla, Revit, Rhino and Grasshopper
- Addons available for steel structures design
- Steel connection design
- Data exchange with CAD files
- IFC drawings can be imported and exported to and from ENDUROCAD
- Product interface with steel construction
- Bidirectional interface with Revit
- Every model can be equipped with virtual and augmented realisations.

Tekla Structural Designer (TSD) [79] is an integrated design and analysis software. It is automated with features for optimised concrete and steel design. The key features of the software are listed as follows:

- Contrary to traditional analysis software, TSD allows the user to create physical, information-rich models and thereby integrates well with BIM
- Although TSD automatically calculates building wind loads and applies them to the model, the wind loading wizard is based on the US Associated Criteria for Buildings and Other Structures (ASCE 7)
- TSD automatically generates an underlying analytical model from the physical model. However, difficulties arise where non-standard connections comprising several components are employed
- For other loading conditions, AS 1170.0 and AS 1170.1 are stipulated as the Australian Design Codes for generating loading cases and combinations [80]
- TSD can provide a fully automated design in accordance with the chosen building code. The software will instantly achieve an optimised design for all rebar within concrete beams, columns, slabs, flat plates and walls
- Once designed, detailed reinforcement drawings and accurate material quantities are automatically generated for the entire building. TSD also designs all steelwork automatically, based on specific engineering requirements. This includes the detailed design and optimisation of composite beams, columns, US joists, trusses, braces and plated sections. The software only supports steel given that AS 4100 is stipulated as the Australian standard on the website [81]
- It is worth noting that TSD also integrates with Tekla Tedds design software to access Australian standards.

2.6. Energy/thermal and daylighting analysis tools

2.6.1. Energy/thermal

EnergyPlus is an open-source, Building Energy Modelling (BEM) software and has been considered as the first choice for modelling the energy performance of buildings by researchers, engineers and architects [82]. The development of EnergyPlus is funded by the U.S. Department of Energy (DOE), Building Technologies Office (BTO). This program can be used for simulating energy consumption from lighting, HVAC, and plug and process loads in buildings. EnergyPlus is a console-based program, and thereby processes text-based inputs and returns the results in different text formats (e.g., .html, .txt, .csv).

EnergyPlus works on text input and text output. In between, there is a black box, namely the EnergyPlus engine. This EnergyPlus engine takes an input text file, processes it and then outputs the data in text format. For example, a user enters the basic parameters of the building, and EnergyPlus will output the annual energy consumption and energy bills. Since EnergyPlus uses this text-in/text-out approach, essentially any computer programmer can easily build applications

for interfacing with the software. There are a number of user interfaces for EnergyPlus that are built with the main intention of making it easier to use.

2.6.2. Daylighting/visual transmittance

Radiance is a commonly used backward raytracing simulation tool in the daylight analysis and design field [83, 84]. Radiance includes a set of commands that depend on compiling and scripting using a specific language to perform daylight simulations. There is a good number of computer aided design (CAD) tools and plugins with a graphical user interface (GUI) that use Radiance as the backend tool to perform daylight simulations.

The Revit lighting analysis plugin is a part of Autodesk Insight, a cloud-based service that performs fast daylighting simulations. The tool uses Autodesk's daylight simulation engine that uses bidirectional ray tracing to simulate the daylight inside a space, and also calculates, and visualises key daylighting metrics, like daylight autonomy and annual sunlight exposure. The engine calculates all the ray bounces that are important for making conclusions. The algorithm is called Multidimensional Lightcuts [85], with trade secret/patented extensions. The plugin provides automated settings for specific study types, as well as customisable options.

2.6.3. Combined energy and daylighting plugins

Figure 30 presents the flowchart of using plugins in Rhinoceros software to connect these external software (i.e., EnergyPlus, Radiance) and perform simulations for energy and daylighting. These plugins are Honeybee/Ladybug and ClimateStudio, and their details will be discussed in this section.



Figure 30: Flow chart demonstrating the interoperability between energy and daylighting plugins, and outputs from energy/thermal and daylighting analysis.

Ladybug and Honeybee Grasshopper plugins: Ladybug is an energy simulation plugin that relies on multiple EnergyPlus models, and can run simulations based on geometry created in Rhinoceros and Grasshopper. Ladybug integrates standard EnergyPlus Weather files (.EPW) into Grasshopper and generates a variety of 2D and 3D designer-friendly interactive visualisations to aid decision-making during the design process. Users can also employ verified energy and daylighting engines like EnergyPlus, Radiance and Daysim. Users can customise the tool based on their needs and contribute to the source code because it is free and open source.

Honeybee supports extensive daylighting and thermodynamic modelling, which are especially useful in the middle and later stages of the design process. It develops, runs and visualises the results of Radiance daylight simulations, EnergyPlus/OpenStudio energy models and Berkeley Lab

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

Therm/Window heat flow through architectural details. It accomplishes this by connecting simulation engines to CAD and visual scripting interfaces like Grasshopper/Rhino. For these engines, it also functions as an object-oriented Application Programming Interface (API). As a result, Honeybee is one of the most comprehensive environmental design plugins currently accessible. In Honeybee, there are four key steps to conduct an analysis:

1. **Preparing simulation geometry:** Honeybee automates the process of intersecting masses and discovering neighbouring surfaces, so the user only needs to input floor heights and a programme for each space. Honeybee separates the mass into various pieces, and uses the algorithm to assign construction sets, schedules and internal loads to each space.
2. **Check the input file:** Before running the simulation, the user can import the simulation file and visualise it in the Rhino/Grasshopper environment using Honeybee's two-way import/export connection.
3. **Run simulation:** Users can specify a location to the weather file, desired outputs, working directory and project name for the energy simulation. Context geometries can also be used as shading objects. The user should provide test surfaces or test locations for the daylighting simulation and overwrite Radiance details such as number of bounces and sampling. A path to the weather file, as well as the working directory and project name, are also required. Honeybee employs the same geometry for both energy and daylighting studies by default and derives material attributes from the EnergyPlus construction for the daylighting simulation. Honeybee allows the user to customise working schedules, which would reflect on the results of the metrics used.
4. **Visualise the results:** Honeybee re-imports the results of daylighting and energy simulation visualisations so that users can map the results to the geometry.

ClimateStudio is a newly developed plugin for Rhinoceros (Rhino) 3D and Grasshopper by Solemma LLC. ClimateStudio offers advanced daylighting, electrical lighting, and thermal simulation workflows for buildings, as well as photovoltaics (PV) calculations for buildings. ClimateStudio can be employed within Grasshopper, which allows parametric/generative design. This also allows the possibility of applying optimisation algorithms to generate efficient designs based on the objective function set.

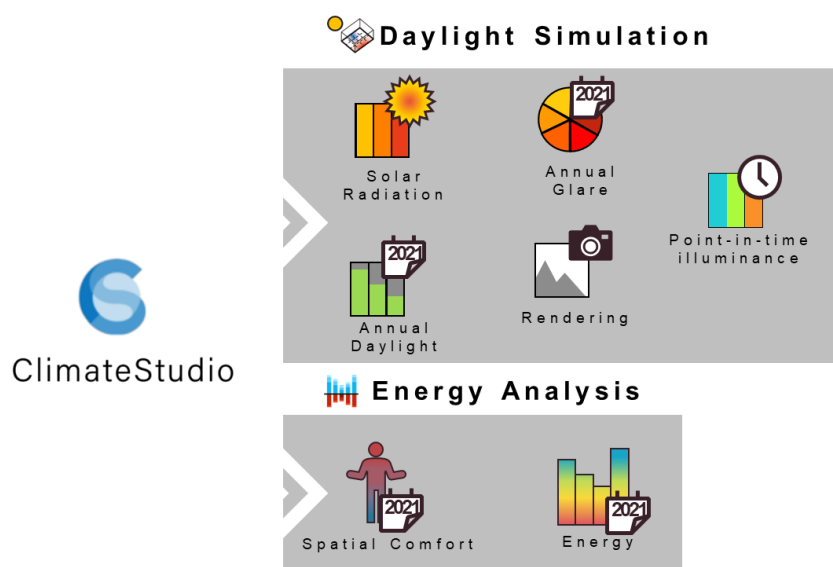


Figure 31: Outputs from energy/thermal and daylighting simulations from ClimateStudio.

ClimateStudio's lighting component is considered a predecessor to DIVA for Rhino which was widely used in daylight research in the last decade. The lighting simulation engine is built based on Radiance and uses progressive path tracing and hardware acceleration, which renders faster yet accurate results.

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

The lighting simulation component is capable of running:

- Annual daylight simulations
- Point in time illuminance simulations
- Rendering simulations
- Annual glare simulations
- Solar radiation maps.

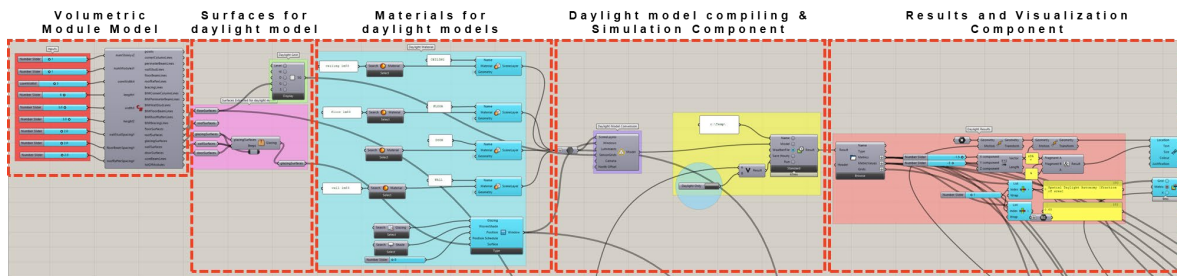


Figure 32: Script for daylighting simulations using ClimateStudio.

Daylight Simulation

Solid Material for daylighting

Celling LM83
Type: Matte
Reflectance: 70.00 %
Specular: 0.00 %
Diffuse: 70.00 %
R: 0.700
G: 0.700
B: 0.700
Roughness: 0.000
Measurement Type: Standard
Credit: IES LM-83

Glazing Material for daylighting

Outside / Top
1 - Solexia - Solarban 60 (3)
2 - Air - EN673 13 [mm]
3 - Solarban 60 on Clear: 6mm - Flipped 6
Inside / Bottom

U-Value[W/m2K] = 1.66
SHGC = 0.368
TVIS = 0.63
Embodied Energy(MJ/m2) = 428.85
Embodied Carbon(kgCO2/m2) = 74.735

Layers: (Outside - Inside)

- 1 - Solexia 6mm Light Green 6 [mm]
- 2 - Air - EN673 13 [mm]
- 3 - Solarban 60 on Clear: 6mm - Flipped 6

Energy Analysis

Constructions for Energy Analysis

Outside / Top
1 - 300mmInsulation 94mmSolidWood 24mmGypsum
2 - Wood fiber insulating board 0.3 [m]
3 - Cross Laminated Timber 0.094 [m]
4 - Wood fiber insulating board 0.08 [m]
5 - Gypsum Board 0.0245 [m]
Inside / Bottom

U-Value[W/m2K] = 0.097
Heat Capacity[kJ/m2K] = 236.994
Embodied Energy(MJ/m2) = 3288.5
Embodied Carbon(kgCO2/m2) = 151.858

Layers: (Outside - Inside)

- 1 - Medium density fiberboard 0.015 [m]
- 2 - Wood fiber insulating board 0.3 [m]
- 3 - Cross Laminated Timber 0.094 [m]
- 4 - Wood fiber insulating board 0.08 [m]
- 5 - Gypsum Board 0.0245 [m]

Glazing Material for Energy Analysis

Outside / Top
1 - Clear - Clear
2 - Air - EN673 13 [mm]
3 - Clear Float Glass Clear 6 [mm]
Inside / Bottom

U-Value[W/m2K] = 2.69
SHGC = 0.707
TVIS = 0.774
Embodied Energy(MJ/m2) = 438.35
Embodied Carbon(kgCO2/m2) = 75.19

Layers: (Outside - Inside)

- 1 - Clear Float Glass Clear 6 [mm]
- 2 - Air - EN673 13 [mm]
- 3 - Clear Float Glass Clear 6 [mm]

Figure 33: Material selection for energy/thermal and daylighting simulations from ClimateStudio.

Figure 33 illustrates the grasshopper script that is used for the daylight simulation. The following list describes the different components in the script:

- Preparing simulation geometry: ClimateStudio accepts Grasshopper B-Rep geometry and surfaces
- Surfaces are assigned material properties that focus on lighting properties. Properties such as reflectance, specularity, diffusion, roughness and colour are defined for solid materials that are used in ceilings, floors, walls, shading devices, and so on. For the glazing materials, visual transmission and refraction index are defined to simulate how much light passes through and the behaviour of the transmitted light
- Daylight model compiling: The daylight model scene consists of the different surfaces with different materials, windows, sensor grids and orientation. Then the model will be coupled with the weather file that will be exported to a user-designated folder
- Run the simulation: The daylight simulation component contains multiple streams and types. They can be categorised into:
 - Solar radiation map

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

- Visual comfort (glare)
- Daylight performance: i) Point-in-time; and ii) Annual performance, where the metrics include Mean Useful Daylight Illuminance (UDI_a), Spatial Daylight Autonomy, Annual Sunlight Exposure, and Mean Illuminance
- Point-in-time rendering.
- Visualise the results: ClimateStudio re-imports the results of daylighting simulation visualisation for daylighting simulations so users can map the results with the geometries.

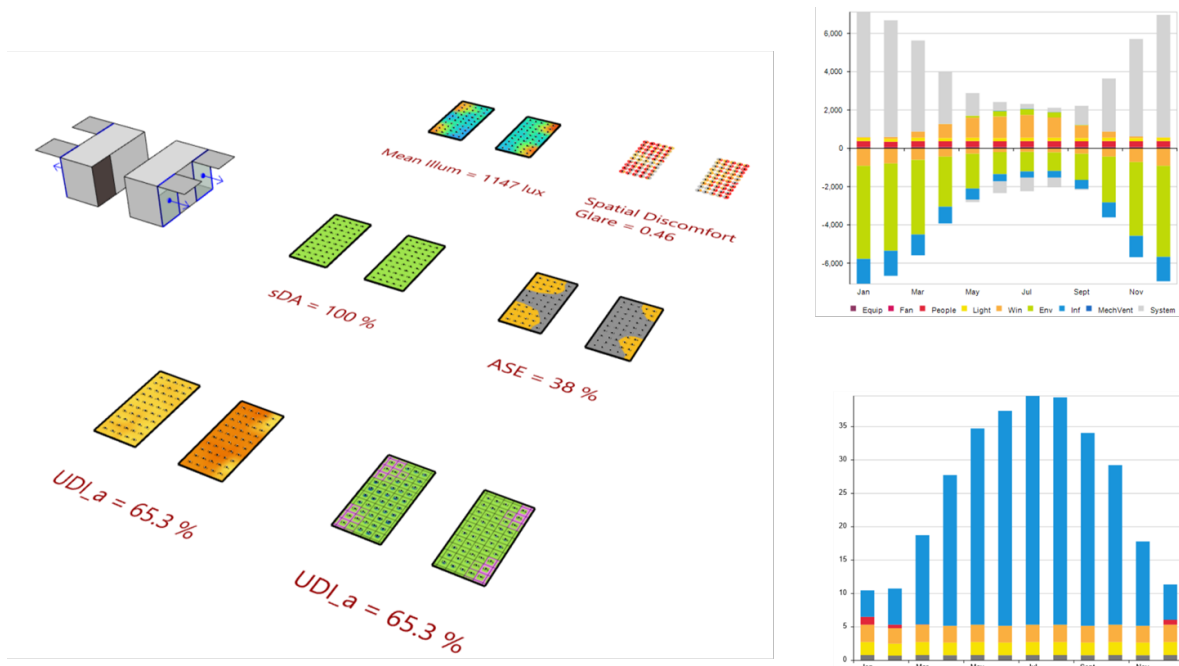


Figure 34: Outputs from energy/thermal and daylighting simulations from ClimateStudio.

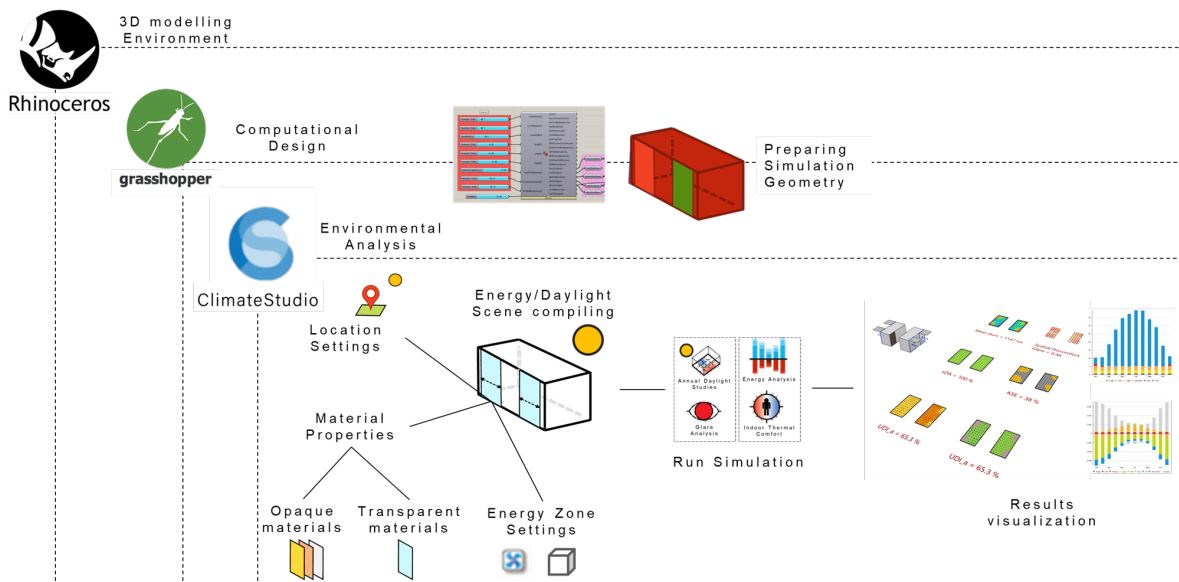


Figure 35: Workflow for energy/thermal and daylighting simulations from ClimateStudio.

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

The strengths of ClimateStudio are summarised as follows:

- Easy to use and integrate with any existing volumetric model as ClimateStudio accepts common grasshopper geometry as part of the daylight model scene and assigns daylight material properties.
- Very fast and accurate results due to its implementation of Radiance in a progressive path tracing mode. Progressive path tracing yields results instantaneously after the first pass of rays and is then followed by gradual denoising which increases the accuracy of the data with each new pass initiated.
- Number of samples can be controlled to produce even faster results, which makes it more applicable to optimisation. Figure 36 illustrates a proposed optimisation workflow using ClimateStudio, showing examples of suggested design variables and objective functions.

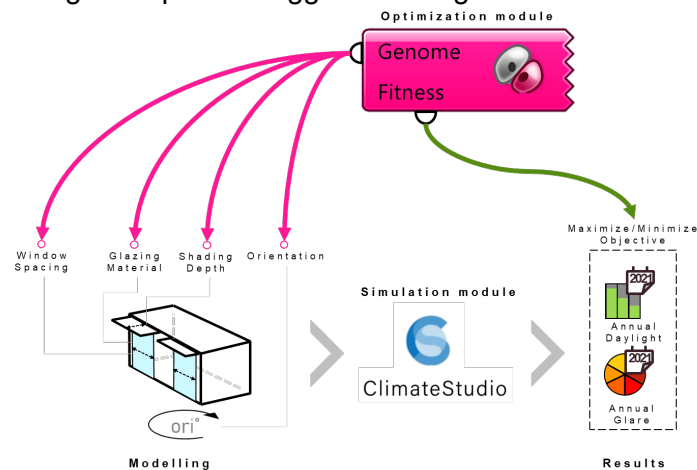


Figure 36: Optimisation workflow integrated with ClimateStudio.

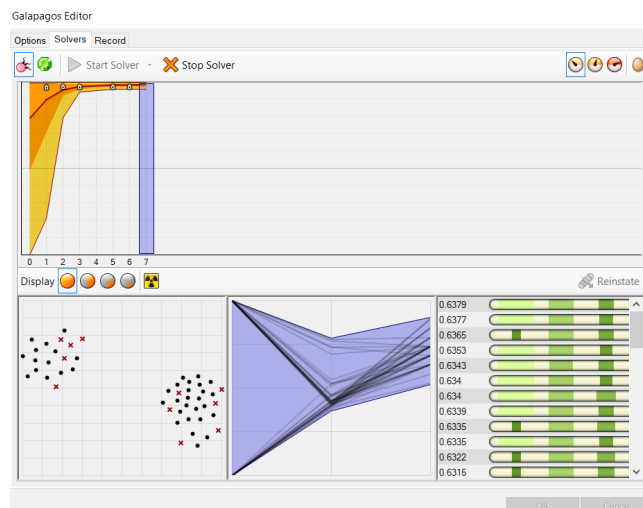


Figure 37: Outputs from energy/thermal and daylighting simulations from ClimateStudio.

The main limitation of the Grasshopper version of ClimateStudio appears to have fewer results reporting features than the mainstream Rhino version, which can affect the decision-making process. However, the number of data points that are collected in the Grasshopper module is sufficient in the larger scale of data points across the entire design process.

Comparison of daylighting simulation component in ClimateStudio and Honeybee: While most features in both plugins are the same, there are a few differences between ClimateStudio and Honeybee. The first thing to notice is the superiority of ClimateStudio in conducting glare studies where it can simulate annual glare on a spatial level. While Honeybee had a single point in time glare analysis tool which ran through Evalglare, it deprecated this tool in later versions of the

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

plugin. The simulation speed difference between the two plugins is comparable, as ClimateStudio uses more advanced simulation technology which yields faster and fairly accurate results in comparison to Honeybee, which uses an older radiance-based engine Daysim. A quick comparison in speed was conducted between the two plugins on the same model with similar settings and it was noticed that ClimateStudio took around 2 to 3 seconds to produce the same results that a 15 to 20 second Honeybee simulation could produce. While most of the result metrics were in a similar range (i.e., UDI for Climate Studio was 57% whereas Honeybee was 63%, and sDA was 100% in both plugins), there were high discrepancies in the ASE calculation between the two plugins (ClimateStudio was 39% and Honeybee was 67%). The difference between the two plugins in ASE was assumed to be attributed to the different radiance simulation parameters that could not be accessible in Honeybee to modify, while the UDI and sDA simulation runs had the option to adjust these parameters.

For energy simulations, ClimateStudio supports multi zone thermal simulations using the EnergyPlus building simulation program. ClimateStudio allows the zone settings to be changed to accurately simulate the energy performance. Some of the settings that can be manipulated are loads, HVAC, ventilation, water, material CO₂ factors and cost factors. Figure 38 shows the different zone settings tabs in ClimateStudio.

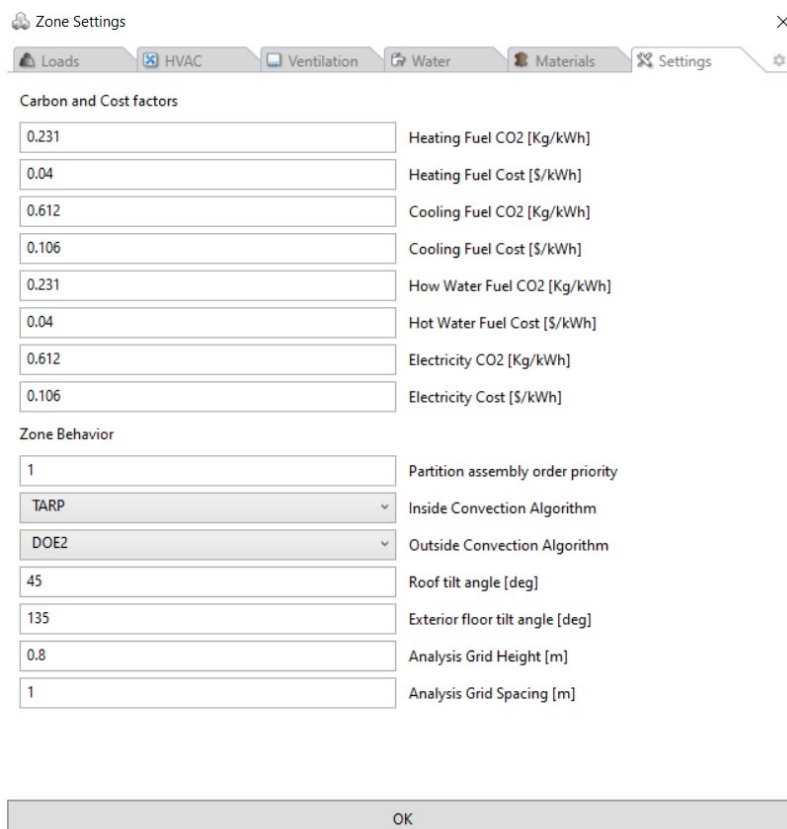


Figure 38: Settings window showing the different zone settings tabs in ClimateStudio.

The simulation results can show several energy performance metrics of a building:

- Energy Use Intensity shows monthly energy use intensity levels for heating, cooling, lighting and equipment
- Energy Use shows total monthly energy use for heating, cooling, lighting and equipment
- Zone Temperature Curves show the number of hours for each zone that the operative temperature is below or above a given temperature
- Energy Flow indicates the monthly sum of heat flows in and out of a zone.

2.7. Emerging planning technologies

For over two decades, BIM has enabled built environment industry professionals to share information in a single, shared project-based set of objects and systems [86]. It helps clients to understand design and engineering choices visually [87]. BIM allows the creative team to generate building design options on the layout of critical services virtually [88].

In space building planning, Generative Design (GD) refers to a method to iterate designs into optimal solutions [89-91]. In nature, a similar design process is based on natural selection principles. These principles, applied to an algorithm, define a genetic algorithm [92], which is an artificial intelligence-based optimisation technique.

GD tools have become an emerging leading approach in any technological field to overcome common design problems. It helps the designers to find the most reliable solution by using planning design software [93]. The main advantage of GD lies in its low time to reach a reliable solution, and its wide range of options and adjustability [94], which helps property professionals drastically reduce the time and risk that is inherent in the property development process [95]. These tools aim to bring transparency and accessibility to property and design, and has the ability to impact the overall project cost as shown in Figure 39. Archistar and Giraffe are emerging GD planning tools covered hereafter.

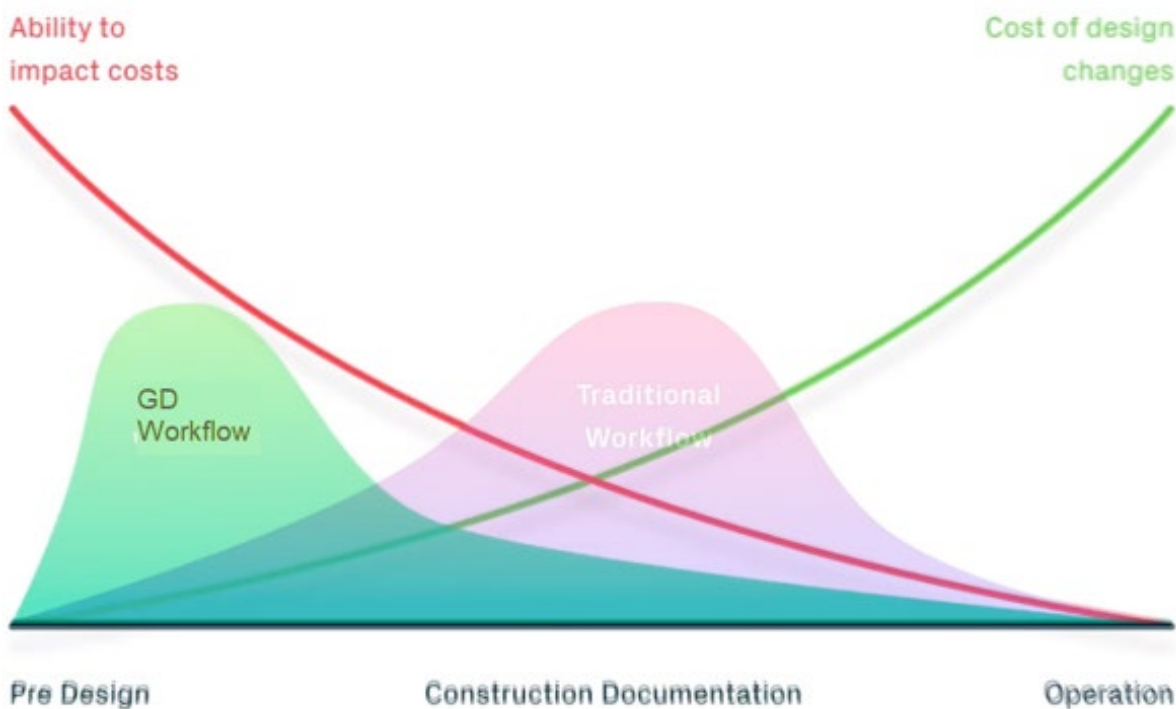


Figure 39: Advantage of Generative Design (GD) tools in the planning phase in terms of project cost.

Archistar is used by the government, architects, planners, developers and agents to access instant information on the highest and best use projects allowable on any development site in Australia based on local planning and zoning rules [96]. Archistar is helping property professionals drastically reduce the time and risk that is inherent in the property development process [97]. Archistar allows a user to select a site and begin from scratch by drawing buildings by line or polygon. Archistar will then take care of the analysis e.g., unit mix and sunlight. The user can select their favourite designs that the generator has created and tweak the unit depth, floor height, hallway layouts and more as shown in Figure 40 [97].

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

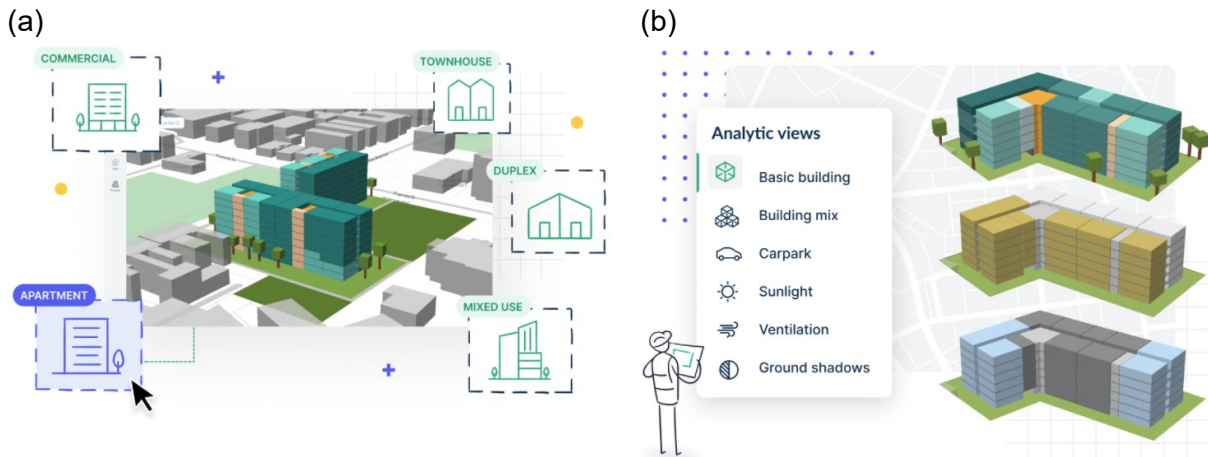


Figure 40: Some Archistar tools: (a) Design generator creates hundreds of building options while respecting site rules and restrictions allowing you to visualise potential concepts early in the process where there is little to no risk and (b) design analysis tool to conduct deep analysis and adjust the design in real time [98].

Giraffe is a technology software that assists urban designers in building planning and producing design options. An example of site analysis using Giraffe is shown in Figure 41. Whether a design becomes reality depends on a financial model. The financial model depends on input areas and assumptions, and Giraffe handles both. Areas are calculated automatically by Giraffe. The user can group and store assumptions on what will be built in sets. These sets are called usages, and each assumption set describes a usage of space, for example: residential, commercial, bathroom and park. Using Giraffe to manage 3D models that manage areas and usages makes it easy to track, communicate, audit and standardise assumptions across an organisation and project. This saves time and reduces risk [99].

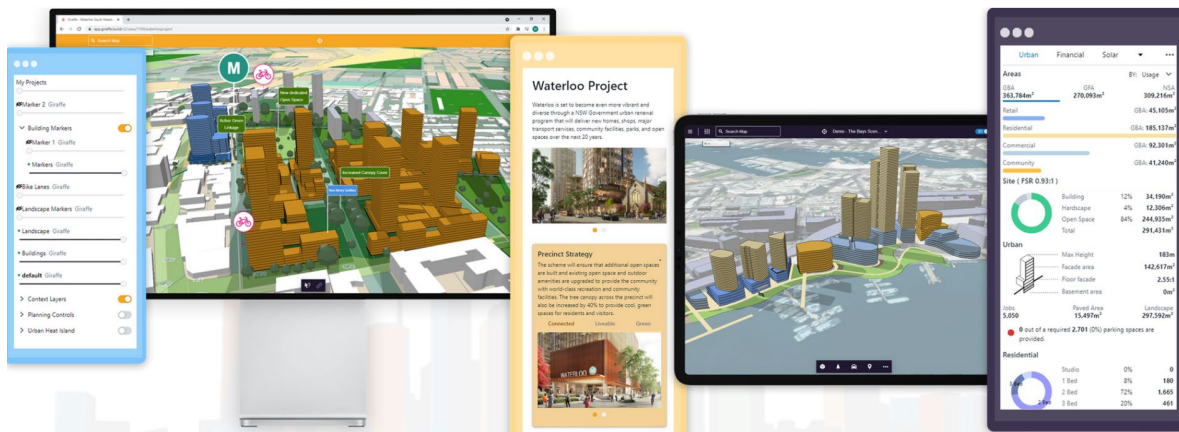


Figure 41: Example of site analysis in real time with architectural design using Giraffe [100].

3. LEADING RESEARCH ON GENERATIVE DESIGN (GD) AND RAPID ENGINEERING (RE) TOOLS FOR STRUCTURAL SYSTEMS

Current leading research is focusing on the application of rapid engineering tools and generative design (GD) to automate the design process, and to assist architects and engineers in decision making. GD and RE tools have been applied in several fields related to building and construction, namely architectural design, design workflows, LGS systems, design and manufacturing processes, modular design and construction, and structural design.

Several applications on GD and RE tools for structural systems have been researched. In terms of RE tools for structural systems, Revit has been employed as a base platform for many plug-ins and add-ons namely AGACAD, StructSoft, FRAMECAD, and ASI. These plug-ins and add-ons widen the application of Revit in developing BIM models by enabling automation in the design and detailing process. Besides RE tools for modelling and detailing, the application of GD in the building and construction industry has also received attention from researchers. Several design workflows with GD were proposed to increase the interoperability between engineers, architects and other parties in a design and construction project. GD has been employed to assist a large number of tasks including optimising the energy performance of a building, assisting design and manufacturing processes, automating structural design, supporting modular design and construction, and also aiding the design of LGS systems.

Most of the current leading research on GD and RE is focused on assisting architectural design at the early stage by proposing frameworks and tools to evaluate the energy performance of buildings [101-112]. However, with the rapid development of GD and RE tools, researchers are focusing on structural design. GD and RE tools were shown to be feasible in the design and manufacturing of mass-timber products (GLT) [113, 114], design and construction planning of modular buildings [115], and also the structural design of a 3D truss comprising different materials [116]. These recent studies ensure the possibility of applying GD and RE for expediting the evaluation of LGS systems for mid-rise buildings.

3.1. Application of GD in architectural design considering energy performance

The majority of leading research in the fields of GD and RE is aimed at assisting decision making at the early architectural design phase by combining the evaluation of energy performance with architectural criteria. Caldas (2006, 2008) [103, 104] developed an evolution-based GD system named GENE_ARCH to achieve energy-efficient and sustainable architectural solutions. The system employed the Pareto Genetic Algorithm as a search engine and the simulation software DOE2.1E to simulate building energy consumption. The software used constraints input from users to find architectural solutions that satisfy the objective of minimising energy consumption. The software is capable of locating the best dimensions and locations of windows to minimise the annual energy consumption of a building, generating alternative façade solutions, selecting materials based on costs and the resulting saved energy. Furthermore, GENE_ARCH can assist architects to optimise between daylight use and thermal performance of a building through arrangements of windows and facades, or generate building shapes to satisfy energy efficiency requirements. However, the author also mentioned that the software also faced some challenges in finding 3D architectural solutions due to the complexity of these solutions with multiple constraints and objectives. Similarly, Mukkavaara et al. [106] proposed a framework to create several architectural conceptual design outcomes using generative design. The framework was demonstrated by applying constraints to a residential block, namely areas, views, sunlight hours, variations and disposable areas to generate possible design options.

Touloupaki (2017) [109] proposed a design workflow to achieve near-zero energy buildings (Figure 42). The workflow is an integration between a GD tool using evolutionary algorithms and energy simulation software. Specifically, the GD tool was the Galapagos Evolutionary Solver, a plugin in Grasshopper for Rhinoceros3d, while Ladybug and Honeybee were the energy simulation plugins. This workflow proved its potential in assisting the early phase of architectural design by effectively providing a solution space that satisfies multiple objectives. However, the authors also pointed out that the efficient collaboration between architects, engineers and contractors remains challenging. Therefore, the authors suggested to develop and apply a cloud-based system to overcome the limitations of the current workflow by allowing seamless data management and collaboration between multiple stakeholders. Prior to Touloupaki et al. [109], Attia et al. [102] and Ochoa et al. [107] also developed tools to assess thermal and energy performance to achieve near-zero energy buildings using EnergyPlus as the energy simulation software. However, these tools were only limited to a few solutions rather than providing a wide solution space as in the study by Touloupaki et al. [109].

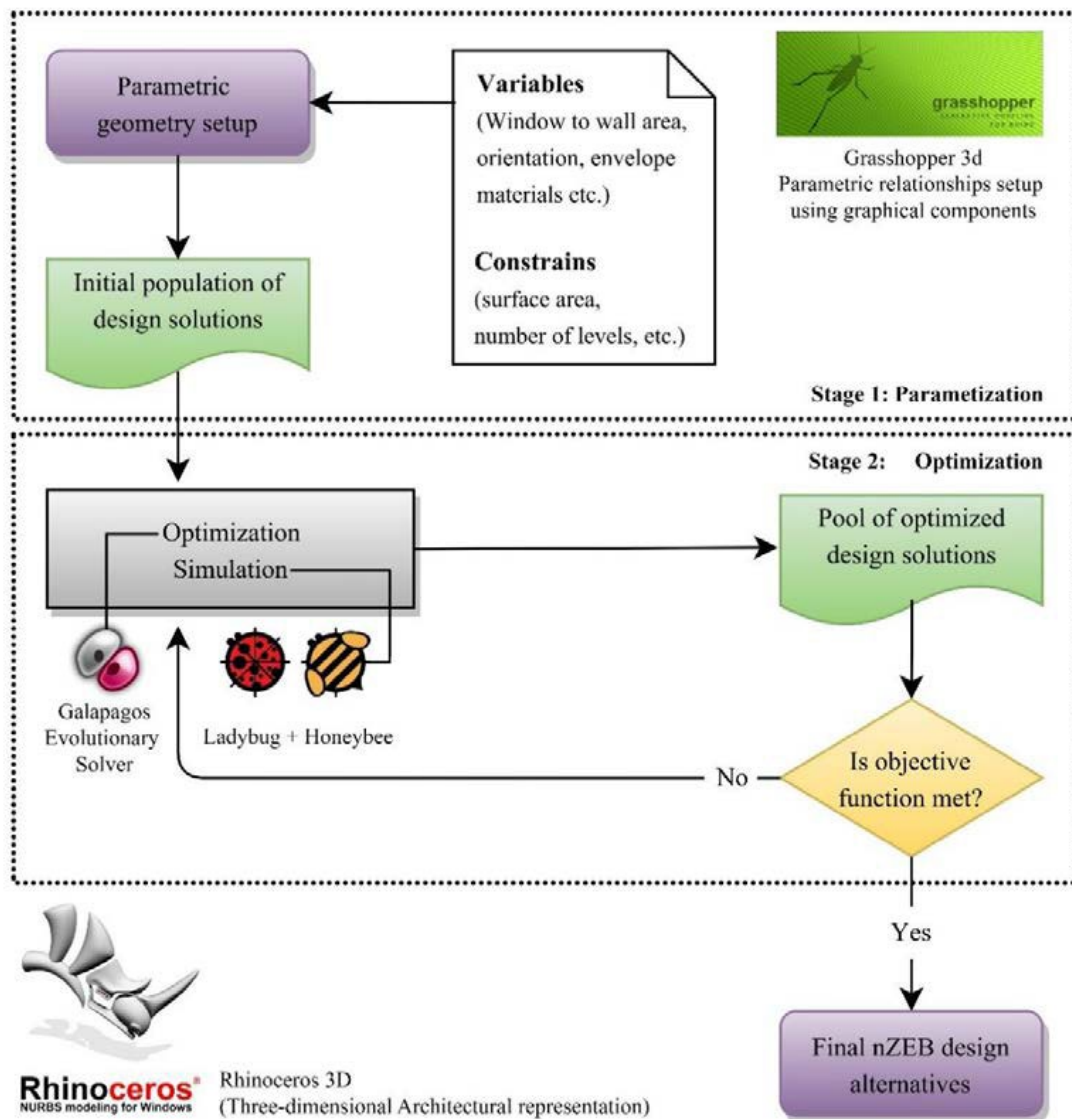


Figure 42: A design workflow to achieve a near-zero energy building (nZEB) [109].

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

Grasshopper was also employed by Zhang et al. [111] to create a generative algorithm (Figure 43) and apply it to optimise the design of a residential building in terms of its total heating and cooling energy load. The authors outlined three steps in the design of a building to optimise its total heating and cooling energy using GD, namely defining parameters, generating possible solutions and evaluating the outcomes. In their case study, the optimal solution was able to reduce the total energy required by 4.2% compared with the original design. However, the authors did not consider the cost and construction aspects in their design.

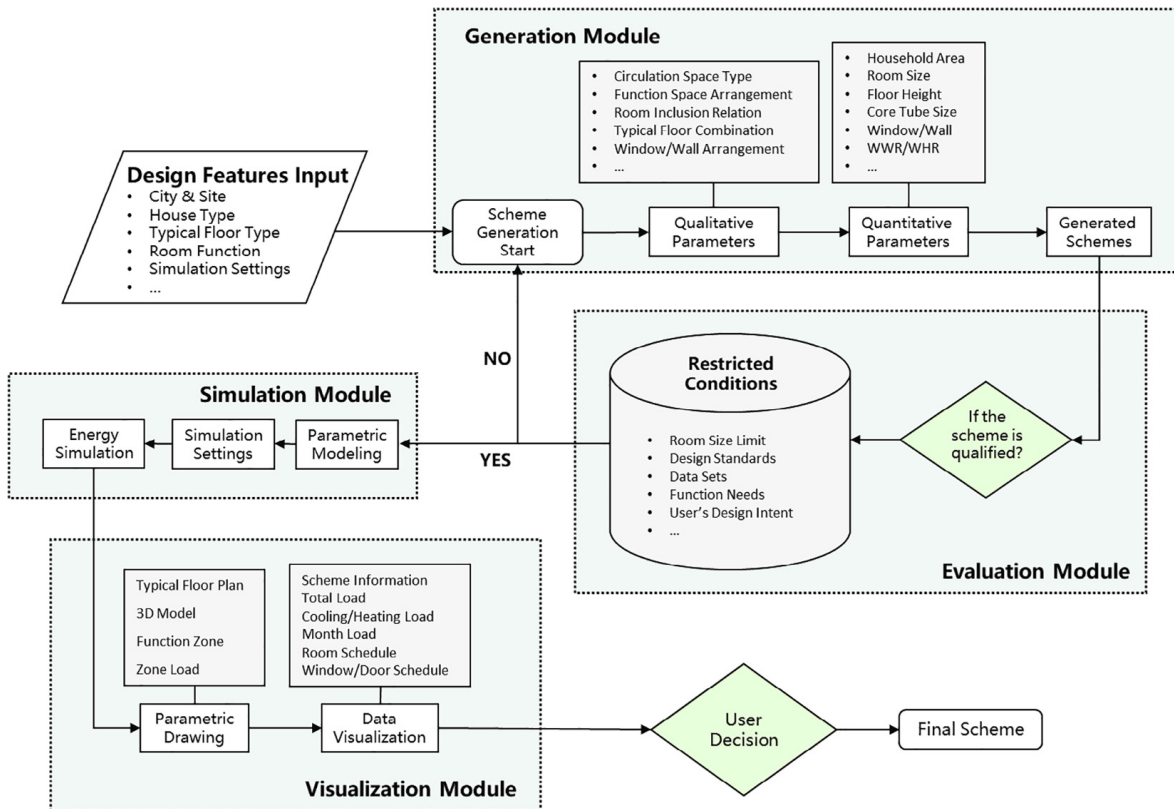


Figure 43: A generative design workflow [111].

Daher et al. [112] applied GD in the spatial development process, namely planning and developing a refugee camp in Luxembourg. The project is a case study using a GD framework to assist policy makers in spatial development. The project considered both the contextual constraints (accessibility, orientation, constructability and usage requirements) and numerical constraints (number of people, container sizes, and distances to critical facilities). In the study, Space Syntax was used to control usage requirements while Kangaroo plugin for Grasshopper was used to manage the relations between spaces. The project successfully optimised the land use. However, materials and costs were not implemented into the model. Therefore, further assessments of construction costs were required to assist decision making at the early phase of the project.

In summary, several tools and workflows were developed to assist the early design phase by determining the structural parameters of buildings (e.g., sizes, shapes, orientations, layouts, windows and doors, and facades) to maximise different energy performance criteria. However, these tools and workflows mainly focused on analysing energy performance with marginal contribution to other stages of the design and build process. Therefore, a workflow that enables the interoperability between different stages and the collaboration between architects, engineers and other stakeholders is necessary to enhance the effectiveness of the design and build process.

3.2. Design workflow using GD

Abrishami (2014) [101] proposed a conceptual framework for a generative BIM environment as presented in Figure 44. This framework enables a fully integrated design and construction process from architectural design, engineering and construction. This framework considers material, fabrication and assembly constraints during the entire process. Moreover, this framework also enables the coordination between all stakeholders in the early stage of architecture-engineering-construction design.

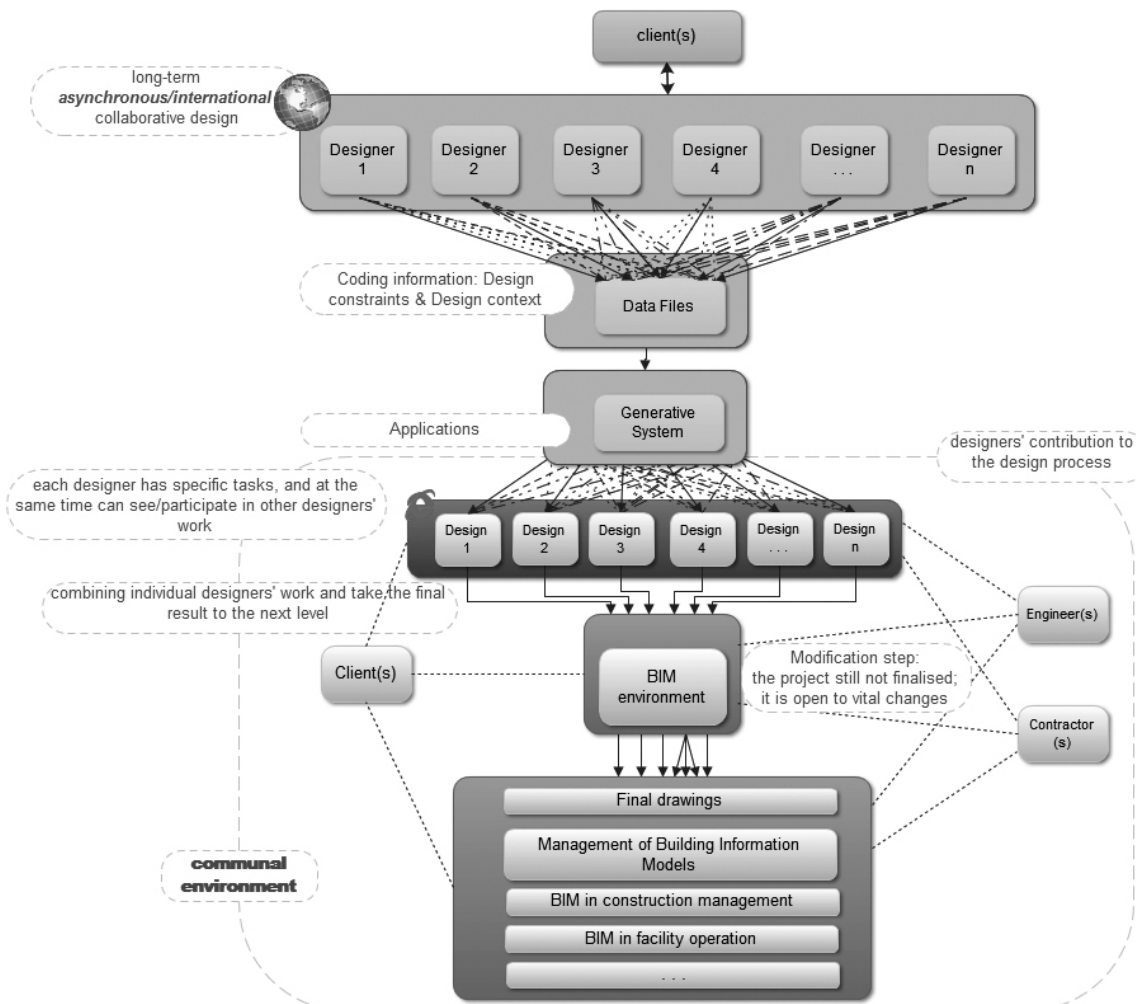


Figure 44: A conceptual framework to link generative design with the BIM environment [101].

Ostergard (2016) [108] conducted a review on different software used to assist architects in the early building design stage. The author outlined the challenges in the early stage of building design and construction, namely the lack of information, uncertainties, rapid change of design and model resolution. To overcome these challenges, the authors proposed a simulation framework (Figure 45) that considered several parameters at the same time to aid decision making at the early design stage. Noticeably, five steps in optimisation were proposed by the authors as follows:

1. Identification of design variables and constraints
2. Selection of the simulation tool and creation of a baseline model
3. Selection of objective function(s)
4. Selection of optimisation algorithm
5. Running simulations until optimisation convergence is achieved
6. Interpretation and presentation of data.

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

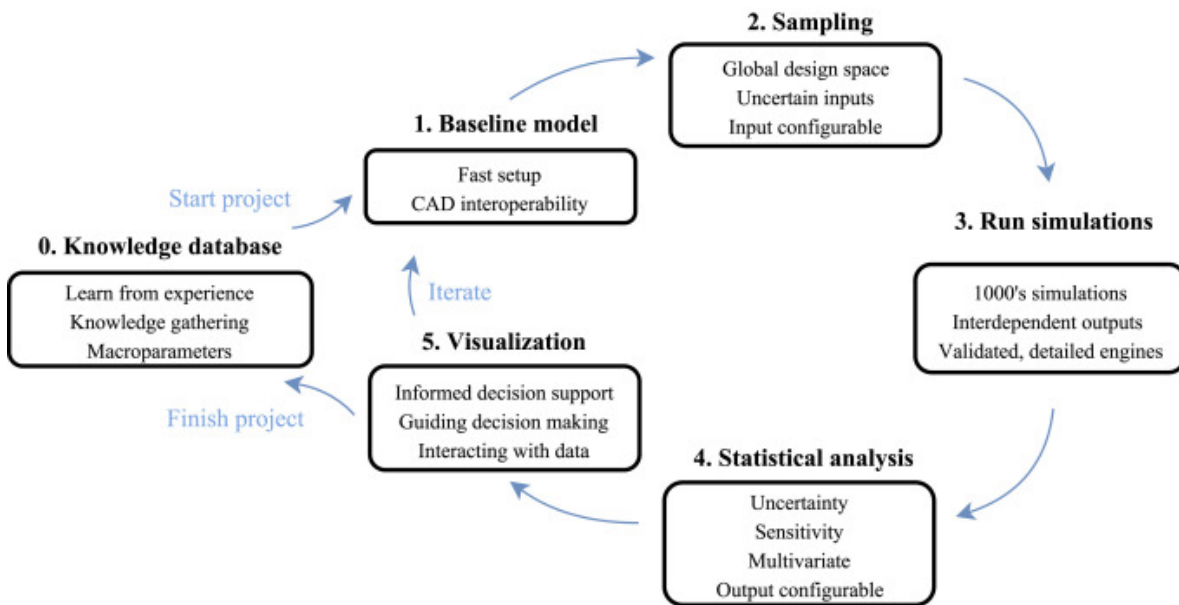


Figure 45: Proposed workflow to assist decision making in the early design phase [108].

Recently, Chang et al. [105] published a framework to assist spatial development (Figure 46). The effectiveness of the framework was shown by applying it to a case study, namely the design of a university campus in China. Numerous geometrical alternatives of the campus design were found from a set of constraints including site geometry and limits, and development requirements. The performance of these design alternatives was then checked using several criteria, namely sky opening, solar radiation, thermal loads and energy consumption to propose feasible optimal design options.

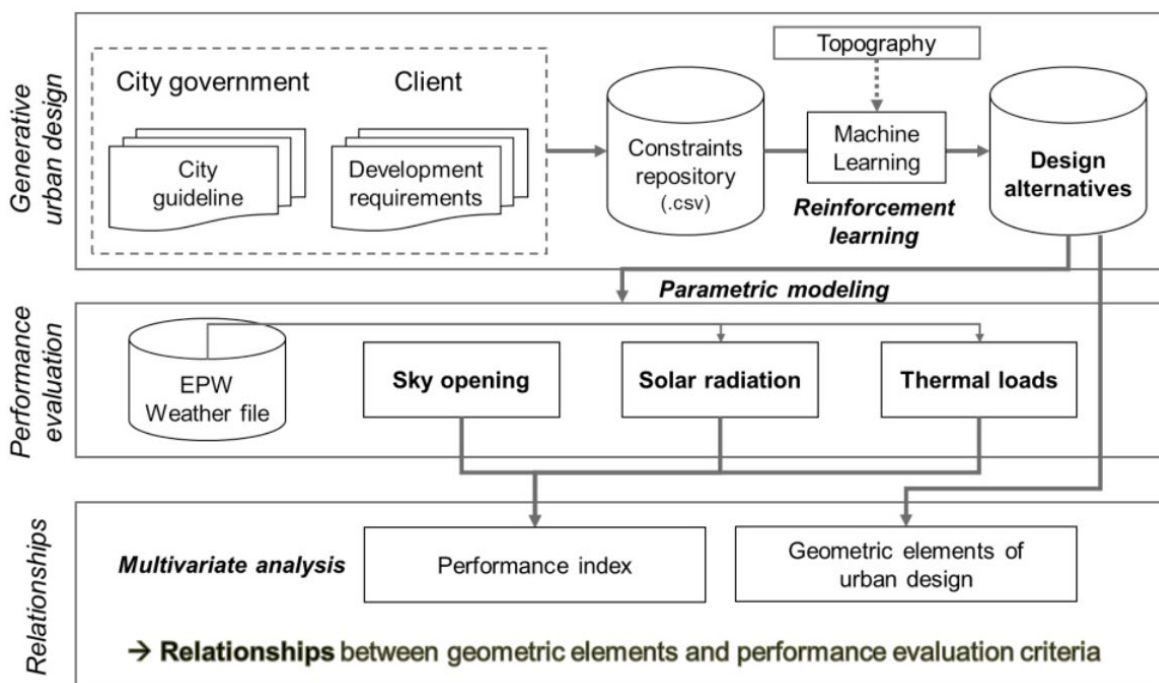


Figure 46: Proposed framework for spatial development [105].

3.3. Application of GD for LGS systems

Rodrigues et al. [110] conducted a comparative study on the energy performance of LGS buildings using GD. The authors proposed a design workflow to evaluate the energy performance of LGS buildings (Figure 47). The Evolutionary Program for the Space Allocation Problem (EPSAP) was employed to develop the GD tool while EnergyPlus was used as the simulation software. A total of 6010 buildings were generated for energy performance evaluation. Each building has a random geometry and a combination of different insulation levels. The authors were capable of comparing different energy performance criteria for buildings with different roof types, building shapes, glazing areas and the position of insulation layers. The result showed that the workflow was capable of evaluating the energy performance of LGS buildings, thereby proposing optimal design outcomes to assist decision making in the early design phase.

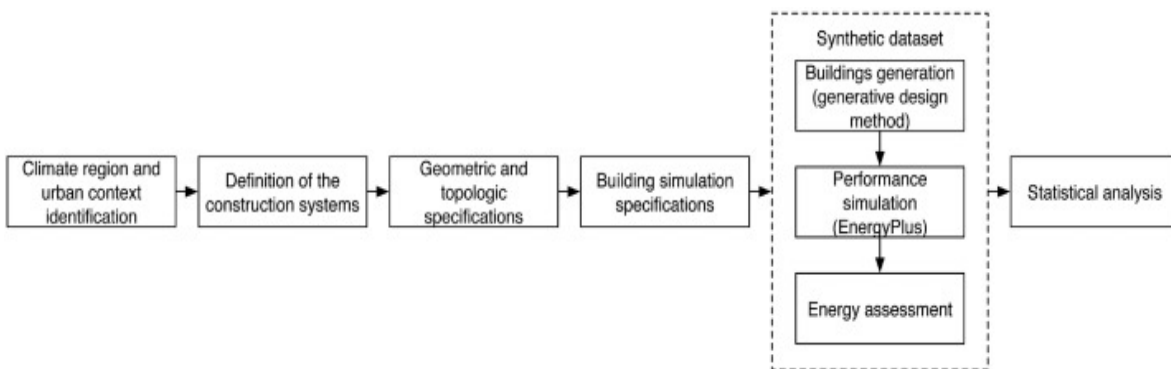


Figure 47: Design workflow to evaluate the energy performance of LGS buildings [110].

3.4. Application of GD in design and manufacturing processes

Monizza et. al. (2016, 2018) [113, 114] proposed parametric and GD techniques for mass-production environments, and employed them to analyse a case study involving the manufacturing of Glue-Laminated Timber (GLT). The proposed workflow for applying this method to the design and manufacturing of GLT is presented in Figure 48. In this method, based on the geometry and working conditions, GLT products were simulated and optimised to satisfy several objectives, namely minimising the usage of high-quality materials and improving the overall efficiency of the production line. Besides the mechanical properties of GLT, the authors also consider many inputs and outputs in the production line such as operation time, processing time, cycle time, process quality and so on, to optimise the manufacturing of GLT.

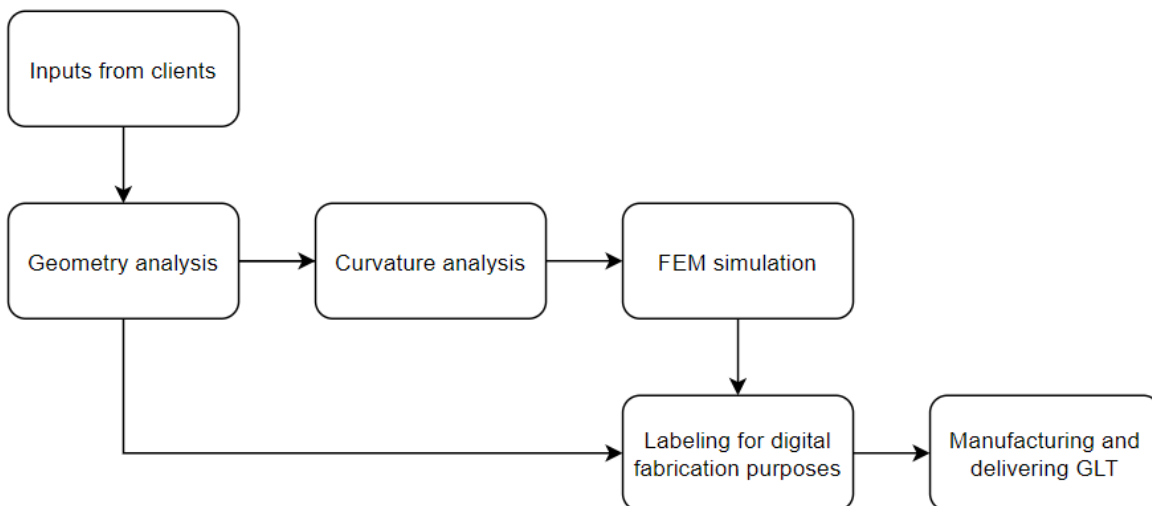


Figure 48: A generative design workflow of GLT (adapted from [113]).

3.5. Application of GD in modular design and construction

Wei et al. [115] applied GD to design a modular building (Figure 49). The authors employed Dynamo to program generative algorithms and Autodesk Revit as a BIM platform to conduct the parametric design of a modular building. The results are building layouts satisfying both design constraints (module dimensions and arrangements to comply with building codes) and construction restraints (the weight of a module and lifting capacity of cranes). The study demonstrated the feasibility of applying GD tools in the design and construction of modular buildings with multiple design and construction objectives.

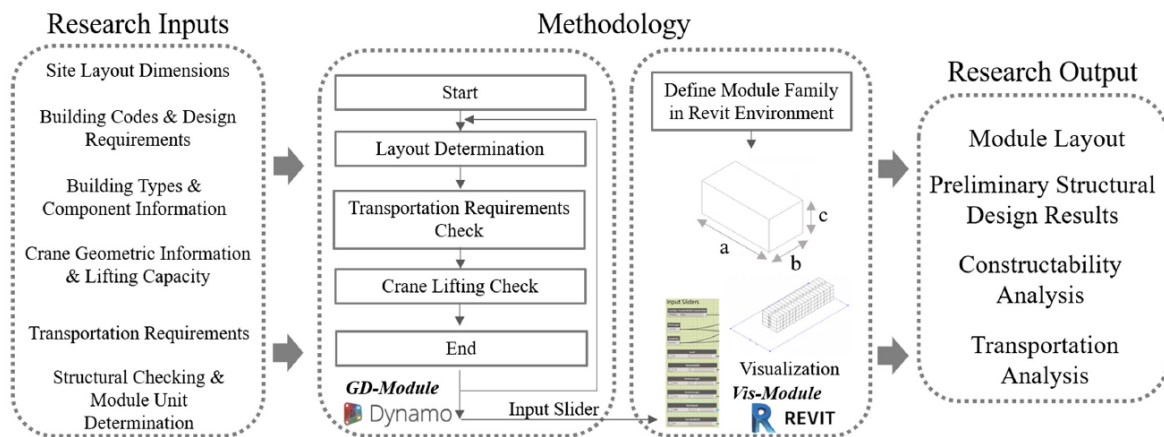


Figure 49: A design workflow of a modular building [115].

Before Wei et al. [115], Alwisy et al. [117] developed a tool named MCMPro to assist the design and construction of modular buildings (Figure 50). The tool was written using Visual Basic for Applications as an add-on to Autodesk AutoCAD. MCMPro was capable of assisting panel prefabrication, production line in the factory, and on-site installation through a BIM model. Furthermore, the tool also created shop drawings, quantity take-off lists, optimum material cut lists and corresponding construction methods. However, the tool requires users to manually input the information from architectural drawings. Therefore, it cannot update the changes from architectural drawings seamlessly.

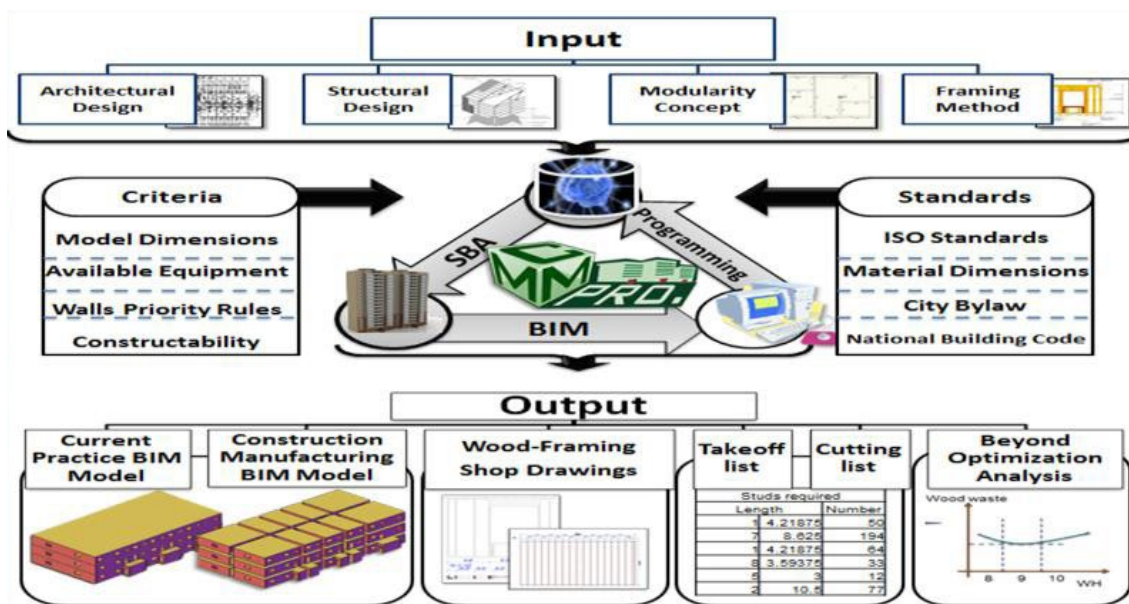


Figure 50: An overview of MCMPro software [117].

3.6. Application of GD in structural design

Johan et al. [116] demonstrate the feasibility of using GD to conduct structural design. The authors developed a GD tool in Grasshopper to execute a design framework in four stages including component generation using C-sharp, structural analysis using Karamba3D plugin, optimisation, and evolution using Galapagos plugin. The tool was capable of providing various optimal designs of a truss that satisfy simple design criteria with different materials such as steel, wood and bamboo. The tool successfully created and optimised the design of a 3D truss. However, due to simple design criteria, the tool requires further development to replace other structural analysis software for structural design purposes.

To improve the level of collaboration between architects and engineers, Hamidavi et al. [118] proposed a new framework that incorporates both the architectural and structural design of a high-rise building. The study is a proof-of-concept prototype outlining a proposed automated design workflow. The proposed automated design workflow is capable of linking architectural aspects through shape optimisation and structural aspects through topology and size optimisation to provide an optimal output (Figure 51). With the help of a visual programming language (such as Dynamo), design tasks can be automated and linked to a BIM platform (such as Autodesk Revit) and structural analysis software (such as Autodesk Robot Structural Analysis), thereby overcoming the separation between current discipline-based design processes. Although in the proof-of-concept stage, the proposed workflow demonstrated the feasibility of overcoming the current discipline-based design process to achieve a fully integrated design using BIM level 3. However, due to the fact that the proposed design workflow required knowledge in programming, stakeholders without design knowledge may find it difficult to follow.

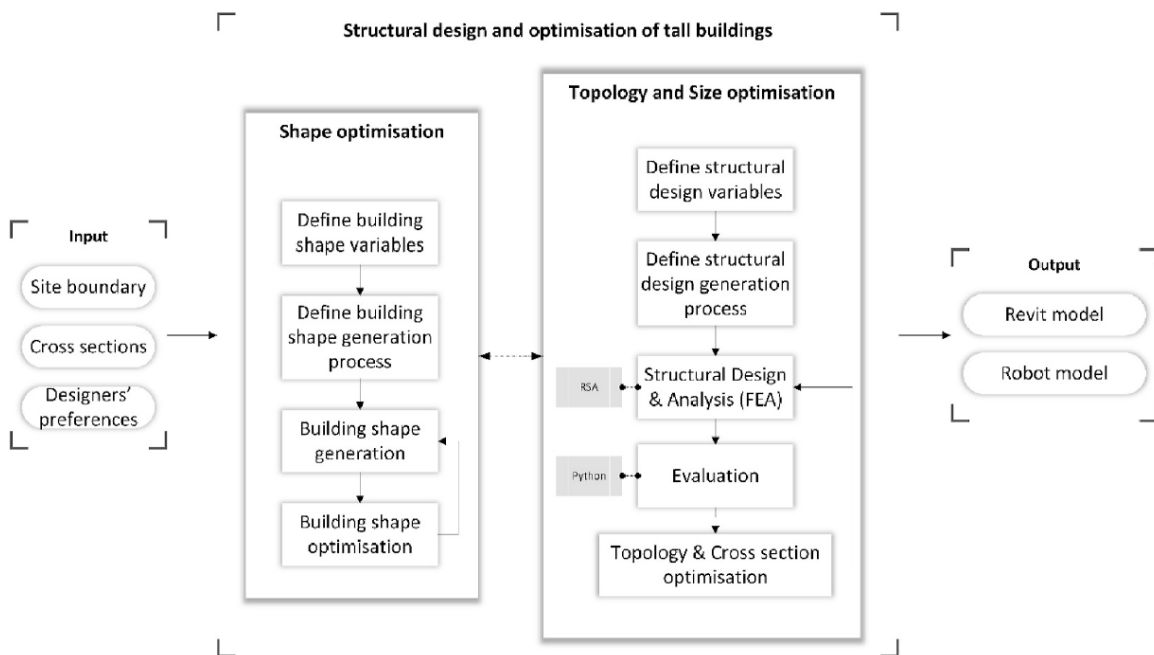


Figure 51: A proposed automated design workflow of a high-rise building [118].

4. CRITICAL TOOLS FOR RAPID EVALUATION OF STRUCTURAL SYSTEMS FOR LOW TO MID-RISE COMMERCIAL PROJECTS

4.1. Software design logic

The critical tools required for expediting the evaluation of LGS in the early planning phase are mainly BIM and structural analysis and design software, which are effectively integrated together with platforms such as Grasshopper and Dynamo. The design logic of these tools based on engineering principles is discussed hereafter.

BIM is based on a holistic view of a structure's life cycle; this includes the initial idea and design planning (architect, building owner), the detailed design and final planning (engineers), and the building's operation and demolition [119]. The software design logic is centred around the following factors:

- Among other things, the objective is to optimise costs over the structure's life cycle [120].
- The structural design itself is only a small part of BIM, and its impact on the structure's costs is usually of secondary importance [121]. Therefore, the great "revolution" of BIM has more influence control by the architect [122]. Nevertheless, structural engineering plays a significant role in a relatively short period of the final planning [123].
- Design determines the feasibility of a particular structural concept, and is a milestone in the planning process, as other services could be delayed without proper design [124]. It also has a strong influence on further planning reliability and the associated costs for the necessary changes [125]. In summary, structural analysis, including any subsequent changes, must be efficient and reliable.
- The current three-dimensional BIM models can provide valuable data input or means of communication and better understanding in regard to structural engineering [126].

There are various options for data exchange file formats. The Industry Foundation Classes (IFC) format as a global standard plays a special role. It is divided into different views and each discipline has its own view [127]. The main view is the Coordination View (CV), where the individual software products can be certified [128]. When considering the IFC format without specifying the individual views, the CV is typically used by default [128]. This is supported by most architectural programs. In contrast, the Structural Analysis View (SAV) for structural engineering includes a description of the structural model, loads and load combinations [129]. This view is currently not certifiable and is only supported by a limited number of structural analysis programs [129]. Although defined as a standard, the IFC format can generally be interpreted in various ways. Therefore, it is necessary to check the format with the relevant software data to achieve successful data exchange.

In addition to the IFC format, established file formats such as DXF/DWG, Product Interface for Steel Construction, or other text-based applications can be used. Direct interfaces also play an important role. They do not have any exchange files, as the individual programs communicate directly with one another via application programming interfaces (APIs).

BIM software already includes an analytical model (structural model) in the architectural model. The advantage of this software is that both models overlap and reference each other, so these models can be analysed efficiently and easily. In addition to the system data, load specifications are possible. When using this software, the user must build both models accurately. Appropriate coordination between all parties involved is necessary. The person who conducts the model editing is often not from the same engineering office, and the issue then becomes who settles the costs for

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

the interdisciplinary models, and who is responsible for precision and accuracy. This must be arranged in advance. Without a doubt, there is great opportunity for BIM and it continues to be recognised by well-known firms. If the entire planning chain can be created, the BIM models can be prepared optimally, at an early stage, and used later for the structural analysis [130].

The support of various data formats is an important aspect in choosing the right software. The description in the existing data format must be transferred into the objects specific for this software. Consideration of the visualisation or data model reference alone is insufficient for structural design and can only contribute to visual checks. If the software can import several models and transfer them into the correct data object model, this may enhance the flexibility significantly, and the chances for successful and effective data exchange are increased. This is a key success factor when the IFC CV files are used in the structural analysis software.

Regardless of additional effort, programming of simple proprietary tools for data exchange should always be included at the outset. This allows the efficient transfer of additional information in the form of parameters. For example, you can display items of a structural model in BIM software, communicate possible modifications or implement company-specific workflows in the software. This requires all software products involved to have the corresponding APIs operated by conventional and simple programming languages (e.g., VBA, C#, Python). Figure 52 shows a proposed rapid evaluation workflow between different software at the planning phase.

The key success factors for successful and efficient data exchange include the following [131-133]:

- Generation of a BIM Model with regard to Structural Design (SD)
- Early involvement of the structural engineer and consultation of the handover time and content
- Setting standards for materials and cross-section descriptions (mapping tables)
- Functional and consistent modelling of structural components (columns, beams as member objects, walls, plates as surface objects)
- Modelling walls, plates, and columns in sections and levels.

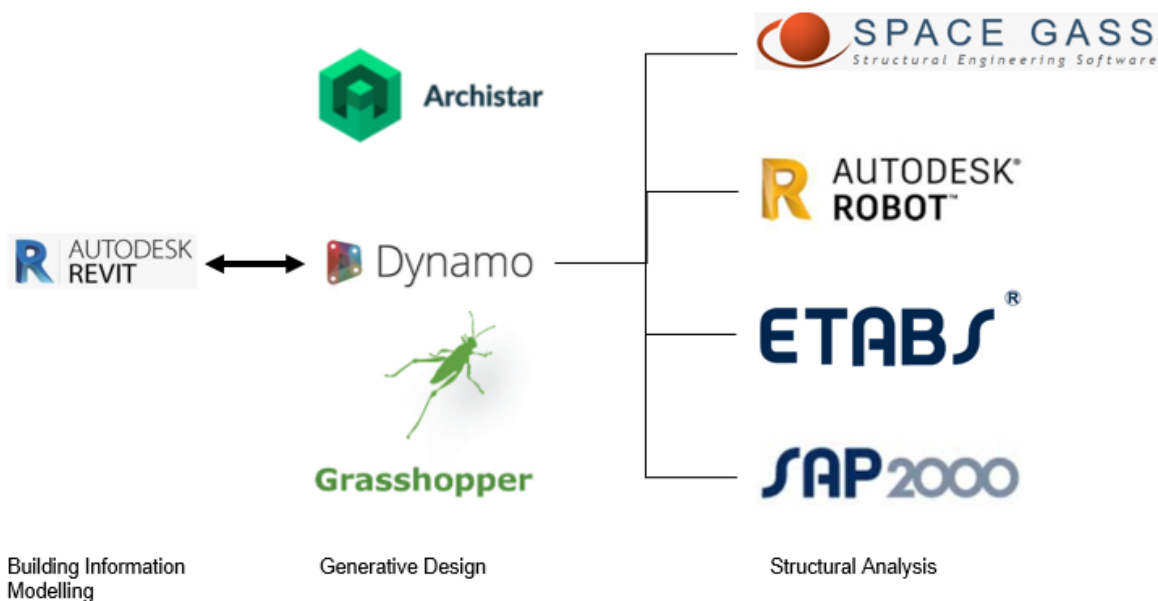


Figure 52: Proposed rapid evaluation workflow for structural system analysis.

4.2. Critical data required for each stakeholder

The critical data required to evaluate LGS against other structural systems in the early planning phase of a project are mainly those that facilitate structural analysis and conceptual design checks, as well as BIM data that facilitates cost calculations, and the generation of assembly drawings and bill of materials. This data is summarised in Table 10.

Structural analysis and conceptual design code checks are the critical components of any structural software package. Specifically, LGS design checks according to AS 4600 is required, which governs the seismic and the wind design for LGS buildings. AS 1170 is the general loading code for any building. These standards provide the load conditions (dead, live and superimposed), minimum section sizes required, and input parameters for seismic and wind analysis for LGS buildings. BlueScope also uses the National Association for Steel Framed Housing (NASH) standards for the design of low-rise LGS buildings. The presence of these three standards for obtaining the allowable limits on shear forces, bending moments, deflections, drift, building time period and modal vibrations is needed. Any component or the entire LGS building (for drift and time period) not satisfying the aforementioned structural parameters needs to undergo some changes to make the building and its components safe and within allowable limits.

The information related to building data and drawings for a LGS building i.e., height, location of rooms, lift, terrace, and so on, from the architect, and the data from the geotechnical report is needed by the structural engineer to develop models for the buildings. Structural engineering inputs include beams, columns and slabs sizes using the parameters from the aforementioned standards in the building model. A quick way of inputting this data is importing information (e.g., building layout, framing parameters) from the Revit BIM model, which can also be imported in structural software.

Table 10. Critical data required by various stakeholders for each tool.

BIM, including cost and installation data	<ul style="list-style-type: none"> • LGS section library, including mechanical, thermal and acoustic properties • Member and component costs • Geometric parameters such as member spacing • Structural design hours • LGS section and component costs (also labour costs based on their location in a building) • Part and assembly IDs for generating assembly drawings and bill of materials • Materials list (from BIM model's take-off drawings) • Hours of operation of the CNC or roll former machine • Number of labourers and their hours involved in fabrication, transportation and installation LGS components • Materials required for the foundation and its casting
Structural analysis and design	<ul style="list-style-type: none"> • LGS section and material properties • Gravity, wind and/or seismic loading parameters according to AS1170 • Boundary conditions • Design parameters (AS4600)
Fire	<ul style="list-style-type: none"> • Fire Resistance Level (FRL) • Insulation R-value • Geometric parameters (e.g., stud thickness, insulation batt density, plasterboard thickness) • Temperature dependent material properties (e.g., Young's modulus, strength and so on)
Acoustic	<ul style="list-style-type: none"> • Standardised weighted sound level difference ($D_{nT,w}$) • Spectrum adaptation term (C_{tr}) • Weighted sound reduction index (R_w) • Geometric parameters (e.g., wall cavity thickness, wall stud thickness and depth) • Acoustic material properties (e.g., bulk modulus, speed of sound through material)

4.2.1. Fire

AS 4600 contains the critical data required to perform fire checks on LGS components. Also, data from fire tests on the construction materials can be obtained experimentally by following the testing procedures in AS 1530.4. The key terminologies related to the fire design are Fire Resistance Level (FRL) and Resistance-value (R-value). The NCC volume 2 Clause 1.2.4 is used for finding the FRL for building elements. The following tables (taken from NASH) [134] shows the FRL and other critical factors for the fire design of external and separating (party) walls.

Table 11: The fire design parameters of steel sheet walls [134].

Wall type	Details	FRL	$\frac{R_w}{R_w + C_w}$	Total R-value
Steel sheet wall (non-load bearing)	External steel sheet TH2042 steel batten Wall membrane 1x16 mm fire-rated plasterboard 70–90 mm steel stud with R2.5 insulation batts (11kg/m ³) Plasterboard lining	-/60/60	44/33	3.2
Steel sheet wall (load bearing)	External steel sheet TH2042 steel batten Wall membrane 2x16 mm fire-rated plasterboard 70–90 mm steel stud with R2.5 insulation batts (11kg/m ³) Plasterboard lining	60/60/60	49/38	3.2

Table 12: The fire design parameters of shaft liner and autoclaved aerated concrete with plasterboard walls [134].

Wall type	Details	FRL	$R_w + C_{tr}$
Plaster shaft liner	Plasterboard 90 mm steel stud with R2.5 insulation batt (11kg/m ³) 20–40 mm air gap 25mm shaft liner 20–40 mm air gap 90 mm steel stud with R2.5 insulation batt (11kg/m ³) Plasterboard	60/60/60	50
50 mm autoclaved aerated concrete (AAC) panels	Plasterboard 90 mm steel stud with R2.0 insulation batt (11kg/m ³) 20 mm air gap 50 mm AAC panel 20 air gap 90 mm steel stud with R2.0 insulation batt (11kg/m ³) Plasterboard	60/60/60	50
75 mm autoclaved aerated concrete (ACC) panel	Plasterboard 90 mm steel stud with R2.0 insulation batt 20 mm air gap 75 mm AAC panel 20 air gap 90 mm steel stud with R2.0 insulation batt (11kg/m ³) Plasterboard	120/120/120	53

4.2.2. Acoustic

For the acoustic design of buildings, whether HRS, RC or timber, there are always some requirements for insulation, which are stipulated in the local building code. Various types of insulations are applied on external walls and floor slabs. The recommended design for the interior acoustic control for a building can be found in AS/NZS 2107:2016 [135]. Sound levels and attenuation (insulation) are presented in decibels, while the frequency (pitch) of the sound is expressed in Hertz (Hz).

Airborne and impact sounds are typically considered in the acoustic design of a steel building. The mitigation measures relate to the mass per unit area of construction, insulation achieved by separating layers and sealing between gaps of construction control flanking, and other direct sounds. The structural designer for the acoustic design of the LGS building will need the following information:

- $D_{nT,w}$ = standardised weighted sound level difference
- C_{tr} = spectrum adaptation term
- R_w = the weighted sound reduction index.

For a LGS wall, the insulation between the studs should be such that the R_w lies between 52 to 66 dB, and $D_{nT,w} + C_{tr} = 45$ to 56 dB, which varies according to the local building codes and authority, and also the type of building (e.g., residential, school, hospital, and so on). National Construction Code (NCC) volume two clause P2.4.6 [136] provides instructions for employing sound insulation in LGS buildings. As per NCC 2019, $R_w + C_{tr}$ should not be less than 50 dB and the cavity between the wall should be kept to a minimum of 20 mm between leaves. In addition, the steel wall stud thickness should be a minimum of 0.6 mm and not less than 63 mm in depth. Also, the airborne sound ratings can be obtained from AS/NZS ISO 717.1 and AS 2021 for buildings near the airport. There are no insulation requirements for the internal and external walls along with the roof and ceiling according to the NCC. However, the builder and designer can propose sound insulation if it is required. The separating walls of buildings and residential LGS construction require provisions for insulation. The specific requirements for the sound insulation including the provision of plasterboards (type and thicknesses) can be obtained from Table 5.1 of the NASH handbook which is based on NCC.

4.2.3. Cost and installation

The calculation of cost is a critical aspect for the project and probably the most difficult part of any construction project. The estimation of the exact cost of the various systems can vary with the geographical location and the prices of the material in a particular place. A comparative analysis between LGS and other structural systems is presented from the literature.

From a study conducted overseas, the cost of structural footings and services with LGS was found to be the cheaper option (along with RC) [137]. The study was conducted overseas where the work was done onsite (no prefabrication). However, considering the prefabrication and lower labour wages (in the factory) for the LGS components, the overall cost for LGS components can prove to be cheaper than RC in Australia. The end-of-life cost of the various system also suggested LGS as the optimal solution for minimising cost. The total life cycle cost of LGS was 9.3 % and 19.4 % lower than that of steel and RC framing, respectively.

The critical data for the cost calculations is obtained from the BIM model, which is approved by the structural engineer. Therefore, the total cost of the LGS building from the structural point of view will require the following critical data:

- Structural design hours
- Materials list (from BIM model's take-off drawings)
- Hours of operation of the CNC or roll former machine

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

- Number of labourers and their hours involved in fabrication, transportation, installation cost of the LGS components
- Materials required for the foundation and its casting.

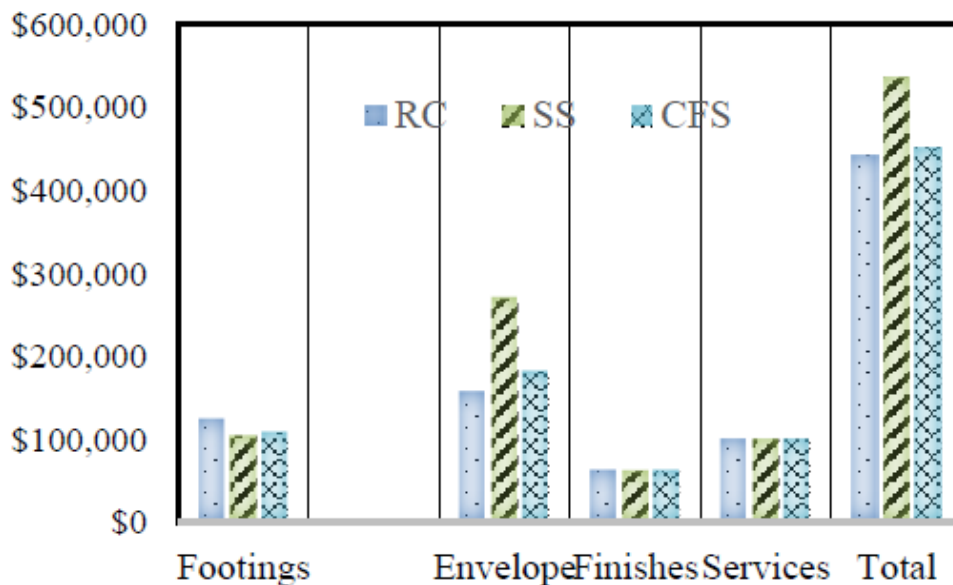


Figure 53: Cost of construction of footing and services with various materials (reinforced concrete, structural steel and LGS).

The installation of the LGS components in buildings can be simple and straight forward. The LGS components can be fabricated in the factory with the need of transportation to the site, or they can be assembled onsite. If the components such as walls of the LGS building are manufactured in the factory, then they are easy to install onsite. The fabricator only requires the structural drawings with the connection details to install walls in the correct locations. The external wall panels are connected to each other by bolts and brackets, and also to the ground foundation. Assuming the floor and the columns of the building are constructed from RC, then the external and internal walls are the main LGS components that need to be installed on the ground and on all floors, except the roof. Nevertheless, technically, the installation procedures for prefabricated HRS and LGS can be identical. However due to the light weight of LGS components (walls, floors, columns), the transport and installation of the LGS components can be made comparatively easier by using trolleys and cranes.

4.3. Recommendations

4.3.1. Software plug-in development

In the previous sections, it is well known that software supporting LGS structures for mid- and high-rise structures are limited. Most of the applications for LGS in mid- and high-rise structures are plug-ins for a BIM platform such as Revit or Tekla Structures (TS). Table 4 from Section 1.3 clearly shows this trend with the majority of LGS projects in the US, UK and Canada successfully completed with the help of Revit or TS plugins. Plugins for a BIM platform have been proven effective in utilising the powerful features of the BIM platform whilst providing additional tools to deal with specific problems and challenges related to LGS. Furthermore, a plug-in within a BIM platform will not require intensive training for users who are familiar with the platform. This will help to overcome the challenge related to a shift in the construction industry from one design platform/software to another, which is one of the biggest barriers to adopt LGS for mid-rise buildings. As a result, developing software plug-ins will allow early access for architects and engineers who currently use a BIM platform such as Revit or TS to inform their decision making in the early planning phase of a project. This can be effective in accelerating the adoption of LGS in mid-rise buildings in Australia.

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

Considering the success of Prescient [21] who built a plugin for Revit for the design, manufacturing and construction of LGS in North America, a successful plugin should consider the following aspects:

- Modelling LGS structures with several levels of detail. This is the most important factor for the success of the new plugin. The plugin must have the ability to model LGS structures with different components as well as their connections. A lower level of detail is needed to assist decision making at the early planning phase of a construction project while a higher level of detail (down to connections) is required for manufacturing and construction
- Connect and export the structural geometry to LGS machinery to control the manufacturing process. The design and manufacturing of LGS are strongly dependent. The plugin should have the ability to control and provide accurate instruction to LGS machinery to ensure the consistent quality of LGS from design to manufacturing
- Assist manufacturing and construction using a data management system such as naming and labelling all elements using QR codes. This will maximise quality control during manufacturing and onsite assembly
- Provide a load alignment checking tool to check the alignment of LGS walls across different stories. One of the main challenges of adopting LGS in mid-rise structures is that the wall needs to be well-aligned to utilise load transfer. Therefore, alignment checking is a necessary function for the plugin
- Able to export the BIM model to an analytical model for structural analysis. Connections used for LGS are different to those in HRS. The plugin should be able to export these discrepancies into the analytical model to minimise rework.

4.3.2. BIM industry standard and information delivery manual for LGS structures and components

There are several BIM industry standards around the world [138]. These standards have been developed and applied separately in each country and region, namely the UK and Europe, North America, Singapore, Hong Kong, and Australia. The general idea is to standardise the application BIM for the architectural, engineering and construction (AEC) industry, thereby enabling interoperability among all parties and phases of a project. The main BIM industry standards and information delivery manuals are discussed hereafter.

The UK is the leading country in developing BIM industry standards and information delivery manuals. Following the initiative of adopting BIM in the building industry in the UK, the British Standards Institution developed the standard BS 1192 [139] as a code of practice to ensure the collaborative production of AEC information. The BS 1192 provides a method to ensure the interoperability between different stakeholders including the owner, architects and engineers, by setting out a scheme to store, distribute and manage construction information. This standard is a key input of the international standard ISO 19650 [140]. Therefore, the standard BS 1192 was replaced by the ISO 19650 in 2018. Besides these standards, the AEC (UK) BIM Protocols [141] also contributes to the development of BIM industry standards and information delivery manuals in the UK. The AEC (UK) BIM Protocols aims to provide a unified standard for the ARC industry. The document was first published in 2009 and the current version was updated in 2015. The AEC (UK) BIM Protocols defines and provides recommendations for several phases of a project using BIM including implementation planning, collaborative BIM working, interoperability, structural modelling information, modelling methodology, folder structure and naming conventions, and presentation styles. Other countries in Europe also develop their own BIM industry standards such as Denmark, Spain, Finland, Norway and Netherlands [138].

Similar to the AEC BIM Protocols in the UK, the United States National Cad Standard (NCS) with the latest version (V6) published in 2014 [142] also determines the standard CAD layer guidelines, uniform drawing systems, BIM implementation and plotting guidelines. The NCS also provides

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

excel and CAD templates to assist users to unify their documents to a single standard across all parties. Besides the NCS, there are two format systems, namely UniFormat [143] and MasterFormat [144], which aim to standardise the arrangement of construction information in North America. These format systems help to facilitate communication between the stakeholders of a project by organising data on construction requirements, products and activities. Different from the UK, where there are only a few standards and manuals to guide the application of BIM in the construction industry, there are a large number of guidelines and standards available in the US, making it complicated to unify the application of BIM in the construction industry. These guidelines and standards were published by state governments, universities, and federal government agencies and departments [138].

In Australia, the Australia BIM advisory board published the Australian BIM Strategic Framework [145]. The framework outlines the definition of BIM, provides recommendations for national policy principles, and supports an integrated approach in building and infrastructure construction projects. The framework also describes the benefits and challenges to the adoption of BIM, and strategic action areas to enhance the adoption of BIM for all stakeholders including government, industry, researchers and educators. Prior to the publication of the Australia BIM Strategic Framework, the National Building Specification (NATSPEC) also developed several documents and guidelines to assist all stakeholders in clarifying their BIM requirements consistently nationwide. Specifically, the NATSPEC National BIM Guide [146] is developed as a set of documents and templates to ensure the interoperability through a standard format. Therefore, building information can be kept intact while being transferring to different stakeholders during the lifetime of a project. The NATSPEC National BIM Guide outlines the setup procedure of major information such as roles and responsibilities, modelling requirements, approved software, collaboration procedures and digital deliverables, which are similar to other aforementioned standards. Furthermore, NATSPEC National BIM Guide also provides templates to manage construction information as similar to those from UniFormat [143] and MasterFormat [144]. At a higher level, the National BIM Initiative (NBI) [147] developed by buildingSMART Australia aims to increase the adoption of BIM in the Australian building and construction industry. The NBI draws a strategic framework to achieve six key targets, namely procurement, BIM guidelines, education, product data and BIM libraries, process and data exchange, and regulatory framework.

In terms of BIM adoption rate, the percentage of companies who reported that they were aware of and currently using BIM in different countries is presented in Table 13 [148]. It can be noted that these values are reported based on interviews and surveys. Therefore, they may not indicate the real BIM adoption rate. However, the information still provides an indication that the adoption of BIM is increasing in developed countries such as Australia, Canada, UK and US.

Table 13: BIM awareness and application rate [148].

Country	BIM adoption rate
Australia	67%, 2016
Canada	78%, 2018
China	67%, 2014
Czech Republic	25%, 2016
Denmark	78%, 2016
Estonia	51%, 2015
Japan	46%, 2016
Poland	23%, 2015
United Kingdom	74%, 2018
United States	79%, 2015

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

In summary, the BIM industry standards and information delivery manuals in Australia and other regions around the world are presented in Table 14. It can be noted that there is no unique BIM standard or information delivery manual for LGS structures and components. However, standards, guidelines and manuals are created as a general format with the levels of detail increasing gradually, which can be observed in Figure 54. Therefore, developing information delivery manuals for LGS structures and components can be easily adapted to existing component categories such as internal walls, external walls, beams or floors by adding information such as material and section properties. Considering that the BIM adoption rate in Australia as of 2016 is approximately 67% as indicated in Table 13, the application of BIM industry standards and information delivery manuals is necessary for the development of LGS structures in the future.

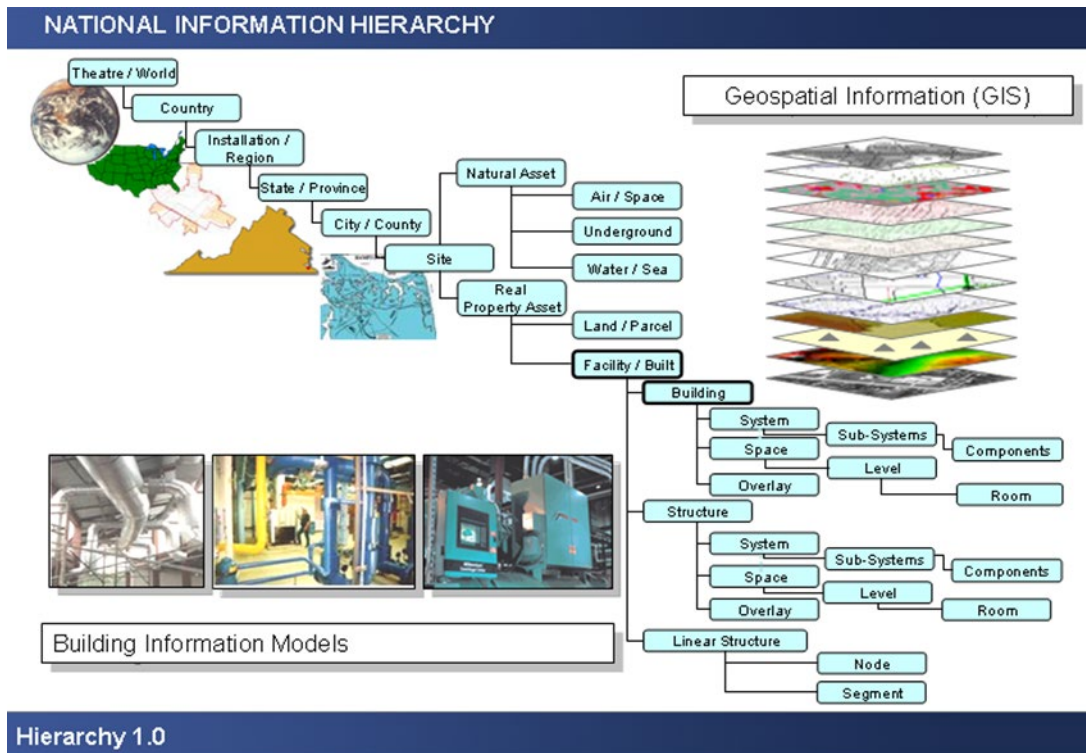


Figure 54: The building information hierarchy [146].

Table 14: BIM industry standards and information delivery manuals.

Region/Country	BIM industry standards and information delivery manual
International	ISO 19650 (2018) [140]
UK and Europe	BS 1192 (2007) [139] AEC BIM Protocol (2015) [141]
North America	The United States National Cad Standard (NCS) v6 (2014) [142] UniFormat (2010) [143] MasterFormat (2020) [144] National BIM standard (2012) [149]
Australia	Australia BIM Strategic Framework (2019) [145] NATSPEC National BIM Guide (2011) [146] National BIM Initiative (NBI) (2012) [147] Australian and New Zealand Revit Standard (2012) [150] National Guidelines and Case Studies for Digital Modelling (2009) [151]

4.3.3. BIM platform

With the above review of different projects across the world and a large number of BIM platforms, tools and software, it is clear that Revit is the most common and powerful BIM platform that is being used predominantly for architects, engineers and other parties in the construction industry. Revit has been developed for more than 20 years. It has a large number of users all over the world, as well as many third-party plug-ins available. Therefore, using Revit will ensure the compatibility between traditional building systems such as RC, HRS and LGS. Strong comparison between these different building systems can be easily made within the same platform in the early planning phase of the project, thereby influencing the early selection of LGS over other systems. As a result, Revit is recommended as a BIM platform to build further plugins for LGS. Floor, wall and roof assemblies can be generated using existing plugins and the costs, fire parameters, acoustic parameters, thermal parameters can be input in LGS section libraries.

5. INPUTS REQUIRED BY GD TOOLS TO ASSESS STRUCTURAL SYSTEMS

5.1. Project cost and cost-based comparisons of different construction systems/materials

Early design plays a key role in determining the life cycle cost of structures or buildings, as demonstrated in Figure 55 [152]. The life cycle cost analysis of LGS frames and its assessment was carried out recently in the latest research overseas [153]. The findings of the research revealed that LGS portal frames are more economic than HRS portal frames up to a span of 30 m. Using LGS frames can reduce labour and crane hiring costs by up to 14% compared to HRS. With 18 m span buildings, the LGS frame required 33% less steel than other HRS systems and the overall building was found to be 33% cheaper than HRS, primarily due to the reduced crane hiring cost. However, the differences between the two types were negligible when the building cladding was also considered. Furthermore, with the BIM and structural analysis models, the weights of different structural forms are more readily available and may be used to calculate the embodied carbon very quickly. The cost of LGS and HRS with other elements including labour, plant, side rails, purlins, cladding and primary structure play an important role. Similarly, in another study, the life cycle cost optimisation for steel structures was studied [154]. The factors affecting the lifecycle cost are shown in Figure 56. In summary, the inputs required by GD to assess the total cost of a LGS structure are presented in Table 15. The initial cost comprises all costs for planning and construction of a building while other costs are incurred during its lifetime.

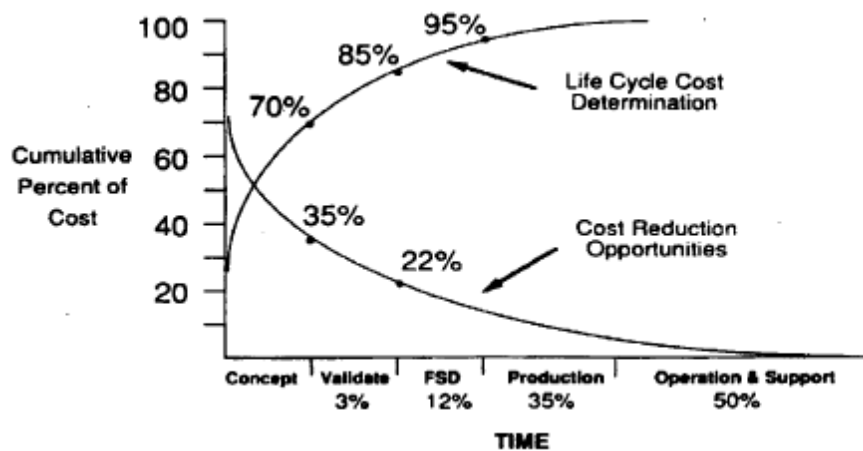


Figure 55: Early design controls the life cycle cost of the building [152].

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

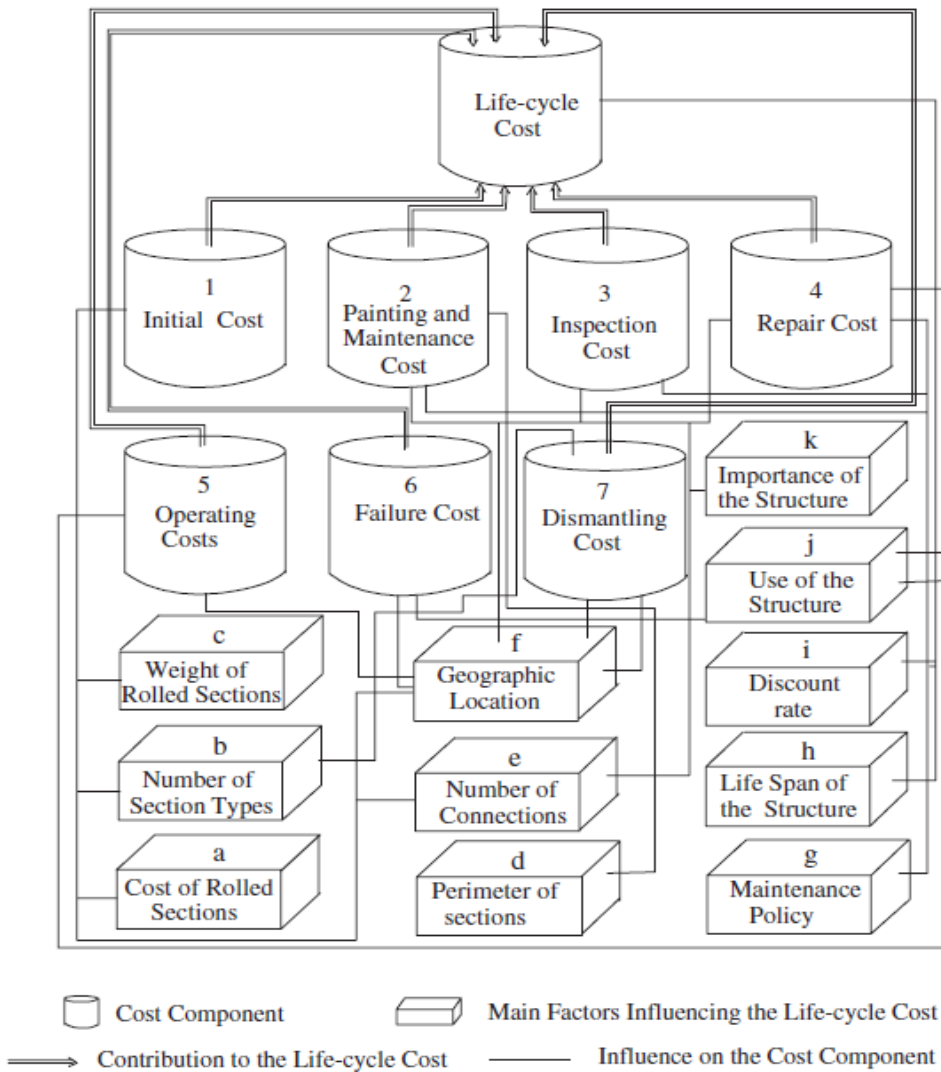


Figure 56: The factors contributing to the life cycle cost [154].

Table 15: Inputs required by GD tools to assess the total cost of a LGS structure.

Input	Purpose
Weight of rolled sections	Initial Cost
Number of section types	Initial Cost; Dismantling Cost
Weight of rolled sections	Initial Cost
Perimeter of sections	Painting and Maintenance Cost
Number of connections	Initial Cost; Painting and Maintenance Cost; Inspection Cost; Repair Cost
Geographic location	Initial Cost; Painting and Maintenance Cost; Inspection Cost; Repair Cost; Operating Costs; Failure Cost; Dismantling Cost
Maintenance policy	Painting and Maintenance Cost; Inspection Cost; Repair Cost
Life span of the structure	Life Cycle Cost
Discount rate	Life Cycle Cost
Use of the structure	Repair Cost; Operating Costs; Failure Cost
Importance of the structure	Painting and Maintenance Cost; Inspection Cost; Repair Cost

5.2. Structural feasibility/efficiency of design

Following the research on LGS reviewed in Section 1.2, it is clear that LGS structures are superior in terms of structural feasibility and design efficiency. Due to the high strength and lightweight of LGS, the total weight of a LGS building is lighter than HRS and RC. As a result, there are three advantages associated with the lower weight of a LGS building. Firstly, it reduces the load bearing capacity of foundations, and thereby reduces their size and volume of concrete required. Secondly, seismic forces, which are dependent on the mass of the structure, will be lower for LGS buildings, thereby reducing the size of shear walls or building cores required for lateral support. Finally, the base shear from seismic forces will also be reduced, leading to lower member sizes in the lower levels of a building and its foundation. However, the area of concern that needs to be looked at in the early design are deflections and buckling. As mentioned by Torabian et al. [5], the capacity of hold downs and the strength of chord stud bracings are the key inputs for evaluating the feasibility of LGS structures in mid-rise buildings. The inputs required to evaluate the structural feasibility and efficiency of LGS design are summarised in Table 16. The design efficiency parameters determine the cost-effectiveness for LGS structures while structural feasibility parameters will determine the limit for the application of LGS structures in mid-rise buildings.

Table 16: Inputs required by GD tools to assess structural feasibility and efficiency of design of LGS buildings.

Input	Purpose
Strength of LGS members	Design efficiency
Weight of LGS members	Design efficiency
Section parameters of LGS	Design efficiency
Lateral structure (LGS, HRS or RC)	Design efficiency
Hold down capacity of LGS frames	Structural feasibility
Bracing capacity of LGS frames	Structural feasibility

5.3. Tools to select materials based on performance requirements

5.3.1. Cost

Common software tools used in Australia for quantity take-off and cost estimation are presented in Table 17. It can be noted that the majority of software tools are using 2D drawings or images as the inputs for the quantity take-off. 3D BIM models can also be inputted to some of the quantity take-off software. However, the interoperability between building design and cost estimation is limited since these software tools only offer one way data exchange and do not support seamless data exchange. BIM modelling platforms such as Revit or Tekla Structures offer quantity take-off, but the cost-estimation has not been supported in these platforms. On the other hand, cost estimation from 3D BIM models enables seamless data exchange, which can be achieved with Navisworks and Revit. However, the adoption of this approach is not common in Australia since it requires a workflow with BIM modelling. In summary, 2D drawings (e.g., PDF, DXF, DWG, and so on) or images are still the main inputs for quantity take-off tools. However, to allow seamless update on the cost estimation during the life of a project, a 3D BIM model and suitable 5D BIM software should be used such as Autodesk Construction Cloud Software (Autodesk Takeoff) [155], Navisworks [37] and its plugins (e.g., True CADD) [156].

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

Table 17: Inputs for quantity take-off and cost estimation of common software used in the Australian building industry.

Software	Inputs for quantity take-off and cost estimation	Seamless data exchange
Constructor [157]	2D drawings/images	No
Estimating software services [158]	2D drawings/images	No
Beams Building Estimation & Management Software [159]	2D drawings/images	No
Planswift Pro Metric [160]	2D drawings/images	No
BuildXact [161]	2D drawings/images	No
BuildSoft [162]	2D drawings/images, 3D BIM model	No
Eclipsecs [163]	2D drawings/images, 3D BIM model	No
ITWO costX [164]	2D drawings/images, 3D BIM model	No
Autodesk Construction Cloud Software (Autodesk Takeoff) [155]	2D drawings/images, 3D BIM model	Yes
Navisworks [37]	2D drawings/images, 3D BIM model	Yes
True CADD [156]	3D BIM model (Navisworks Add-ins)	Yes

5.3.2. Structural performance

As determined from research evaluating LGS against other structural systems (see Section 1.2), there are a several software tools that can be used for LGS. Among them, ETABS and Spacegass provide the highest level of support for the design of LGS. The inputs for all structural performance analysis are similar among all software. The inputs to select materials based on structural performance are a subset of the inputs to check structural feasibility and design efficiency as outlined in Section 5.2. For material selections based on structural performance, only member performance is required, whereas the overall structural performance of a building requires checks for structural feasibility and design efficiency. The main inputs for evaluating the structural performance of LGS in the early planning phase of a project are listed as follows:

- Structural member coordinates
- Section properties (e.g., height, width, gauge thickness, second moment of area and so on)
- Material properties (Young's modulus, strength, and so on)
- Design parameters (e.g., safety and reduction factors, buckling constants, member capacities)
- Loading and boundary conditions
- Analysis type (e.g., buckling, linear static analysis)
- Specified result outputs (e.g., axial load to the foundation, base shear, member bending moments).

5.3.3. Fire

In general, the GD workflow to be developed in this project will fill the design gap of structural analysis and design software to incorporate design checks according to AS 4600. This functionality can be implemented as a plugin in the selected structural analysis and design software or directly as a script in interoperable tools such as Dynamo and Grasshopper. Specifically, the following fire design inputs are specified in Section 9 of AS 4600, which are used in equations and charts to determine the fire resistance capacity of LGS:

- Fire Resistance Level
- Load ratio

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

- Period of structural adequacy
- Elevated temperature mechanical and thermal properties
- Fire protection layers (sheathing layers, coatings).

For non-standard LGS systems (e.g., hybrid LGS-timber floor systems), 3D thermal finite element models of tested LGS configurations are required to assess fire performance using sophisticated software. The development of such models will be addressed in Project #21, which investigates the fire resistance of LGS floor systems. The outputs from these fire simulation models will be used in the GD workflow in our project by accessing the API of the simulation tool or reading a text file that is generated by this tool. ABAQUS and ANSYS are the main tools that can be used for fire simulations and even for analysing the protection of LGS systems under fire [165]. The inputs required for such models are typically elevated temperature mechanical and thermal properties of LGS, plasterboard and insulation materials, which will be used here.

5.3.4. Acoustic

Specialised acoustic analysis tools are only required to evaluate the acoustic performance of non-standard LGS systems. ABAQUS is an effective tool that can be used for simulating the acoustic performance of buildings. However, the run times for the analysis in this software can be extensive. Therefore, other tools are explored for the acoustic evaluation of buildings that can compare various materials. Buildings acoustic tools including *Multiphysics*, *COMSOL*, *Ecotect*, *CATT*, *Odeon*, *EASE*, *Ramsete*, *VNoise*, *SoundPlan* and *SEAM 3D* are interoperable with BIM packages with some limitations e.g., absorption coefficients need to be added manually in the tools [166]. For acoustic simulations, GD tools require plugins. Pachyderm (plug in) is needed for Rhinoceros to connect it with Graphisoft. Similarly, an addon for Revit-Dynamo interaction is required [167]. Besides, there are some other commercially available tools for building acoustics e.g., SoundPLAN is essential [168] for sound mapping and simulations, and SONarchitect [169]. The main inputs for acoustic simulation tools are:

- Material (or acoustic medium) properties (e.g., density, stiffness, bulk modulus, speed of sound)
- Detailed design parameters (coating and sheathing layers, openings).

5.3.5. Thermal

Thermal analysis tools that are interoperable with BIM packages are Design Builder, EnergyPlus, TRACE 700, Green Building Studio, IES VE, Eco designer, and so on [170]. In these software tools, various materials can be selected for thermal analysis. Thermal analysis is essential to calculate the operating cost of a building. The main inputs for material selection based on thermal analysis are:

- Location of the building
- Building mass geometrical parameters
- Building zone selection
- Design details (materials, coating and sheathing layers, opening arrangement and façade systems).

5.4. Methods to select prefab components, floor and wall assemblies, and other members

A recent study, which investigates an approach for the automation of wood modular structures for residential buildings [171] can serve as a guide for automating drawings, drafting and manufacturing of LGS modular wall panels for residential buildings. Visual Basic for Applications (VBA) in CAD software was incorporated in MCMPro, which employed scenario-based analyses (SBA) for the three-stage generation of the BIM model, BIM model for MCM and the drawings. SBA was employed to convert 2D to 3D walls, corridors, and so on. The algorithm was also used to automatically adjust the wall locations, slab locations, and separate structural and architectural walls. Drawings for fabrication were generated with minor adjustments. The proposed model was

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

found to reduce design costs and improved accuracy for users with limited experience with the technology. The overall methodology adopted in this research is shown in Figure 57.

Automation can be achieved by using Simulink in MATLAB. Recent research has shown that a tool carnotUIBK in MATLAB can be used for dynamic simulations of buildings. The BIM model, gbXML, coordinates from excel and so on can be imported to MATLAB which offers an object-orientated programming language. Heating, Ventilation and Cooling (HVAC) and building simulation toolboxes in MATLAB Simulink are available that can be applied for LGS structures and buildings. Furthermore, the Simulink tool allows the user to run optimisation studies, which is an added benefit for the cost-effectiveness of LGS building projects [172].

The layout of the walls for automating the material take-off of a LGS wall structure has been studied recently [173]. Various components of the LGS wall frame systems and their layout, which includes intersections, cross intersections and the corners, were considered (Figure 58). The proposed methodology is shown in Figure 59 with the procedures adopted. This research demonstrated, through flow charts and their execution, how various components of drywalls and their locations including positions of doors and windows can be modelled accurately. Furthermore, based on the BIM models, materials take-off sheets can be generated. A similar approach with some enhancements can be applied to real LGS buildings to observe the benefits and assess the practicality of the research.

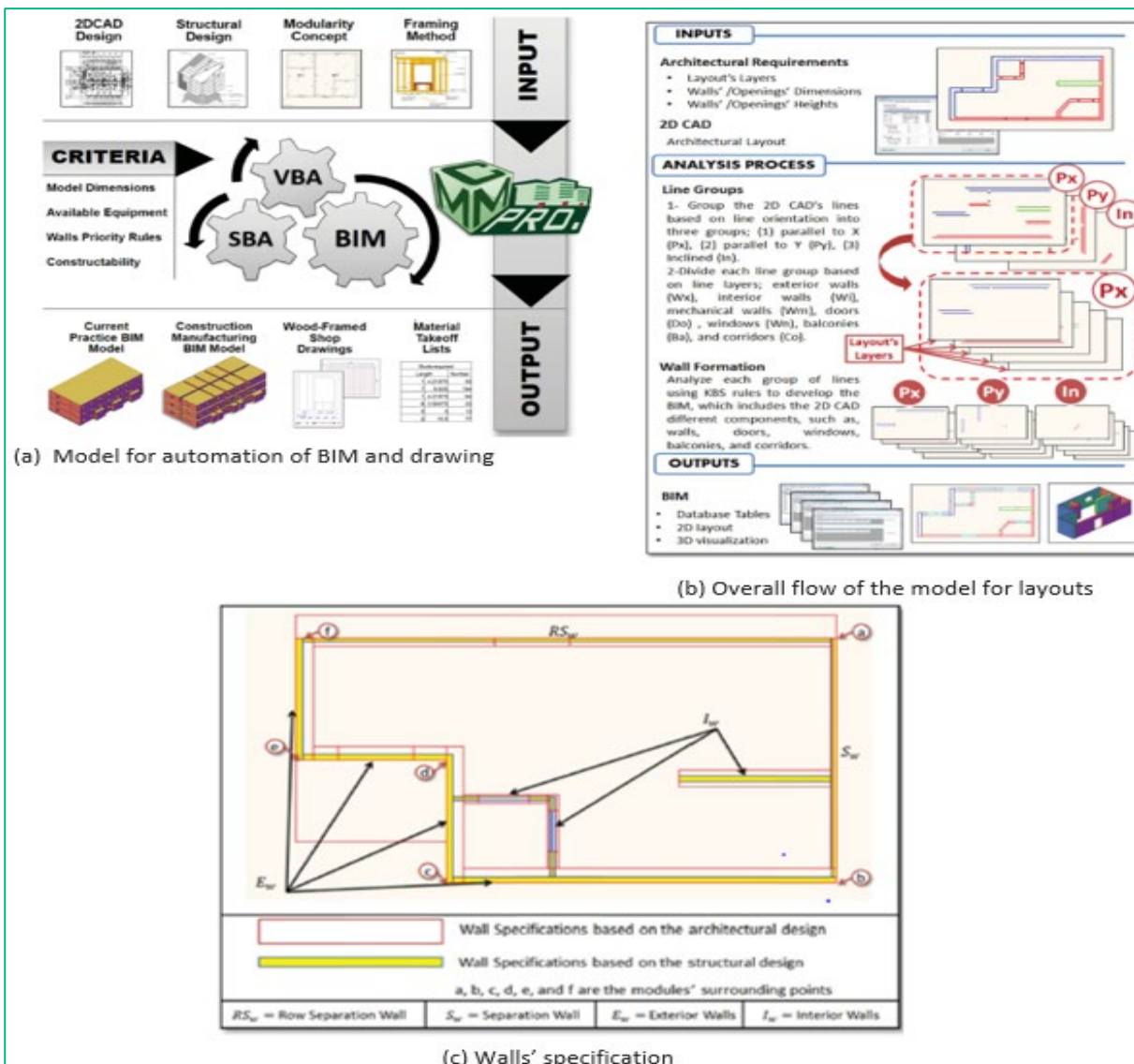
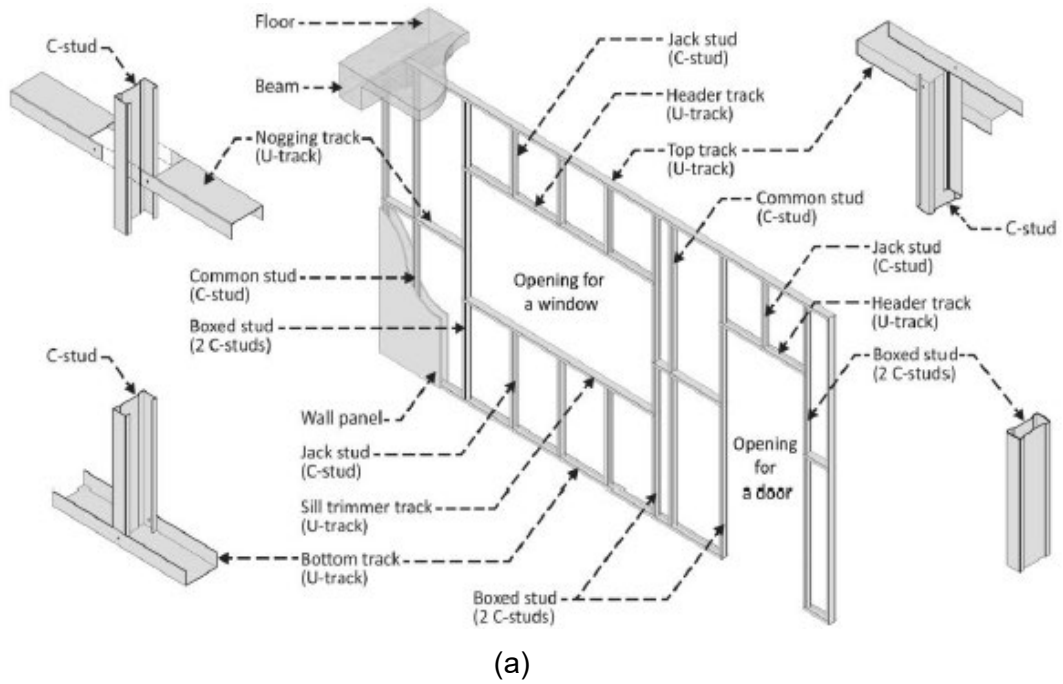


Figure 57: The methodology for automating BIM, drafting and manufacturing.

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1



Construction detail	Corner	T-intersection	Cross-intersection
A			
B			

(b)

Figure 58: Framing systems for LGS walls and their connections.

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

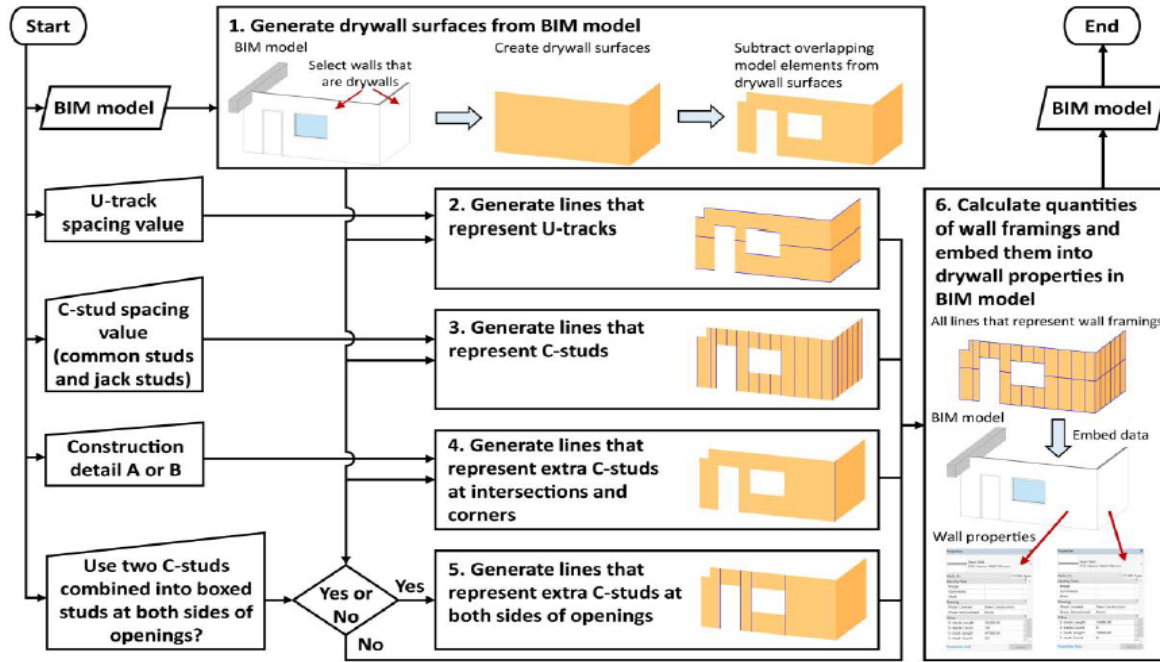


Figure 59: The automatic methodology for wall connections and take-off [173].

5.5. Management of clash detection of services with structural elements in building design

Clash detection of services (such as penetrations for air-conditioning, plumbing and the placement of vertical rises) with structural elements can be conducted within a BIM platform/software or by a separate software. Table 18 outlines common software that support clash detection. The clash detection is usually a function of a BIM platform/software. Both Revit and Tekla Structures have their own clash detection function within the software. Several Revit models can also be exported and combined in Navisworks to perform further clash detection during the construction process. Clash detection can also be developed as an add-in for a BIM platform or a separate software. For separate clash detection software, the software usually requires input data from IFC files. Therefore, IFC files can be considered as the input for the clash detection of services with structural elements in building design.

Table 18: BIM clash detection software [174].

Type	Software
BIM platform/software	Autodesk Revit, Navisworks
	Tekla, Trimble Connect
Add-in	MagiCAD (Revit and AutoCAD)
Separate software	Cintoo Cloud
	usBIM.clash
	Solibri Model Checker
	BIM vision
	Verity
	Fuzor
	Revizto

6. INTEROPERABILITY OF GENERATIVE DESIGN TOOLS WITH DETAILED LGS DESIGN AND ENGINEERING SOFTWARE

6.1 Compatibility issues and rework/integration requirements

Rework is generally required when seamless data exchange between different software (e.g., BIM, and structural analysis and design) is not feasible. During the data exchange, some data may not be transferable due to the limitations of the software or errors. This data needs to be inputted manually after the exchange. Rework reduces the level of design automation and interoperability, and needs to be minimised.

The following compatibility issues between GD tools and LGS design and engineering software are identified, and suggested integration measures are provided:

- Compatibility with specialised LGS detailing and fabrication packages such as ENDUROCAD, which do not have an Application Programming Interface (API), can be achieved through data exchange formats such as Industry Foundation Classes (IFC)
- The lack of support for generating LGS systems in BIM and structural design and analysis software with a wide customer base (e.g., Revit and ETABS) can be mitigated by utilising industry accepted plugins such as AGACAD to generate LGS framing systems. The plugin has been successfully adopted by many customers (ARUP, AECOM, SMEC Australia and WSP) as per Section 2.4.1. Once the evaluation of LGS in the early planning phase is complete, the geometry can be exported to specialised LGS design and detailing software via IFC
- As connections in LGS structures are different from those used in HRS (e.g., angle cleat, moment resisting and so on), which are well recognised by commercial structural analysis and design packages, the discrepancy needs to be addressed when the BIM model is transferred to structural analysis model. Logic may need to be implemented to generate this analytical model as the plugins may fail to recognise the connection restraints in some of these areas
- Missing LGS sections may need to be manually implemented as libraries in BIM and structural analysis software packages. Computer algorithms may be developed to expedite this by transferring the section and material data from existing excel spreadsheets
- Non-standardised LGS sections which are subjected to available machinery in each separate company. In this case, compatibility can be achieved by transferring the model to specialised LGS detailing and fabrication software using IFC
- The lack of support for AS 4600 can be mitigated by implementing design checks via a plugin in existing structural analysis and design software packages, or via scripts in interoperable platforms such as Dynamo or Grasshopper
- Specialised functionalities such as load rundowns and replacing LGS systems that cannot support the loading demand with HRS will require logic to be implemented via programming.

6.2 Recommendations on minimising rework

As aforementioned, rework often occurs due to data exchange incompatibilities between different software when conducting several tasks including architectural and structural design, construction and cost estimation. Using the same platform/software for several purposes will minimise rework but this may not always be possible. A plugin for LGS in a BIM platform as opposed to utilising a specialised LGS software package (e.g., ENDUROCAD) will minimise rework as it inherits all properties of the BIM platform. However, this may not be a viable option, as disruption current LGS design and construction processes can hinder industry acceptance. A BIM industry standard is generally required to ensure seamless information exchange between different phases of a project and different departments including architectural, structural, MEP and so on.

The following key factors to minimise rework should be considered whilst minimising disruption to current LGS design and construction processes:

- Minimise disruption by automating the important aspects that are prevalent to evaluating LGS against other structural systems in the early planning phases of a project. Automating the development of the BIM and structural analysis models are envisioned to yield the most savings and demonstrate the most significant benefits as per the review conducted in this report (e.g., due to labour savings incurred from modular construction processes of LGS systems and reduced foundation costs)
- Minimise dependencies on existing software packages by implementing a modular GD workflow. For example, the structural analysis workflow should be easy to replace (e.g., switch from Spacegass to ETABS) without disrupting the BIM modelling workflow
- Utilise plugins with a wide customer base to instil confidence in the LGS industry AGACAD, a plugin that is capable of modelling RC, timber and LGS systems
- Maintain compatibility with specialised LGS detailing and fabrication software packages via IFC or developing plugins where the software has an API. This will maintain industry confidence in the computational workflow as their specialised software will not be disrupted
- Programming is required to implement specialised functionality such as replacing LGS with HRS systems where the loading demand is exceeded, which is unavoidable and project-dependent i.e., where the LGS walls are not aligned up the height of the building.

7. CONCLUSIONS AND RECOMMENDATIONS

In conclusion, this scoping study report identified the challenges that are hindering the adoption of LGS systems over traditional structural systems (such as RC and HRS) in mid-rise buildings. The Steel Research Hub listed the following challenges as the most prevalent:

- LGS is currently used in low-rise buildings that do not require a high production capacity. In order to adopt LGS in mid-rise buildings, a high production capacity is required, which incurs significant set-up costs for a new production line
- The adoption of LGS in mid-rise buildings requires a shift in the Australian construction process. More logistics and planning are required to adapt current construction processes for reinforced concrete and hot rolled steel to LGS
- Due to the nature of LGS structures, which are mainly manufactured in factories, design for transportation must be considered in the early phase of a project.

Although these challenges with production capacities and LGS supply chain need to be ultimately tackled in future projects to increase the speed of adopting LGS in mid-rise buildings, this project can add value by using GD automation to rapidly demonstrate the significant savings that can be incurred by LGS over RC, timber and HRS structural systems in the early planning phase of a project. Proving the cost-effectiveness of LGS against other materials will be the key barrier to the success of adopting LGS in mid-rise buildings.

The following key topics were covered with a view of demonstrating significant savings incurred by LGS over RC, HRS and timber systems:

- Recent research and case studies of LGS buildings: the review showed the advantages of LGS in mid-rise buildings compared to RC and HRS in terms of savings in material, construction and foundation costs
- Evaluation of industry accepted generative design (GD) and rapid engineering (RE) tools: the review demonstrated the need to adopt GD and RE for LGS buildings to assist decision making in the early phase of a project, and increase the acceptance of LGS for mid-rise buildings
- Leading research on GD and RE tools for structural systems: this section covered broad applications of GD and RE tools in several fields of the construction industry namely design workflow, architectural design, structural design, design and manufacturing processes, modular design and construction, and also LGS systems
- Critical tools for the rapid evaluation of structural systems for low- to mid-rise commercial projects: Revit was shown to be the most common BIM platform to enhance collaborations between different departments and parties during a construction project. AGACAD was identified as the most powerful plugin to expedite the evaluation of LGS against HRS, RC and timber structural systems in the early planning phase of a project
- Inputs required by GD tools to assess structural systems: the list of critical inputs required by GD tools to assess structural systems was outlined against several criteria including project costs and cost-based comparisons of different construction systems, structural feasibility and design efficiency, material selection based on performance requirements, methods to select prefab components, and clash detection and management
- Interoperability of generative design tools with detailed LGS design and engineering software: the compatibility issues associated with LGS structures were discussed to provide recommendations on minimising rework for expediting the evaluation of LGS mid-rise buildings in the early project planning phase. A BIM platform with plug-ins designed for LGS framing is necessary to minimise rework, thereby ensuring seamless data exchange

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

between different departments in a construction project namely architectural design, structural design, quantity take-off, manufacturing, and assembly.

The following key recommendations are provided for Phase 2 of the project, which are targeted at expediting the evaluation of LGS over other structural systems in mid-rise buildings in the early planning phase of a project:

- A generic GD workflow should be developed in Revit-Dynamo or Revit-Grasshopper to enhance interoperability between BIM and structural analysis and design software packages
- Revit is recommended as the BIM platform to evaluate the costs of LGS against other structural systems, which has been extensively employed in Australia and abroad
- AGACAD plugin for Revit is recommended as it supports the generation of different structural systems, including LGS, timber, RC and HRS, and has capabilities of computing costs and generating LGS geometry for CNC fabrication machinery
- Any structural analysis and design software package may be used (ETABS is selected by the Steel Research Hub)
- A library of LGS sections adopted in Australia should be developed in Revit and the selected structural analysis and design package
- AS 4600 conceptual design checks should be implemented in structural analysis and design software
- Logic may be implemented to provide a load rundown and replace LGS systems with HRS systems where the loading demand is exceeded
- Energy, acoustic and fire analysis tools developed in other projects in the Building 4.0 CRC may be added to the workflow to perform multi-objective optimisation and yield the most benefits in future.

REFERENCES

1. Franklin, N.P., Loadbearing Cold-Formed Steel for Mid-Rise Residential Buildings in Australia. 2019.
2. Franklin, N.P., Ahmed, A., Teh, L.H., Heffernan, E.E., and McCarthy, T.J., Efficient 3D lateral analysis of cold-formed steel buildings. *Journal of Constructional Steel Research*, 2019. **160**: p. 16-22.
3. Harshavardhan, P., Das, T.V., Reddy, K.R.K., and Borusu, V., Modelling and design analysis of light gauge steel systems against conventional structural systems. *Materials Today: Proceedings*, 2021.
4. Doctolero, L. and Batikha, M. Using cold-formed steel section in buildings-comparative study. in 104th IASTEM International Conference 2018. 2018.
5. Torabian, S., Nia, Z.S., and Schafer, B., An Archetype Mid-Rise Building for Novel Complete Cold-Formed Steel Buildings. 2016.
6. Abouhamad, M. and Abu-Hamd, M., Life Cycle Assessment Framework for Embodied Environmental Impacts of Building Construction Systems. *Sustainability*, 2021. **13**(2): p. 461.
7. IntelligentSteel. Vita Student Westgate. Available from: <https://www.intelligentsteel.com/projects/westgate-road/>.
8. IntelligentSteel. Brent House. Available from: <https://www.intelligentsteel.com/case-studies/>.
9. IntelligentSteel. Whiting Avenue. Available from: <https://www.intelligentsteel.com/case-studies/whiting-avenue-cs/>.
10. Metek. Streatham Regeneration. Available from: <https://www.metek.co.uk/casestudies/streatham/>.
11. Metek. Oval Quarter. Available from: <https://www.metek.co.uk/casestudies/ovalquarter/>.
12. Metek. Harbour Court. Available from: <https://www.metek.co.uk/casestudies/harbourcourt/>.
13. Sigmat. iQ Bristol. Available from: <https://www.sigmat.co.uk/case-studies/iq-bristol/>.
14. Prescient. Generation Atlanta. Available from: <https://prescientco.com/project/generation-atlanta/>.
15. SIFA. Metreau Apartments. Available from: <https://f.hubspotusercontent30.net/hubfs/6980883/Project%20Profiles%20Case%20Studies/SFIA-Metreau-Case-Study.pdf>.
16. SFIA. Tall Order. Available from: <https://f.hubspotusercontent30.net/hubfs/6980883/Project%20Profiles%20Case%20Studies/SFIA%20Case%20Study%20316-Madison.pdf>.
17. SFIA. Convent Hill. Available from: <https://sfia.memberclicks.net/assets/CaseStudies/conventhill.pdf>.
18. IntelligentSteel. About Intelligent Steel Solutions. Available from: <https://www.intelligentsteel.com/>.
19. Metek. About Metek. Available from: <https://www.metek.co.uk/>.
20. Sigmat. About Sigmat. Available from: <https://www.sigmat.co.uk/>.
21. Prescient. About Prescient. Available from: <https://prescientco.com/>.
22. Terzidis, K., *Expressive form: A conceptual approach to computational design*. 2004: Routledge.
23. Fernandes, R., *Generative Design: a new stage in the design process*. Lisboa: Instituto Superior Técnico, 2013.

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

24. Kolarevic, B., Architecture in the digital age: design and manufacturing. 2004: Taylor & Francis.
25. Wikipedia. Grasshopper 3D. 2021; Available from: https://en.wikipedia.org/wiki/Grasshopper_3D.
26. Rhinoceros. Grasshopper - Overview. 2021; Available from: <https://www.rhino3d.com/6/new/grasshopper/>.
27. Marchal, T. Esquissons. 2021; Available from: <https://www.food4rhino.com/en/app/esquissons>.
28. Autodesk. Discover Dynamo. 2021 [07 June, 2021]; Available from: <https://dynamobim.org/explore/>.
29. Dynamobim. Generative Design and Dynamo for Optimizing Multiple Structure Location. 2020; Available from: <https://forum.dynamobim.com/t/generative-design-and-dynamo-for-optimizing-multiple-structure-location/55042>.
30. Fudala, T. Structural Design package version 1.0.5. 2018; Available from: <https://blogs.autodesk.com/revit/2019/02/07/structural-design-package-version-1-0-5/>.
31. Autodesk. Revit support and learning. 2021; Available from: <https://knowledge.autodesk.com/support/revit>.
32. Autodesk. Revit Generative Design. 2021 [cited 2021; Available from: <https://knowledge.autodesk.com/support/revit-products/learn-explore/caas/CloudHelp/cloudhelp/2021/ENU/Revit-Model/files/GUID-492527AD-AAB9-4BAA-82AE-9B95B6C3E5FE-htm.html>.
33. Autodesk. Project Refinery Beta. 2021 [cited 2021; Available from: <https://www.autodesk.com/campaigns/refinery-beta>.
34. Autodesk. Autodesk Bim 360. 2021; Available from: <https://www.autodesk.com/bim-360>.
35. Keane, P. Generative Design Comes to Fusion 360. 2018; Available from: <https://www.engineering.com/story/generative-design-comes-to-fusion-360>.
36. Autodesk. The future of making generative design for manufacturing with Fusion 360. 2021; Available from: <https://www.autodesk.com/solutions/generative-design/manufacturing>.
37. Autodesk. Naviswork overview. 2021; Available from: <https://www.autodesk.com.au/products/navisworks/overview>.
38. Autodesk. China construction first group - Modern digital technology solves historic construction challenges. 2021; Available from: <https://www.autodesk.com/customer-stories/jingdezhen-museum>.
39. Corporation, T.S. Tekla Structures. 2021 [cited 2021; Available from: <https://www.tekla.com/products/tekla-structures>.
40. Corporation, T.S. Tekla Promotes Open Approach to BIM. 2021 [cited 2021; Available from: <https://www.tekla.com/about/collaboration>.
41. Corporation, T.S. Tekla Structures Interoperability and Partners. 2021 [cited 2021; Available from: <https://www.tekla.com/products/tekla-structures/partners>.
42. Corporation, T.S. Where to use Tekla Structures Open API? 2021 [cited 2021; Available from: <https://developer.tekla.com/tekla-structures/documentation/where-use-tekla-structures-open-api>.
43. Tekla. Light Metal Framing. 2021; Available from: <https://www.tekla.com/solutions/steel-fabricators/project-types/light-metal-framing>.
44. Sydora, C. and Stroulia, E., Rule-based compliance checking and generative design for building interiors using BIM. Automation in Construction, 2020. **120**: p. 103368.

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

45. Law, M. Extending BIM Design Value Using the Revit Api. 2019; Available from: <https://www.augi.com/articles/detail/extending-bim-design-value-using-the-revit-api>.
46. Revizto. Revizto - Next Generation BIM Coordination. 2021; Available from: <https://www.sydneybuildexpo.com/exhibitor-videos/revizto-next-generation-bim-coordination>.
47. Vectorworks. Vectorworks features. Available from: <https://www.vectorworks.net/en-AU/architect/features>.
48. Ketchup. Ketchup overview. Available from: <https://www.sketchup.com/>.
49. Ketchup. Sefaira overview. Available from: <https://www.sketchup.com/products/sefaira>.
50. Ma, W., Wang, X., Wang, J., Xiang, X., and Sun, J., Generative Design in Building Information Modelling (BIM): Approaches and Requirements. Sensors, 2021. **21**(16): p. 5439.
51. Ferreira, B. and Leitão, A., Generative design for building information modeling. 2015.
52. Banfi, F., Fai, S., and Brumana, R. BIM automation: advanced modeling generative process for complex structures. in 26th International CIPA Symposium on Digital Workflows for Heritage Conservation 2017. 2017. Copernicus GmbH.
53. Root, S.P., Cribbs, J., and Chasey, A.D., Case Study: Off-site manufacturing of EIFS Panelized Wall Assemblies to Gain Efficiency in Construction Sequencing. Modular and Offsite Construction (MOC) Summit Proceedings, 2019: p. 357-364.
54. Khosakitchalert, C., Yabuki, N., and Fukuda, T. BIM-based wall framing calculation algorithms for detailed quantity takeoff. in Proceedings of the 4th International Conference on Civil and Building Engineering Informatics (ICCBIE). 2019.
55. Wu, W. and Loza, R. Exploring the Cost Benefit of Building Information Modeling Implementation in Metal Stud Framing—A Central Valley Specialty Contractor’s Perspective. in Construction Research Congress 2020: Project Management and Controls, Materials, and Contracts. 2020. American Society of Civil Engineers Reston, VA.
56. AGACAD. Building BIM Together. 2021; Available from: <https://agacad.com/company/about-us>.
57. AGACAD. BIM SOLUTIONS FOR REVIT PROFESSIONALS. 2021; Available from: <https://agacad.com/products/bim-solutions>.
58. AGACAD. Metal framing BIM software for automated light steel wall frame design in Revit® including optional CNC output. 2021; Available from: <https://agacad.com/products/bim-solutions/metal-framing-wall-for-revit/overview>.
59. AGACAD. Metal Framing Wall Features. 2021; Available from: <https://agacad.com/products/bim-solutions/metal-framing-wall-for-revit/features>.
60. AGACAD. The T4R© (Tools 4 Revit®) add-ons and BIM solutions in more than 130 countries worldwide. 2021; Available from: <https://agacad.com/company/customers>.
61. Group, S.G. MWF Pro Metal. 2021; Available from: <https://strucsoftsolutions.com/mwf-pro-metal/>.
62. Group, S.G. StructSoft Products. 2021; Available from: <https://strucsoftsolutions.com/products/>.
63. Group, S.G. StructSoft - About. 2021; Available from: <https://strucsoftsolutions.com/about-us/>.
64. FRAMECAD. Improve The Process of Design and Engineering with FRAMECAD Integrated End-To-End Software Solutions. 2021; Available from: <https://www.framecad.com/en/framecad-system/software/>.
65. FRAMECAD. FRAMECAD Structure Features. 2021; Available from: <https://www.framecad.com/en/framecad-system/software/structure/?tab=features>.

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

66. FRAMECAD. FRAMECAD Structure. 2021; Available from: <https://www.framecad.com/en/framecad-system/software/structure/?tab=overview>.
67. FRAMECAD. FRAMECAD - FAQs. 2021; Available from: <https://www.framecad.com/en/resource-center/faqs/>.
68. FRAMECAD. FRAMECAD - Partners. 2021; Available from: <https://www.framecad.com/en/partners/>.
69. International, A.S. SteelSmart Framer. 2021; Available from: <https://www.steelSMARTsystem.com/steel-smart-framer-light-steel-framing-bim-software/>.
70. International, A.S. SteelSmart Framer - Frequently Asked Questions. 2021; Available from: <https://www.steelSMARTsystem.com/training-services-support/fag/>.
71. International, A.S. ASI Clients. 2021; Available from: <https://www.appliedscienceint.com/clients/>.
72. Ltd, I.P. SPACEGASS Specifications: Technical Overview. 2021; Available from: <https://www.spacegass.com/manual/>.
73. 14.00, S.G. Steel member design. 2021; Available from: <https://www.spacegass.com/manual/>.
74. CSIAmerica. ETABS building analysis and design. 2021; Available from: <https://www.csiamerica.com/products/etabs>.
75. CSIAmerica. SAP 2000. 2021; Available from: <https://wiki.csiamerica.com/display/sap2000/Home>.
76. Autodesk. Robot Structural Analysis Products. 2021 [cited 2021; Available from: <https://knowledge.autodesk.com/support/robot-structural-analysis-products/learn-explore/caas/CloudHelp/cloudhelp/2018/ENU/RSAPRO-UsersGuide/files/GUID-130B5F9B-B450-4F84-9870-15B608D69B1B-htm.html>.
77. Atirsoft. STRAP STRuctural Analasys Program. 2021; Available from: <https://atirsoft.com/strap/>.
78. Dlubal. Dlubal Structural Analysis and Design Software. 2021; Available from: <https://www.dlubal.com/en/solutions>.
79. Corporation, T.S. Tekla Structural Designer. 2021 [cited 2021; Available from: <https://www.tekla.com/products/tekla-structural-designer>.
80. Corporation, T.S. Loading to AS/NZS 1170.0 and AS 1170.1 (Australian Standards). 2021 [cited 2021; Available from: https://teklastructuraldesigner.support.tekla.com/tekla-structural-designer-2019/en/ref_loadingaustralianstandards.
81. Corporation, T.S. Australian Standards. 2021 [cited 2021; Available from: https://teklastructuraldesigner.support.tekla.com/tekla-structural-designer-2021/en/ref_australianstandardslandingpage.
82. Crawley, D.B., Lawrie, L.K., Pedersen, C.O., and Winkelmann, F.C., Energy plus: energy simulation program. *Ashrae Journal*, 2000. **42**(4): p. 49-56.
83. Ward, G.J. The RADIANCE lighting simulation and rendering system. in *Proceedings of the 21st annual conference on Computer graphics and interactive techniques*. 1994.
84. Jakica, N., State-of-the-art review of solar design tools and methods for assessing daylighting and solar potential for building-integrated photovoltaics. *Renewable and Sustainable Energy Reviews*, 2018. **81**: p. 1296-1328.
85. Walter, B., Arbree, A., Bala, K., and Greenberg, D.P., Multidimensional lightcuts, in *ACM SIGGRAPH 2006 Papers*. 2006. p. 1081-1088.
86. Azhar, S., Building information modeling (BIM): Trends, benefits, risks, and challenges for the AEC industry. *Leadership and management in engineering*, 2011. **11**(3): p. 241-252.

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

87. ARUP. Building Information Modelling (BIM). 2021; Available from: https://www.arup.com/expertise/services/buildings/building-information-modelling?qclid=Cj0KCQiAsgOMBhDFARIsAFBTN3dVOeOnapFqjEyD4Te9X7NXN2A1xd666E74sSf6u2P6neRL547pPGcaAm-aEALw_wcB.
88. Bryde, D., Broquetas, M., and Volm, J.M., The project benefits of building information modelling (BIM). *International journal of project management*, 2013. **31**(7): p. 971-980.
89. Nagy, D., Lau, D., Locke, J., Stoddart, J., Villaggi, L., Wang, R., Zhao, D., and Benjamin, D. Project discover: An application of generative design for architectural space planning. in *Proceedings of the Symposium on Simulation for Architecture and Urban Design*. 2017.
90. Rodrigues, E., Automated floor plan design: generation, simulation, and optimization. 2014.
91. Singh, V. and Gu, N., Towards an integrated generative design framework. *Design studies*, 2012. **33**(2): p. 185-207.
92. Pérez-Martínez, I., Martínez-Rojas, M., and Soto-Hidalgo, J.M. A Preliminary Approach to Allocate Categories of Buildings into Lands based on Generative Design. in *2020 IEEE International Conference on Fuzzy Systems (FUZZ-IEEE)*. 2020. IEEE.
93. Rai, S.K., Keawmuang, H., Variyavwala, H., and Shatnawi, L., Generative Design of Articulated Rod of Radial Engine. *International Journal of Engineering and Management Sciences*, 2021. **6**(1): p. 36-47.
94. Malik, N., Ahmad, R., and Al-Hussein, M., Generation of safe tool-paths for automatic manufacturing of light gauge steel panels in residential construction. *Automation in Construction*, 2019. **98**: p. 46-60.
95. Caetano, I., Santos, L., and Leitão, A., Computational design in architecture: Defining parametric, generative, and algorithmic design. *Frontiers of Architectural Research*, 2020. **9**(2): p. 287-300.
96. Ogg, M. Archistar raises \$6m to take intelligent property planning tech global. 2021; Available from: <https://www.businessnewsaustralia.com/articles/property-and-planning-design-intelligence-venture-archistar-raises--6m-for-global-ambitions.html>.
97. Archistar. Archistar for Architects. 2021a; Available from: <https://archistar.ai/for-architects>.
98. Archistar. How it works for property developers. 2021b; Available from: <https://archistar.ai/for-property-developers#design-analysis>.
99. Girrafe. Generative. 2021a; Available from: <https://www.giraffe.build/generative>.
100. Girrafe. Create vibrant cities with simplicity. 2021b; Available from: <https://www.giraffe.build/>.
101. Abrishami, S., Goulding, J., Rahimian, F.P., and Ganah, A., Integration of BIM and generative design to exploit AEC conceptual design innovation. *Information Technology in Construction*, 2014. **19**: p. 350-359.
102. Attia, S., Gratia, E., De Herde, A., and Hensen, J.L., Simulation-based decision support tool for early stages of zero-energy building design. *Energy and buildings*, 2012. **49**: p. 2-15.
103. Caldas, L. GENE_ARCH: an evolution-based generative design system for sustainable architecture. in *Workshop of the European Group for Intelligent Computing in Engineering*. 2006. Springer.
104. Caldas, L., Generation of energy-efficient architecture solutions applying GENE_ARCH: An evolution-based generative design system. *Advanced Engineering Informatics*, 2008. **22**(1): p. 59-70.
105. Chang, S., Saha, N., Castro-Lacouture, D., and Yang, P.P.-J., Generative design and performance modeling for relationships between urban built forms, sky opening, solar radiation and energy. *Energy Procedia*, 2019. **158**: p. 3994-4002.

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

106. Mukkavaara, J. and Sandberg, M., Architectural Design Exploration Using Generative Design: Framework Development and Case Study of a Residential Block. *Buildings*, 2020. **10**(11): p. 201.
107. Ochoa, C.E. and Capeluto, I.G., Advice tool for early design stages of intelligent facades based on energy and visual comfort approach. *Energy and buildings*, 2009. **41**(5): p. 480-488.
108. Østergård, T., Jensen, R.L., and Maagaard, S.E., Building simulations supporting decision making in early design—A review. *Renewable and Sustainable Energy Reviews*, 2016. **61**: p. 187-201.
109. Touloupaki, E. and Theodosiou, T., Energy performance optimization as a generative design tool for nearly zero energy buildings. *Procedia engineering*, 2017. **180**: p. 1178-1185.
110. Rodrigues, E., Soares, N., Fernandes, M.S., Gaspar, A.R., Gomes, Á., and Costa, J.J., An integrated energy performance-driven generative design methodology to foster modular lightweight steel framed dwellings in hot climates. *Energy for sustainable development*, 2018. **44**: p. 21-36.
111. Zhang, J., Liu, N., and Wang, S., Generative design and performance optimization of residential buildings based on parametric algorithm. *Energy and Buildings*, 2021. **244**: p. 111033.
112. Daher, E., Kubicki, S., and Guerriero, A., Data-driven development in the smart city: Generative design for refugee camps in Luxembourg. *Entrepreneurship and Sustainability Issues*, 2017. **4**(3): p. 364.
113. Monizza, G.P., Bendetti, C., and Matt, D.T., Parametric and Generative Design techniques in mass-production environments as effective enablers of Industry 4.0 approaches in the Building Industry. *Automation in Construction*, 2018. **92**: p. 270-285.
114. Monizza, G.P., Matt, D., and Benedetti, C., Programming a parametric design algorithm to improve manufacturing processes' efficiency: The case study of glued-laminated timber. *Journal of Civil Engineering and Architecture*, 2016. **10**: p. 1203-1212.
115. Wei, Y., Choi, H., and Lei, Z., A generative design approach for modular construction in congested urban areas. *Smart and Sustainable Built Environment*, 2021.
116. Johan, R., Chernyavsky, M., Fabbri, A., Gardner, N., Haeusler, M.H., and Zavoileas, Y., Building Intelligence Through Generative Design-Structural analysis and optimisation informed by material performance. 2019.
117. Alwisy, A., Al-Hussein, M., and Al-Jibouri, S., BIM approach for automated drafting and design for modular construction manufacturing, in *Computing in civil engineering (2012)*. 2012. p. 221-228.
118. Hamidavi, T., Abrishami, S., and Hosseini, M.R., Towards intelligent structural design of buildings: A BIM-based solution. *Journal of Building Engineering*, 2020. **32**: p. 101685.
119. Muller, M.F., Esmanioto, F., Huber, N., Loures, E.R., and Junior, O.C., A systematic literature review of interoperability in the green Building Information Modeling lifecycle. *Journal of cleaner production*, 2019. **223**: p. 397-412.
120. Asiedu, Y. and Gu, P., Product life cycle cost analysis: state of the art review. *International journal of production research*, 1998. **36**(4): p. 883-908.
121. Zhang, J. and Hu, Z., BIM-and 4D-based integrated solution of analysis and management for conflicts and structural safety problems during construction: 1. Principles and methodologies. *Automation in construction*, 2011. **20**(2): p. 155-166.
122. Jasiński, A., Impact of BIM implementation on architectural practice. *Architectural Engineering and Design Management*, 2020: p. 1-11.
123. Davenport, T.H. and Short, J.E., *The new industrial engineering: information technology and business process redesign*. 1990.
124. Reijers, H.A., *Design and control of workflow processes: business process management for the service industry*. Vol. 2617. 2003: Springer.

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

125. Alanne, K. and Saari, A., Sustainable small-scale CHP technologies for buildings: the basis for multi-perspective decision-making. *Renewable and Sustainable Energy Reviews*, 2004. **8**(5): p. 401-431.
126. Holness, G.V., *BIMGaining*. 2008.
127. Laakso, M. and Kiviniemi, A., The IFC standard: A review of history, development, and standardization, information technology. *ITcon*, 2012. **17**(9): p. 134-161.
128. Hitchcock, R.J. and Wong, J. Transforming IFC architectural view BIMs for energy simulation: 2011. in *Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association*. 2011.
129. Wan, C., Chen, P.-H., and Tiong, R.L., Assessment of IFCs for structural analysis domain. *Journal of Information Technology in Construction (ITcon)*, 2004. **9**(5): p. 75-95.
130. Sheikhhoshkar, M., Rahimian, F.P., Kaveh, M.H., Hosseini, M.R., and Edwards, D.J., Automated planning of concrete joint layouts with 4D-BIM. *Automation in construction*, 2019. **107**: p. 102943.
131. Getuli, V., Capone, P., Bruttini, A., and Rahimian, F.P., On-demand generation of as-built infrastructure information models for mechanised Tunnelling from TBM data: A computational design approach. *Automation in Construction*, 2021. **121**: p. 103434.
132. Helminen, J., Automated generation of steel connections of BIM by machine learning. 2019.
133. Sampaio, A.Z., BIM as a computer-aided design methodology in civil engineering. *Journal of software engineering and applications*, 2017. **10**(2): p. 194-210.
134. NASH, NASH STANDARD - RESIDENTIAL AND LOW-RISE STEEL FRAMING. 2014.
135. Australia, S., AS/NZS 2107:2016 Acoustics - Recommended design sound levels and reverberation times for building interiors. 2014.
136. ABCB, National Construction Code. 2021.
137. Metwally, H. and Abouhamad, M.M., LIFE CYCLE COST ANALYSIS OF LIGHT STEEL FRAMED BUILDINGS WITH CEMENT-BASED WALLS AND FLOORS. 2019.
138. Shou, W., Wang, J., Wang, X., and Chong, H.Y., A comparative review of building information modelling implementation in building and infrastructure industries. *Archives of computational methods in engineering*, 2015. **22**(2): p. 291-308.
139. 2016, T.B.S.I., BS 1192:2007 Collaborative production of architectural, engineering and construction information. Code of practice. 2016, BSI Standards Limited 2016.
140. Standardization, I.O.f., ISO 19650-1:2018 Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) — Information management using building information modelling. 2018, International Organization for Standardization: Geneva, Switzerland.
141. Evans, A.G., Suo, Z., Wang, R.Z., Aksay, I.A., He, M.Y., and Hutchinson, J.W., Model for the robust mechanical behavior of nacre. *Journal of Materials Research*, 2001. **16**(9): p. 2475-2484.
142. Katti, K.S. and Katti, D.R., Why is nacre so tough and strong? *Materials Science and Engineering C*, 2006. **26**: p. 1317-1324.
143. Construction Specifications Canada, T., Ontario. , *UniFormat™: A Uniform Classification of Construction Systems and Assemblies*. 2010, The Construction Specifications Institute: Toronto, Ontario, Canada. .
144. Institute, C.S., *MasterFormat : master list of numbers and titles for the construction industry*. 2020, Construction Specifications Institute, Inc. 2020.: Alexandria, Virginia, Canada.
145. Board, A.B.A., *Australian BIM Strategic Framework*. 2019, Australasian BIM Advisory Board: Australia.
146. NATSPEC, *NATSPEC National BIM Guide*. 2011: Australia.

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

147. Australasia, b., The National BIM Initiative (NBI). 2012, buildingSMART Australasia: Australia.
148. Ullah, K., Lill, I., and Witt, E. An overview of BIM adoption in the construction industry: Benefits and barriers. in 10th Nordic Conference on Construction Economics and Organization. 2019. Emerald Publishing Limited.
149. Science, N.I.o.B., National BIM standard. 2012, National Institute of Building Science: USA.
150. Committee, A.a.N.Z.R.S., Australian and New Zealand Revit Standards. 2012, Australian and New Zealand Revit Standard Committee: Australia.
151. Innovation, C.R.C.f.C., National guidelines and case studies for digital modelling. 2009, Cooperative Research Centre for Construction Innovation: Australia.
152. Buckley, M.J., Enabling Technologies for Unified Life-Cycle Engineering of Structural Components. Vol. 455. 1991: National Academy Press.
153. Johnston, R.P., McGrath, T., Nanukuttan, S., Lim, J.B., Soutsos, M., Chiang, M.C., Masood, R., and Rahman, M.A. Sustainability of cold-formed steel portal frames in developing countries in the context of life cycle assessment and life cycle costs. in Structures. 2018. Elsevier.
154. Sarma, K.C. and Adeli, H., Life - cycle cost optimization of steel structures. International Journal for Numerical Methods in Engineering, 2002. **55**(12): p. 1451-1462.
155. Autodesk. Autodesk Construction Cloud - Autodesk Takeoff. 2021; Available from: https://construction.autodesk.com/precon/autodesk-takeoff-trial/?utm_medium=paid-referral&utm_source=capterra&utm_campaign=tko-trial&utm_audience=prospecting&utm_content=text&utm_region=global.
156. TrueCadd. True Cadd 5D BIM - Cost Estimation. 2021; Available from: <https://www.truecadd.com/bim-cost-estimation.php>.
157. Constructor. Constructor Estimating Software for builder. 2021; Available from: <https://constructor.com.au/full-list-features/estimating/>.
158. EstimatingServices. Estimating Software Services. 2021; Available from: <https://www.estimateingservices.com.au/>.
159. BeamsBuild. Beams Building Estimation and Management Software 2021; Available from: <https://beamsbuild.com.au/our-products/beams/>.
160. Planswift. Planswift Pro Metric. 2021; Available from: <https://planswift.com.au/download/>.
161. BuildXACT. BuildXACT. 2021; Available from: <https://www.buildxact.com.au/features/construction-takeoff-software/>.
162. BuildSoft. Build Soft. 2021; Available from: <https://www.buildsoft.com.au/>.
163. EclipseCS. Eclipse CS
2021; Available from: <https://www.eclipsecs.com.au/software>.
164. Naglieri, V., Gludovatz, B., Tomsia, A.P., and Ritchie, R.O., Developing strength and toughness in bio-inspired silicon carbide hybrid materials containing a compliant phase. Acta Materialia, 2015. **98**: p. 141-151.
165. Gravit, M., Terekh, M., Lyulikov, V., and Svintsov, S. Software packages for calculation of fire resistance of building construction, including fire protection. in IOP Conference Series: Materials Science and Engineering. 2018. IOP Publishing.
166. Sušnik, M., Tagliabue, L.C., and Cairolì, M., BIM-based energy and acoustic analysis through CVE tools. Energy Reports, 2021.
167. Kirkegaard, P.H. and Kamari, A., Building Information Modeling (BIM) for Indoor Environmental Performance Analysis. Technical Report Civil and Architectural Engineering, 2017. **4**(3).

Project #22: Generative design and BIM-based design automation methods for steel framed buildings – Phase 1

168. SoundPlan. SoundPLANessential - Compact Noise Mapping / Prediction Software Solution - Acoustic Simulation. Available from: <https://www.environmental-expert.com/software/soundplanessential-compact-noise-mapping-prediction-software-solution-acoustic-simulation-744844>.
169. SONarchitect. SONarchitect - Acoustics Performance Software. Available from: <https://www.environmental-expert.com/software/sonarchitect-acoustics-performance-software-536702>.
170. Bahar, Y.N., Pere, C., Landrieu, J., and Nicolle, C., A thermal simulation tool for building and its interoperability through the building information modeling (BIM) platform. Buildings, 2013. **3**(2): p. 380-398.
171. Alwisy, A., Bu Hamdan, S., Barkokebas, B., Bouferguene, A., and Al-Hussein, M., A BIM-based automation of design and drafting for manufacturing of wood panels for modular residential buildings. International Journal of Construction Management, 2019. **19**(3): p. 187-205.
172. Siegele, D., Leonardi, E., and Ochs, F. A new MATLAB Simulink Toolbox for Dynamic Building Simulation with BIM and Hardware in the Loop compatibility. in Proceedings from BS 2019: Building Performance Simulation conference. 2019.
173. Khosakitchalert, C., Yabuki, N., and Fukuda, T., Development of BIM-based quantity takeoff for light-gauge steel wall framing systems. J. Inf. Technol. Constr., 2020. **25**: p. 522-544.
174. Ocean, J. BIM Clash Detection: Definition, Benefits and Software Types. 2021; Available from: <https://revizto.com/en/clash-detection-in-bim/>.



info@building40crc.org



www.building4pointzero.org



[/building-4-0-crc](https://www.linkedin.com/company/building-4-0-crc)