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Optimisation tools to assist efficient and sustainable tall building design

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of the degree of Doctor of Philosophy

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I declare that, except where explicit reference is made to the work of others, this dissertation is the result of my own work and has not been submitted for any other degree at Imperial College London or any other institution.

Laura C. Bellamy

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Abstract

Sustainability is an increasingly important factor in global decision-making, and provision of infrastructure is responsible for a substantial volume of global greenhouse gas emissions. Whilst efforts are ongoing to reduce operational carbon in the construction industry, work is still necessary to lower embodied carbon. Currently, the optimisation and design process of structures is largely based on engineers' experience. Whilst this experience is extremely valuable and will often reach good results, making use of computational technologies that are now available could achieve improved results whilst also saving time in the design process. This could lead to more efficient designs and savings on material quantities, lowering the embodied carbon of structures. This thesis aims to develop optimisation tools for tall buildings, which are an increasingly common structural form constructed, to assist their efficient and sustainable design.

The PhD project has been conducted in collaboration with industry to ensure its applicability to projects encountered in structural consultancy offices, with relevant outputs. A qualitative study has been conducted to assess the current and future place of computational engineering in the construction industry. The computational tools developed include concrete core, slab and column optimisation including sizing of core and columns, and grid layout and bracing arrangement optimisation for steel buildings including sizing optimisation. They aim to be versatile, robust and user-friendly, having been developed in an accessible, widely used software environment. They have been tested on theoretical and retrospective case studies and are now accessible to practising engineers.

The engineering research presented is intended to be used in various design stages with a focus on early design stages, an area where valuable benefits both on environmental sustainability and design process efficiency can be reached. It enables engineers, in conjunction with their technical experience, to search the design space available more efficiently, to conduct analysis and optimisation and to make informed decisions earlier in the design process than would be possible with standard design methods.

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Chapter 1

Introduction

This thesis presents doctoral research conducted on optimisation tools to assist efficient and sustainable tall building design. It is believed that an uptake of available but under-used computational tools could reduce the time spend for analysis and optimisation in design stages and enable exploration of a larger design space than is feasible with standard design methods to reach more efficient designs, with the potential of reducing the embodied carbon of tall buildings. The motivation of the research is discussed in this Chapter. The research objectives and the thesis outline are given.

1.1 Context and motivation of the research

Climate change is a major concern of the twenty-first century with substantial efforts required to reduce or halt it. For example, during the COP21 (21st session of the Conference of the Parties) in Paris in December 2015, global and local objectives were set to try to slow climate change. One of those objectives is for each country to monitor and reduce its carbon emissions (Center for Climate and Energy Solutions 2015). The UK has committed to reduce its emissions by 80% by 2050, taking emissions in 1990 as a baseline (HM Treasury 2013). Provision of infrastructure services represented 53% of UK carbon emissions in 2010, making it the highest contributor in the country. This is expected to rise to 90% of the country's carbon emissions by 2050 (The Green Construction Board 2013). The need to reduce carbon emissions in infrastructure in the UK is therefore essential if the COP21 goals are to be met.

However, reducing carbon emissions in the infrastructure sector is a very wide problem to tackle and should be broken down into smaller challenges where changes can be made. The research is conducted in partnership with industry to develop applicable optimisation tools and tall buildings were identified as a relevant structural form for the research. There is no strict definition of a tall building and the classification tends to depend on the context of where the structure is built. A 20-storey building may not be classified as tall in a high-rise city such as Chicago or New York, but it may be distinctly taller than most other structures in a smaller European city (CTBUH 2019). In a country like the UK for example, churches were the tallest buildings until the middle of the nineteenth century and buildings taller than 6 storeys could be classified as tall only 20 years ago (Kunze 2005). Nowadays, as cities have grown in height, there appears to be consensus on buildings above 20 storeys being classified as tall in the UK (Block 2019; NLA 2019). This categorisation is used in this thesis, though the engineering research can also be applied to shorter buildings which are still a common structural form being constructed. 'Tall' and 'high-rise' are used interchangeably in this thesis when referring to building height. Tall buildings were not common in the UK until the late 1990s when their number started to increase. Figure 1.1 shows tall buildings construction trends in the UK between 1990 and 2005 (Short 2007). This trend has kept going in the last 10 years with variations. In London alone, the number of tall buildings completed was 2 in 2003, 10 in 2008, 18 in 2017, 25 in 2018 with 76 expected in 2019 (NLA 2019). More than 60% of these buildings are below 29 storeys. Concrete, either in situ or precast, and steel are the main materials used for construction in the UK, either separately or in composite structures. Concrete cores are a particularly common feature (NLA 2019).

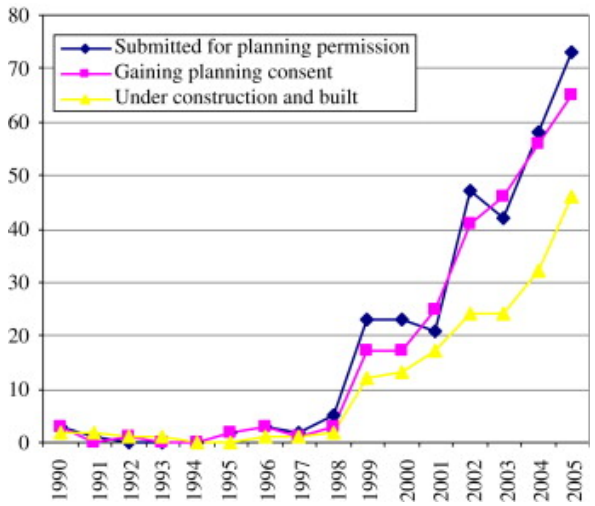


Figure 1.1: Tall building proposal submitted, approved, under construction and built between 1990 and 2005 in the UK, reproduced from Short (2007) with permission from Elsevier.

Tall buildings therefore appeared as a structural form where carbon emission reductions would be meaningful. Carbon emissions can be classified in two categories: operational carbon which for buildings is the carbon emitted due to use of the building, from air conditionning, lighting or maintenance for example, and embodied carbon, which is the carbon emitted to build the structure, from materials for example, and which cannot be reduced once the structure is built. The ratio of embodied to operational carbon can vary between 20:80 and 40:60 in buildings such as office and residential, and can reach up to 65:45 in structures such as warehouses (Vukotic et al. 2010; UK Green Building Council 2015). Whilst efforts are made to reduce the operational carbon in the construction industry, work is still necessary to lower embodied carbon (De Wolf et al. 2017) and it is a place where structural engineers can have an impact. There are various ways to reduce embodied carbon. This study focusses on changes that can be made to the design of structures that are currently being proposed and the methods currently used by engineers in order to have an impact now.

In order for the work to be applicable to industry projects, time was spent with engineers in Robert Bird Group to understand what other aspects of the design process could be improved. In early design stages there may be many iterations and engineers need to be able to provide feedback on a design in a short time frame. Cost savings are essential to industry and may drive a number of decisions. Construction is known to be one of the least digitalised industries (Manyika et al. 2015). Engineers sometimes develop automation or optimisation processes for a particular project, but the need to work on billable projects means that they rarely have time to develop these processes and make them applicable to other projects. It also appeared that the dialogue between the various stakeholders on a project in terms of digital information and knowledge sharing was not always the most efficient. The contact with industry enabled some insight on what one company does, however the rate of adoption of computational design tools in the construction industry on a wider scale appears under-researched in literature. Based on these observations, research objectives were drawn and are outlined.

1.2 Research objectives

The thesis focusses on the development of computational tools to assist efficient and sustainable tall building design optimisation. The design process, particularly in early design stages, could be made more efficient compared with standard design methods currently used in practice, which could enable searching a greater design space, reducing the time needed by engineers to respond to architectural changes, and lead to more efficient

designs where material reductions could have a direct impact on the embodied carbon of the tall buildings that are currently being designed. The main objectives therefore are:

- To identify optimisation techniques and design methods in the available literature, both in academia and in industry, and to identify gaps in literature and in industry practices regarding the optimisation of tall buildings.
- To create sophisticated, robust, automated and user-friendly tools to assist engineers in tall building design. Concrete and steel high-rise buildings are of interest as such forms are often built as cities become more populated, while given the scale of the structures, even small improvements can lead to substantial savings.
- To ensure that the tools are applicable to multiple projects and that they encompass constructability considerations that engineers face during design and construction.
- To make use of available but under-used computational tools to complete the aforementioned objectives such as the computer-aided design (CAD) software Rhinoceros 3D (Robert McNeel & Associates 2018) and its parametric design tool Grasshopper 3D (Rutten 2016), as it allows efficient optimisation using techniques such as genetic algorithms; this software also allows finite element analysis through the plug-in Karamba (Preisinger 2013).
- To validate the tools produced using reliable finite element analysis software such as Abaqus (Dassault Systèmes 2013) on defined case studies; to apply the various tools to a range of problems starting from simple cases for proof of concept and including real industry case studies.

1.3 Thesis outline

In this Chapter, motivation for the project and research objectives are provided.

In Chapter 2, a literature review on optimisation in structural engineering is provided. It includes the various levels of optimisation typically conducted, where academic research has been focussed, and what progress industry is making, whilst identifying gaps.

During the literature review, it became clear that there is a lack of published information from industry. In Chapter 3, a qualitative study on the current and future uptake of computational design tools in the construction industry is presented. This study was conducted through interviews with construction industry leaders.

In Chapter 4, the first computational tool developed is presented. The tool is to be used for the core optimisation of concrete high-rise buildings. It enables optimising various core arrangements available for a project in order to minimise the material volume required to resist lateral loading and facilitates the comparison between the arrangements. The methods used to develop the tool are presented. The tool is tested on different case studies, including comparison with Abaqus and a retrospective project, and is discussed.

In Chapter 5, a computational tool developed for slab and column optimisation of concrete high-rise buildings is introduced. The column arrangement on a slab can be optimised to minimise the slab material volume required to resist vertical loading through surrogate objective functions. The columns can be sized in the analysis. A similar structure to the previous Chapter is followed: presenting the methods, using the tool on case studies and discussing the tool.

In Chapter 6, the last computational tool developed is presented. The tool is aimed at steel high-rise building optimisation. The grid of primary and secondary beams can be optimised to minimise the steel volume, the beams can be sized in the analysis. Vertical and lateral loading is considered. A similar structure to the previous two Chapters is followed: the methods are explained, the tool is used on case studies and is discussed.

Additional discussion and concluding remarks are made in Chapter 7.

Chapter 2

Literature Review

In this Chapter, a literature review of optimisation methods applied to structural engineering is provided.

2.1 Optimisation in structural engineering

Until the end of the twentieth century, structural optimisation was mostly performed for theoretical or small problems. Recently however, there has been a shift to bring it to engineering practice on more complex projects such as roof structures or high-rise buildings. This includes for example the British Museum's Great Court roof, completed in 2000, which required "state-of-the-art engineering and economy of form" (Foster + Partners 2003), partly for shape optimisation.

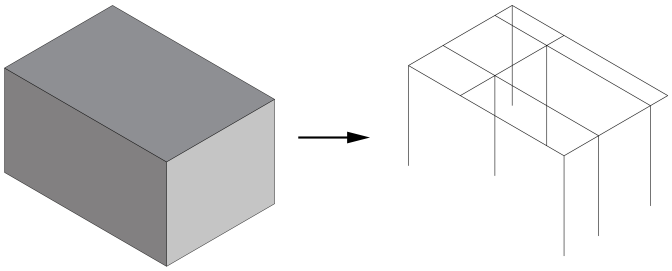
The optimisation problems faced in structural design are commonly defined into three categories. The names and precise definition of each category vary in literature (Xie and Steven 1993; Kicinger et al. 2005; Kociecki and Adeli 2015). The following classification is adopted here:

Structural form optimisation: There are different levels to structural form optimisation. The first and most broad aspect is form-finding. Another level is optimisation over a controlled domain. It is refered to as layout optimisation by Xie and Steven (1993) or more commonly topology optimisation (Suzuki and Kikuchi 1991; Kicinger et al. 2005). This is expected to happen upstream in the design process, it often is highly

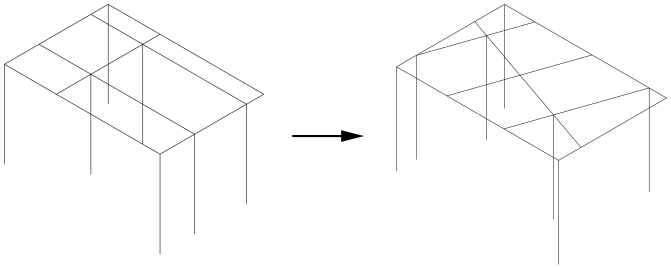
influenced by architectural decisions and can be dependent on the available design space and constraints. It is illustrated in Figure 2.1a.

Structural arrangement optimisation: For a given form, the members can be rearranged, added or removed. This level of optimisation includes topology optimisation as described by Kociecki and Adeli (2014) and is often described as shape optimisation. (Ding 1986; Kicinger et al. 2005; Kociecki and Adeli 2015). Some optimisation techniques can be used for parts of structural form optimisation as well as structural arrangement. It is illustrated in Figure 2.1b.

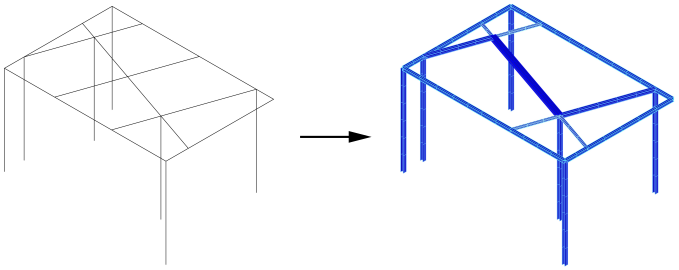
Sizing optimisation: Each member's cross-section can be modified. It is introduced as size or sizing optimisation (Ding 1986; Kicinger et al. 2005; Kociecki and Adeli 2013). It is illustrated in Figure 2.1c.



(a) Structural form optimisation.



(b) Structural arrangement optimisation.



(c) Sizing optimisation.

Figure 2.1: Illustration of three categories of structural optimisation.

This naming convention has been established as it gives a clearer representation of the respective optimisation aims. These three levels of optimisation have commonly been dealt with separately in the past but can now be looked at simultaneously as done by Tang et al. (2005) and Miguel et al. (2013) with improved results. When used in industry, the various levels of optimisation are often constrained to particular activities for design or constructablity considerations. A common one is rationalisation, which can be applied in different ways to the three categories. For example, for constructability considerations and cost reduction, the number of section sizes of steel beams used on a project may be reduced to use the same section for all primary beams.

2.2 Motivation and objective function

To formulate an optimisation problem, variables, constraints dependent on the variables and an objective function need to be established. The aim is to obtain a design with set values for the variables to minimise or maximise an objective function while complying with the constraints. Variables are the parameters of the model that can be modified and the objective function is a measure to be optimised towards an objective. For example, to minimise the mass of a beam subjected to an axial force in tension, the variable could be the beam cross-sectional area, the objective function would be minimising the mass of the beam and the constraint may be for the design tension resistance of the section to be less than or equal to the design value of the tension force in the beam. The constraint here ensures that the beam can sustain the load it is subjected to whilst its mass is minimised. An objective function can be constrained or unconstrained. In constrained optimisation, the variables are subjected to limitations that can be written mathematically which make certain values of the variables illegal even though they may be the global optimum (Skiena 1998). In unconstrained optimisation, the variables are not subjected to mathematical limitations. If constraints are still needed, they can be added in the form of penalties to the objective function, rendering some solutions suboptimal even though they are not eliminated from the design space. The design space is made of the combination of all the possible values that each variable can take. In the beam example, if a discrete beam section area is used as variable and there are 100 section areas available, the design space would be made of 100 possible solutions as there is only one variable. If rectangular hollow sections are used for the beam, the section width, depth and wall thickness are parameters that influence the section area. They could be used as variables instead of the section area. If there are 50 depths and widths available and 10 thicknesses, the design space size increases to $50 \times 50 \times 10$ equal to 25000. It is 250 times larger: the optimisation run time could be longer, or the probability of finding the global optimum could be reduced,

but a lighter section may be obtained as there is more variability in the cross-section. Depending on the size of the design space and the objective function, there could be local optima which could trap the solution away from the global optimum. This is further developed in § 2.3 and is illustrated in Figure 2.2.

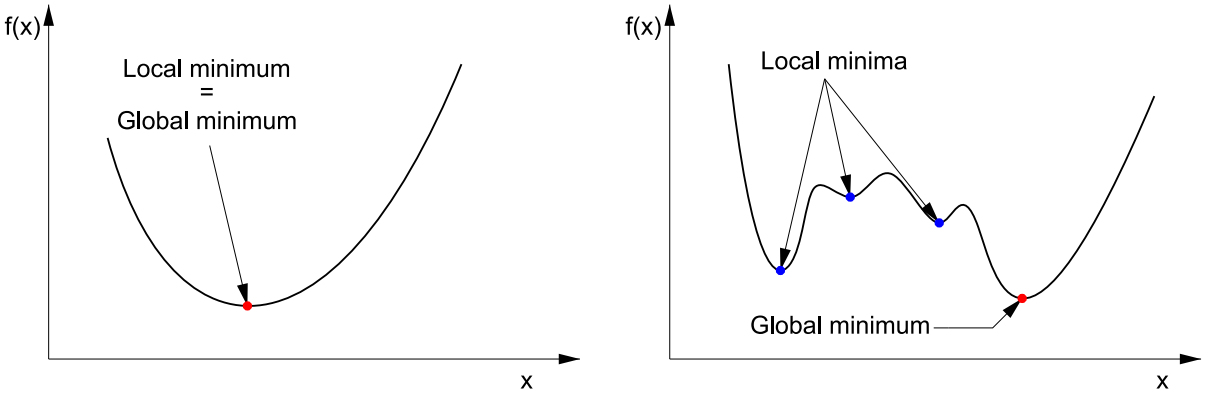


Figure 2.2: 2D example of two different functions leading to global and local minima.

The usual goal of optimisation for industry is to minimise cost. A common surrogate for cost minimisation in structural design is the minimisation of the mass or volume of material in the structure (Ding 1986; Flager et al. 2014). The three categories of optimisation derived in § 2.1 are frequently led by this motivation. Another aim of optimisation often encountered in industry is rationalisation of the design due to constructability and modelling considerations.

Sarma and Adeli (2000) and Tomás and Martí (2010) note that mass minimisation is used in the majority of structural optimisation studies and that cost minimisation itself is rarely considered and if so, for theoretical or small examples mostly. Material volume is however not the only cost factor when designing and constructing tall buildings. Sarma and Adeli (2000) identify nine components contributing to the cost of steel structures in particular, which include planning and design as well as the number of different section types and connection types used.

The objective function of mass minimisation often has constraints such as stress or displacement limitations. Fully stressed design (FSD) is often used in structural optimisation. The optimum corresponds to a design where all structural members reach the limit of allowable stress under at least one of the loading conditions (Gallagher 1973). In such a design, it is believed that a structure where all members are fully utilised has to be optimal. Mass is therefore not directly used to derive the optimum and there is no overall objective function where an extreme value is reached. For this reason, debates occurred on the validity of FSD (Razani 1965; McNeill 1971; Fleury 1979) and Gallagher

(1973) explains that statically indeterminate structures or structures with multiple load cases can reach multiple FSDs thus not reaching a unique mass optimum. Patnaik and Hopkins (1998) explained that FSD can be optimum for determinate structures but other methods need to be used for more complicated cases. Patnaik et al. (1997) proposed a modified design method where displacement constraints are included.

It should be noted that for genetic algorithms (GA), which are described in § 2.3.2.2, and other optimisation algorithms, only unconstrained objective functions are suitable. This requires the modification of the objective function to include any required constraint (Kociecki and Adeli 2013) which can easily be done through penalties. Stresses are usually considered within the objective function or constraints (Kociecki and Adeli 2013) and displacements are sometimes considered as well (Sandgren et al. 1990; Chapman et al. 1994; Coello and Christiansen 2000; Hamda et al. 2002). Some algorithms that allow for multiple objective functions, unlike GA, can have minimisation of mass and minimisation of displacements as two objective functions and constrain stresses (Kicinger et al. 2005).

In structural form optimisation, compliance minimisation is a common objective function of continuum optimisation (Bendsøe and Kikuchi 1988; Suzuki and Kikuchi 1991; Sigmund 2001). The compliance is a measure of the mechanical work of force and is represented by one scalar thus facilitating optimisation (Kohn and Wirth 2014). Other constraints can be included to limit stresses, strains, displacements (Suzuki and Kikuchi 1991), complicating the formulation but potentially reaching more optimal results.

In light of embodied carbon reductions which are discussed in Chapter 1, there are many factors that impact the embodied carbon of a building and many ways to reduce it. Typically, the embodied carbon of a building can be written as:

$$C_{material} = CO2e_{material} \times W_{material} \tag{2.1}$$

where $C_{material}$ is the total embodied carbon from the material used in construction, $CO2e_{material}$ is the embodied carbon of this material per unit mass and $W_{material}$ is the mass of material used (Zhao and Haojia 2015). Whilst the mass of material used could easily be computed during the design process, there is no reliable sources on how to calculate the embodied carbon per unit mass $CO2e$ of a material (De Wolf et al. 2017) which should account for many factors such as extraction of the material, transportation and wastage. Material quantities may also impact $CO2e_{material}$ which could increase if a large variety of sections or connections are used on a project because of manufacturing requirements. Hammond and Jones (2008) provide a database for the UK which reached a consensus to measure embodied carbon in the UK but it is only local and has not been updated since 2011 (De Wolf et al. 2017). As discussed in Chapter 1,§ 1.1, the research

project is particularly interested in the building forms that are currently being designed and built in order to reduce embodied carbon in tall buildings in the immediate future with current construction methods. With this motivation, reducing the mass of material used appears as the most suitable surrogate to reducing embodied carbon of tall buildings.

These objective functions are related to the physical side of building designs. Using optimisation tools in structural engineering can have other benefits which are particularly discussed in Chapter 3 from conversations with construction industry leaders in the use of computational tools. Such information is not consistently found in literature which is in part why the qualitative study in Chapter 3 was conducted. Some motivations from industry to use computational tools include increase in productivity and automation of repetitive tasks. Another important point to note from this qualitative study and from the objective functions discussed here is the importance of analysis and of ensuring that designs are safe under the loading they may be subjected to.

2.3 Structural optimisation techniques

A number of optimisation techniques have been developed through time as optimisation is at the centre of structural design. They make use of the increasing computational power available. A considerable amount of research is conducted in developing new optimisation methods and algorithms and some are outlined.

2.3.1 High level optimisation methods

The highest level of structural optimisation is form optimisation. Structural form optimisation problems have been investigated extensively in the last 40 years (Kicinger et al. 2005). As explained previously, different levels of optimisation fall into structural form optimisation.

One level is topology optimisation or layout optimisation when in a controlled domain. This form of optimisation can also pertain to structural arrangement optimisation. The problems that are part of topology optimisation can be divided into two categories: continuum and discrete. In the first case, the domain is discretised into elements that either contain material or void. Homogenisation methods have been developed where each element in a grid contains composite material of continuously-variable density and orientation (Bendsøe and Kikuchi 1988; Suzuki and Kikuchi 1991). These methods have been applied to linear elastic structural members which converged and reached satisfactory

results. This is of interest when investigating continuum form optimisation. Xie and Steven (1993) proposed a method where lightly stressed elements are removed, following the concept of evolution where inefficient material is removed. Research is conducted in continuum structural form optimisation to include material non-linearities (Zhao et al. 2019) or multi-material compliance minimisation (Sanders et al. 2018). This category of structural form optimisation is often linked with natural forms, such as the work perfomed by Otto (1982). Whilst direct imitation of nature may lead to invalid results in structural design, it often serves as a source of inspiration. GA have also been used for such problems (Sandgren et al. 1990; Winter et al. 1996) modifying the layout of material and void, the latter using Voronoi-based representations. Such methods have been mostly applied to plates in structural engineering. This could mean that continuum form optimisation is not the most applicable to practical structural engineering problems of bigger scale. The other category is discrete form optimisation. Here the domain is discretised into a structural mesh and the elements' thickness is modified depending on the target. The main problem for such cases is regarding the connectivity and whether every node needs to be connected to every other node in the domain at first, which would prove computationally demanding. Kicinger et al. (2005) surveyed methods applied to such problems and discrete form optimisation has mainly been performed for trusses and frames. For large problems, the number of variables increases dramatically. They however noted that GA have been used for such optimisation. These continuum and discrete optimisation methods have been used regularly for bone adaptation and benefits could be gained in both disciplines if more knowledge was shared. Particularly, Phillips et al. (2015) use discrete methods for bone structure prediction which impact both the layout and the section sizes, and applications could be found in structural engineering.

Another, higher level of structural form optimisation is that of form-finding, with for example dynamic relaxation. It is a common technique for large-scale structural form optimisation. Form-finding is based on the principle that form follows force. One of many definitions of form-finding can be "Finding a shape of equilibrium of forces in a given boundary with respect to a certain stress state" (Veenendaal and Block 2012). Many methods for form-finding exist nowadays and it is usually applied to networks of cables, rods or bars. Bending and shear forces in the structure are eliminated, reducing the mass of the structure (Fund 2008). A classic example is the hanging chains by Antoni Gaudí, most famously used for the Sagrada Familia in Barcelona. Figure 2.3 (Marmulla 2008) shows the principle of hanging chains that was used by Gaudí when designing the church. Numerical methods have since been developed.

There are other methods that have been developed through time for structural form and arrangement optimisation such as the work from Maxwell (1890) followed by Michell

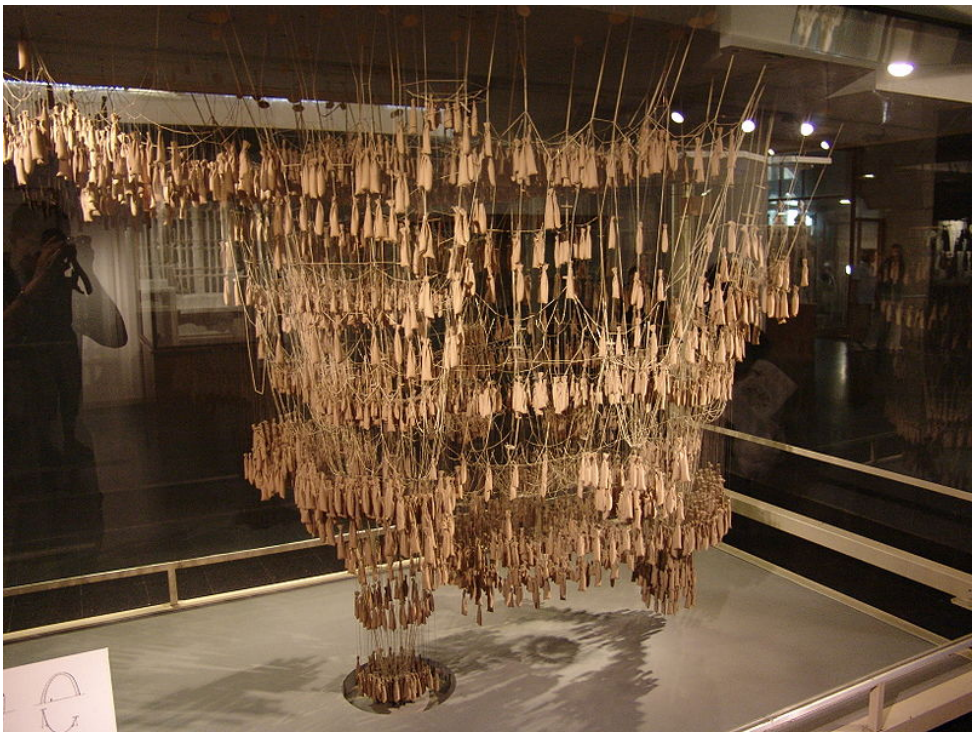


Figure 2.3: Picture of Antoni Gaudí's hanging chains model, reproduced from Marmulla (2008). Creative Commons Attribution-ShareAlike 3.0 License available at https://creativecommons.org/.

(1904) who may have produced the best known early work in analytical methods for solving structural arrangement optimisation problems. Whilst some of these methods do not necessarily find applications in current structures (Kirsch 1989) and particularly the ones that are of interest in this research project, it is worth observing that even in higher levels, structural optimisation often relies on structural analysis.

2.3.2 Lower level optimisation methods

Traditionally, structural element sizing is an iterative process implemented by engineers manually. This process can be tedious and time consuming, particularly because an increase in the number of variables increases with a power law the number of possible design alternatives (Flager et al. 2014). Whilst engineers can use experience to help in sizing problems, the increasingly large design space also means that better options are likely to be left unknown.

To resolve this problem, optimisation methods have been developed to automate member sizing. Sizing optimisation relies on the fact that engineers are usually required to use discrete cross-sections which imposes the use of discrete variables and a number

of algorithms have been developed over time for this type of optimisation as reviewed by Arora (2002). Two main groups of optimisation methods are used for sizing optimisation: gradient-based, which are efficient when gradient information is reliable and the objective function is differentiable, and non-gradient-based, which includes methods such as GA. As mentioned previously, these methods can also be used for structural arrangement optimisation.

2.3.2.1 Gradient-based methods

Gradient-based methods can be seen as more conventional. They require a starting point for the design and iteratively explore other designs depending on the objective function by modifying the design variables. FSD, described previously, has been a common method used in sizing optimisation (Gallagher 1973; Patnaik and Hopkins 1998). However, even though FSD is known to converge rapidly irrespective of the number of design variables (Gallagher 1973), displacements can be required to be constrained for practical designs. Other methods have been developed, such as fully utilised design. This method uses simultaneously stress and displacement constraints and sometimes other factors such as vibration frequency constraints (Patnaik et al. 1993, 1997).

Optimality criteria is a another common gradient-based method used for sizing optimisation (Prager 1968; Venkayya 1971; Gellatly and Berke 1973). A large-scale example using optimality criteria is the design of the North East Tower, Hong Kong Station (Chan et al. 2000). In this case the goal was to minimise cost. It was decided to increase the element size of the steel outrigger trusses of the building, which increased the material cost but allowed for a smaller concrete core and columns which increased the usable floor area. That led to cost savings, thanks to greater revenue, of 9% compared to the non-optimised structure. Another gradient-based method commonly used is that of steepest descent when looking for a minimum. Here a new solution is found after each iteration in the direction of steepest descent from the previous point, reaching a lower value for the objective function, until the minimum is reached (Dommel and Tinney 1968).

The most common limitation of gradient-based methods is the presence of local minima. When using gradient-based algorithm, there is a risk of reaching premature convergence on a local minimum (or maximum depending on the objective function) and missing the global optimum (Yuryevich and Wong 1999). Snyman (2005) argues that local optima may not be problematic if gradient-based methods are cautiously applied, and they require a substantially lower computational cost than non-gradient methods, which are described later. Flager et al. (2014) have developed a deterministic algorithm (based on

optimality criteria) which they call the fully constrained design method. The goal of this new algorithm is to be more generally applicable than optimality criteria methods can be, without requiring gradient information. They have incorporated a mapping between the design variables and a governing constraint allowing section modification. They have applied their algorithm to the design of a stadium roof, showing its adaptability. They also benchmarked their method against recognised optimality criteria optimisation methods and non-deterministic methods for various trusses and obtained superior quality solutions than the former whilst being substantially less computationally demanding than the later. This method therefore allows the user to save time and obtain better results.

2.3.2.2 Non-deterministic methods

The other category of methods typically used for sizing optimisation is non-deterministic. Arora et al. (1995) present a number of these methods used for engineering applications. Common non-deterministic approaches include simulated annealing (SA) and GA. The main principle of such algorithms is to simulate a natural phenomenon such as the cooling of melted metals or survival of the fittest respectively (Mourtis 2016).

SA is actually a refined gradient method based on the meta-heuristic of annealing cooling metal. In real life, this process allows for the metal atoms to reach a stable, desirable position with low and global energy state whereas a fast cooling can lead to an undesirable effect on the atoms which reach a low but local energy state. In SA algorithms, the 'temperature' variable reduces gradually over the iteration process (Debney 2016). At higher temperatures, the members of the population which represent potential optimum designs are more likely to jump further out in the design space and a worse performing new solution can be accepted. This allows to escape local optima. As the temperature decreases, the jumps are smaller and the probability of accepting a worse performing solution decreases. The process is illustrated in Figure 2.4. SA is used preferentially for constrained and discrete problems.

GA are inspired by biological evolution such as reproduction and selection. In the algorithm, each member is represented by a character string mimicking a chromosome, with each character representing a gene. All members of the population are potential optimum designs and are created in generations. Offspring designs are created from the best parent designs through crossover (mating of best parent designs passing on the best 'genes' to the next generation) and mutation (variability is involved in the evolution process to ensure that the solution is not solely dependent on the starting population even though mutations are often discarded over the following iterations) (Chapman et al. 1994). This is shown in Figure 2.5 with two members in an optimisation with ten

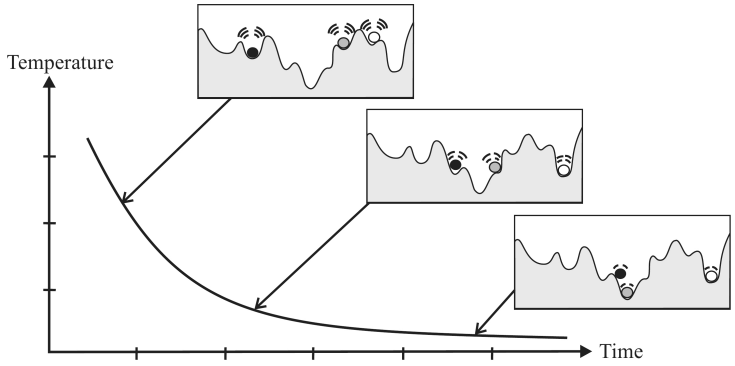


Figure 2.4: Simplified illustration of SA, reproduced from Ledesma et al. (2012). Creative Commons Attribution-ShareAlike 3.0 License available at https://creativecommons.org/.

variables which each have two possible values. This process is iterated and terminates either after a selected number of iterations, until no better design is found for a certain time or when an acceptable solution is reached, which may reduce the iteration time. As mentioned previously, GA perform better for discrete problems and accept only one objective function.

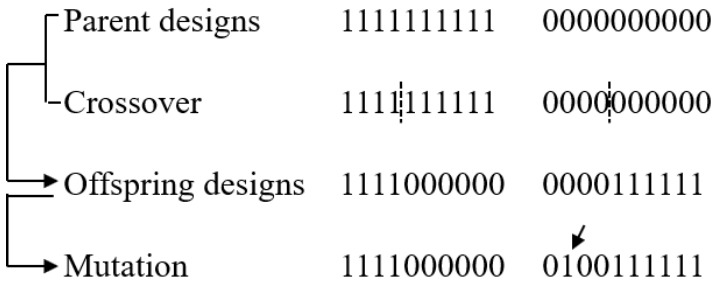


Figure 2.5: Simplified example of crossover and mutation in GA.

Particle swarm optimisation (PSO) is another common type of non-deterministic methods used in structural optimisation. Swarm algorithms are inspired by self-organising systems. PSO is based on the behaviour of bees when exploring a new location for the best food source. In this algorithm, a number of particles, representing possible solutions, fly within the design space. The particles assess the new location they reach whilst comparing it with the best previous location encountered. The selection of the new location depends on its distance to the current location and the movement vector of the particle which is influenced by the best previous solution the particle has encountered, as well as the group's best solution. Some particles will therefore gravitate rapidly towards an optimum, whilst others will gravitate further due to weighting factors on the attraction towards the best previous solution (Debney 2016). Such an algorithm works well for problems with a

continuous design space. In general, swarm algorithms tend to be highly effective for the problems they have designed for but are not particularly versatile (Hare et al. 2013).

Many other natural phenomena inspired methods exist and are being developed currently. They include artificial bee colony (Karaboga 2005) and ant colony optimisation (Dorigo and Caro 1999) which are swarm algorithms, harmony search (Geem et al. 2001) inspired by the process that musicians go through during improvisation, or artificial neural networks (Debney 2016) which is an analogy to the way the brain performs for example when recognising patterns to find the best answer. They have been reviewed (Saka 2007; Debney 2016) and compared (Hasançebi et al. 2010). They noted that GA has been widely accepted and applied to a variety of problems. The latter also noted that all non-deterministic optimisation methods are problem dependent and that GA led to the most effective results out of the non-deterministic algorithms compared. They however used a particular type of GA and note that different results could be obtained with other algorithms and problems. GA therefore appear a good choice for non-deterministic optimisation. Similarly, Hare et al. (2013) surveyed non-gradient optimisation methods used in structural engineering and noted that these methods are sometimes compared to gradient based methods and often to GA which usually act as a benchmark for new methods. These are the most commonly used type of non-deterministic algorithms due to their versatility even though they are often outperformed by other methods on specific problems, especially when dealing with continuous problems. Hare et al. (2013) and Debney (2016) reached a similar conclusion that not one algorithm is best but will fit specific problems better. Different algorithms can be combined to produce better results. For example, GA can be used in a first phase to explore a large design space and gradient-based methods can then be used when a region around the optimum has been identified (Debney 2016).

The use of parametric design, which is enabled for example by use of the visual programming language Grasshopper 3D (GH) (Rutten 2016) inside of the computer-aided design and drafting software Rhinoceros 3D, helps implementing these methods. Components such as Galapagos use GA or SA for optimisation towards one or a combination of factors in the objective function. When used in combination with Karamba (Preisinger 2013), a finite element (FE) solver native to GH, parametric design and optimisation methods can meaningfully be applied to structural engineering problems. Kangaroo (Piker 2013), another GH plug-in, has been created to use dynamic relaxation in structural design.

The main disadvantage of non-gradient based methods is that they are substantially more computationally demanding than gradient-based algorithms and the population to be investigated grows as a function of the square root of the number of variables (Harik

et al. 1999). This means that such methods are often applied to structures with a limited number of variables. Another limitation specific to the use of Karamba and Galapagos in GH is the uncertainty with regards to the accuracy of the results obtained. This can be addressed by comparing results with those found for the optimised structure using established FE software such as Abaqus (Dassault Systèmes 2013).

2.4 Applications to tall building design

As discussed in § 1.1 of Chapter 1, tall buildings have been identified as a structural form to which the application of optimisation tools could be beneficial. From conversations with Robert Bird Group (RBG) engineers, particular elements of tall buildings have been selected as it was believed that computational tools could have beneficial impacts, either on material savings, thus embodied carbon reductions, or on increased productivity. These elements are concrete cores, discussed in Chapter 4, concrete slabs and columns, which are the object of the computational tool discussed in Chapter 5 and steel grids as explained in Chapter 6. Existing literature on optimisation of these particular structural elements is reviewed here.

2.4.1 Concrete core optimisation

Core systems are one of the methods for tall buildings used to provide lateral stability (Brooker 2009) and it is the focus of the computational tool discussed in Chapter 4 where more information is provided on the design of such structural elements. There is limited literature on optimisation of this structural element or automation of the design. The main focus points encountered are on wind and earthquake modelling and dynamic analysis (Kijewski-Correa et al. 2006; Mendis et al. 2007; Smith and Caracoglia 2011; Lu et al. 2013; Caracoglia 2014). However, from the conversations with RBG engineers, the place where a computational tool could have the greates impact was identified to be on standard mid to high-rise buildings which are common projects in a design office as discussed in Chapter 1. Improvements could be made in early design stages when there may be a number of core arrangements available to be analysed and compared. This is a time consuming step of the design process with standard design methods and the motivation was to create a more efficient tool. From lateral stability systems design guides (The Concrete Centre 2018; Fraser et al. 2008), in early design stages, for standard building envelopes, it is a reasonable simplification to model the wind load as a lateral surface load acting on the façade. For more detailed analysis, for 'super-tall' buildings

or buildings with a complex envelope (Mendis et al. 2007), dynamic analysis under more detailed wind loading must be conducted and it is recommended that engineers gain knowledge of new research produced on these subjects (The Concrete Centre 2018). This however is beyond the scope of the computational tool developed.

Other research encountered in literature includes optimising lift design in tall buildings (Linzey 1973). If there is a core in a building, this is typically where lifts are located (Gardner 2015). Whilst this is important to consider for safety and user-friendly design of a building, this is usually driven by architects and is not part of the analysis role of engineers. Finally, an industry tool from Ramboll called the high rise explorer (Jeffries 2018) produces rapid assessment and generation of multiple structural elements including core systems given some parameters such as the number of storeys, width and depth of the building envelope or façade curvature. Other companies may have similar tools internally. Whilst this can have useful applications early in the design process, it does not seem to analyse the building or account for architectural input but instead relies on design simplifications and engineering 'rules of thumb' used in consultancies. From the typical design process observed in RBG, it appears that research could be valuable to reduce the time spend in early design stages to analyse, size and compare the various core arrangements that are usually proposed by architects, accounting for these engineering 'rules of thumb' but also including structural analysis which is essential to structural design.

2.4.2 Concrete slab and column optimisation

Concrete slabs are a common type of floor system in tall buildings and are part of the vertical load take-down system with columns and structural walls. Vertical distributed loads are applied to the slab and transfered onto vertical elements such as columns and structural walls to be transfered to foundations. Slabs and columns are the object of the computational tool discussed in Chapter 5. Slabs are a particularly interesting element of tall buildings to optimise for minimum mass or cost as the same slab arrangement is typically repeated at each storey, reducing the optimisation time compared with other elements that need to be optimised individually, and mutliplying any savings made by the number of storeys (Taranath 2009). For this reason, research has been conducted on the optimisation of slab performance. Research is typically conducted in terms of cost or mass minimisation (Sarma and Adeli 1998) and when the application is intended to be for industry, optimisation is usually used for sizing of the slab and/or the columns and structural arrangement of the columns. Hossain and Olufemi (2005) use finite element analysis (FEA) to develop charts to analyse the capacity and deflection of simply-

supported one-way slabs only. This is a limitation as two-way slabs are also commonly used. Aldwaik and Adeli (2016) propose a cost optimisation for sizing of slabs for irregular shapes. It is believed that more substantial mass or cost savings could be obtained with column arrangement optimisation in order to improve the slab performance (Taranath 2009). Literature on column arrangement optimisation includes Sahab et al. (2005) who use GA to optimise one, three and four-storey buildings in compliance with BS 8110-1:1997 (1997) and Sharafi et al. (2011) propose a column arrangement optimisation for three and four-storey rectangular reinforced concrete buildings using ant colony optimisation. The main limitation of this work is the range of possible applications which is limited to rectangular floor plates and may not lead to meaningful results in industry (Aldwaik and Adeli 2016). Eleftheriadis et al. (2017a) propose a column arrangement and slab and column sizing optimisation including detailed reinforcement layout for the columns and slab using GA and FEA. In this case, the column arrangement is limited to a grid where the bay number and sizes are the variables. The optimisation has not been applied to an industry case study so the net savings from using the optimisation compared with standard design methods are not provided. From conversations with RBG engineers, it appears that architectural constraints may mean that columns cannot be located in such a grid, particularly in reinforced concrete buildings and it appeared interesting to investigate whether material savings could be reach by deviating from this grid whilst following architectural constraints. The high rise explorer from Ramboll mentioned in the previous section also sizes columns and proposes a column arrangement which is also aligned with a grid. The same drawback of not conducting analysis applies, as well as following a strict grid.

2.4.3 Steel grid optimisation

Steel is another common material used in construction, including in tall buildings (CTBUH 2019). A particular form where benefits could be gained by using computational engineering in the design process is in structural frames with grid layout optimisation, which pertains to structural arrangement optimisation. It is the object of the tool discussed in Chapter 6. Moynihan and Allwood (2014) analysed the utilisation of structural steel members in 79 steel frame buildings and identified that up to 46% of the buildings' mass may not be necessary relative to design standards. This was confirmed by Dunant et al. (2018) who analysed 27 steel frame buildings and found that 35 to 45% of the steel mass is not required in terms of structural efficiency. Whilst rationalisation of design due to architectural and construction constraints could in part be responsible for these results, the latter suggest that engineers may be reluctant to design beams with a utilisation higher than 0.8 because of frequent design changes. They suggest that the

use of computational tools could help in that regard by reducing the time necessary to optimise element sizes despite frequent design changes.

Steel space-frames or multi-storey frames appear as a topic of interest in literature. Kociecki and Adeli (2013, 2014) use this structural form for their simultaneous sizing and structural arrangement optimisation using GA. They reach up to 9% material reductions on a case study compared to the orginial solution, with a run time of up to 15 h. In early design stages, which is where the research is aimed at, this could be too long, particularly when design changes happen frequently as highlighted by Dunant et al. (2018). Frans and Arfiadi (2014) and Cicconi et al. (2016) propose different optimisations applied to steel trusses and frames using GA for sizing and structural arrangement. The methods are however not directly applicable to multi-storey buildings and do not encompass constructability considerations. Eleftheriadis et al. (2017b) proposes an analysis method to facilitate decision-making towards reduced embodied carbon in structures. The method does not encompass structural arrangement optimisation and it is believed that further material savings could be reached by adding this level of optimisation. The Digital Structures group in the Massachusetts Institute of Technology is conducting work in various areas of architectural structures and for example proposed a multi-objective optimisation of long-span steel buildings for conceptual design stages (Brown and Mueller 2016). This work is however not necessarily aimed at tall building design. Some structural engineering companies such as Thornton Tomasetti with their generative structure tools (Thornton Tomasetti 2012) and design explorer (Howes 2016) or Ramboll with the high rise explorer appear to have tools applied to such structural forms, however limited information is provided.

2.4.4 Industry requirements

The research conducted in this project is aimed at direct application in a structural engineering consultancies. It was therefore important for the computational tools developed to encompass the constraints and challenges faced by engineers when designing and optimising structural forms. Most guidelines provided by RBG engineers are discussed in the relevant Chapters. Because of the limited literature published by industry on this topic, and to widen the insight outside of RBG, a qualitative study led by interviews with industry leaders in the application of computational tools in construction appeared necessary. The scope is not only to understand industry requirements in the design process but also to analyse the impact that computational tools can have in the construction industry. This is explored in Chapter 3.

2.5 Conclusions and discussion

The field of automated structural optimisation, on any level, has been growing for the last few decades and keeps doing so. Efforts are being put into developing new algorithms or improving existing ones in order to optimise different types of structures and for different set ups such as the presence or not of constraints or using a discrete or continuous domain. Some methods developed are now multi-modal in the way that they are able to consider sizing, structural arrangement and sometimes structural form optimisation. Genetics algorithms are one of the most common algorithms used on all levels of optimisation even though they do not always provide the best results. They are particularly versatile which is why they are used.

The most important limitation encountered with current approaches is that while more and more work is done towards parametric and/or automated structural optimisation and towards improving or creating better performing algorithms, the constraints faced by engineers in design offices, either temporal, architectural or for constructability considerations, are not encompassed and the optimisation tools developed are often not used in engineering design offices. Also, the various algorithms do not always have the required versatility. For some optimisations, the member sections are normalised or connections are minimised which indirectly leads to an easier construction process. However, practical design and constructability considerations are not commonly mentioned or studied in structural optimisation. As sustainability, climate change and carbon emission reduction are currently major concerns and as the computational power available is growing, there is a gap in the available literature that can be addressed. Developing computational tools that can be used on structural forms commonly encountered in design offices could lead to more efficient and sustainable design methods.

Currently, as explained previously, minimising the mass of the structure is predominantly used as a surrogate for embodied carbon and cost minimisation. Given the intended applications of the tools described later, this is deemed appropriate, although potential limitations in this approach are acknowledged.

Chapter 3

Rate of adoption of computational design tools in the construction industry

The author would like to thank the participants for their enthusiastic input in the study:

- **Mark Boyle**
  Global Design Director, Robert Bird Group
- **Paul Jeffries**
  Associate and Computational Design Lead, Ramboll
- **Vladimir Marinov**
  Director, Define Engineers
- **Rob May**
  Group Director, Buro Happold
- **Steve McKechnie**
  Director, ARUP
- **Edoardo Tibuzzi**
  Director, AKT II
- **Chris Walker**
  Director, COWI
- Two additional participants.

The author is grateful to Dr Monika Pazio of the Centre for Higher Education Research and Scholarship for her guidance during the ethical application.

Through interviews with construction industry leaders, a qualitative study has been conducted to assess the current use and potential future uptake of computational design tools in the construction industry.

3.1 Introduction

Many industries have undergone digitalisation, such as automotive (Manyika et al. 2015). This means that their manufacturing processes are radically different from what they used to be (Taub et al. 2007; Sushkevich 2018). The architecture, engineering and construction (AEC) industry on the other hand has been relatively resistant to digitalisation so far, so it is still using similar methods, materials or technologies to what it was several decades ago (Manyika et al. 2015; Agarwal et al. 2016). The focus of this study is to assess the place of computational engineering in the AEC industry and in engineering consultancies in particular. The place it currently has and the place it should have are considered. The reasons why computational engineering is underused in the AEC industry, the obstacles to its adoption and the means to enable it are explored. Industry leaders working in structural engineering consultancies were interviewed to gain insight on the topic.

The author was initially using the term 'digital design' in the interviews and to describe the engineering research conducted. It appeared in the interviews that it is a vague and overly used term, and that 'computational engineering' is a more accurate term for the topics of interest. The two terms may have been used interchangeably in this Chapter, particularly when describing the interviews or in participants' quotes. Definitions of terms are further developed in § 3.3.1.

3.1.1 Motivation for the study

The engineering research undertaken by the author is aimed to be applied in industry. When conducting a literature review of computational engineering in structural engineering consultancies in Chapter 2, it appeared that there are limited formal resources available coming from industry. Consultancies do not always have an interest to publish what they are doing, due to lack of incentives, time constraints and intellectual property ownership. Engineers sometimes present some of their work in industry oriented conferences or talks, such as various events organised by the Institution of Structural Engineers. Institutions such as this one may also have panels discussing computational design in industry. Some companies organise internal talks and seminars around various subjects including digitalisation of industry. They may also publish

their work, either formally through papers or less formally through blog posts such as Ramboll Computational Design[1] or Thornton Tomasetti CORE Studio[2], or on the company website. However, this material is not easy to track and it is not always accessible to third parties. Also, there are many aspects to digitalisation of industry. One or multiple aspects may have been discussed in each article or presentation but it may lack depth, breadth or consistency given the topic.

It therefore appeared important to gather information to assess the rate of adoption of computational design tools in the AEC industry. The first motivation for this study was to justify the need for the engineering research of the author. Given that companies do not necessarily communicate on the technologies that they are developing, the validity and novelty of the author's research could be questioned. Talking to engineers working in leading consultancies and with a particular interest in computational design was identified as a good approach to answer this question. A second factor motivated this study as a gap in literature, bigger than the author's research emerged. The need to formalise the industry's standard in computational engineering and where it is aiming to go could be answered by talking with industry leaders. It could help open the conversation in industry and in academic research and education. The Department of Civil and Environmental Engineering of Imperial College London is developing its Design Thread and this study is prescient in considering the introduction of computational engineering components to it. Digitalisation is an increasingly important topic and communication could help solving ever more complex problems. These interviews allowed to access information that is not otherwise easily available and to answer under-researched questions.

3.1.2 Aims and objectives

The research aim of this study is to assess the rate of adoption of computational design tools in the construction industry. It aims to assess where the industry is at currently as well as where it should and could be going in the future. The objective is to examine the need for change in that regard, and how this change could happen if deemed necessary. The objective is also to identify in what areas computational tools have a beneficial impact, whether on direct engineering problems or other tasks that pertain to the structural engineering role, and where further research could lead to improvements.

Some concepts discussed here are not directly relevant to the engineering research conducted by the author. The role of education or technologies very different to those used by the author are for example examined. The aim is to provide a deeper analysis

[1] https://blog.ramboll.com/rcd/
[2] http://core.thorntontomasetti.com

of computational tools in industry than permitted by literature review or questionnaires and it was identified that covering wider topics could be beneficial for industry as a whole. The participants were selected as they are part of leading firms for digitalisation in the construction industry in the UK and the objective is to provide insight to what they are doing as they are likely to drive change, and where industry might go.

The methods used for the study are explained, followed by analysis of the interviews and discussion and conclusions.

3.2 Methods

The study is looking at an under-researched topic with limited information available. Due to the qualitative nature of the questions that the study is aiming to answer, interviews with digital leaders in the construction industry were identified as a suitable source of information. Semi-structured interviews were used, ensuring that all topics of interest were covered whilst allowing for depth in the conversations. A constructivist grounded theory approach as suggested by Charmaz (Savin-Baden and Howell Major 2013) was selected with broad starting points for the questions, based on the researcher's experience.

Details on the methods used are given. The participant selection process is explained, followed by the interview mechanism. The analysis methodology is then described before discussing the ethical considerations relevant to this study.

3.2.1 Participant selection

AEC industry leaders working in renowned structural engineering consultancies have been identified as the most appropriate participants to provide insights on the topic. In particular, engineers working in senior positions, who use or coordinate teams who use computational design tools were of interest in order to understand how state-of-the-art engineering in industry is currently done and how it may evolve with time. Initially, UK-based leading consultancies of varying sizes were identified, from start-ups to multinational firms, to get a representative overview. Then particular people were contacted to take part in the study. First, engineers directly known by the researcher, through work or conferences, were contacted. Then participants known by the researcher or her supervisor to be involved in digital design were contacted. Otherwise, the researcher contacted acquaintances in the companies of interest asking to be put in touch with someone who would fit the description.

Mark Boyle is Global Design Director in Robert Bird Group and is leading their digital transformation initiative. Paul Jeffries is an Associate in Ramboll and leads Ramboll Computational Design. He has had a leading teaching role in a digital parametric design course run in Imperial College London and has other teaching and research roles. Vladimir Marinov is Director of Define Engineers and has been using digital design tools on a variety of projects. He is a honorary lecturer in Imperial College London for the sketching and modelling course and has other teaching and research activities. Rob May is a Group Director in Buro Happold and is a leader in computational design uptake in the company. Steve McKechnie is a Director in ARUP and has worked with digital technologies throughout his career. Edoardo Tibuzzi is a Director in AKT II and oversees p.art, their computational research team. Chris Walker is a Director in COWI and has worked on projects of varying scales, making use of digital design. Two participants wished not to be acknowledged but fit the profile sought after. Multiple participants are or have been on the Digital Workflows and Computational Design Panel of the Institution of Structural Engineers. Some also have been involved in educational and research projects in partnership with various universities.

It was not expected that the participants would know who was part of the study prior to being interviewed. However, due to their leading roles and particular interest in digital technologies, they may know each other and may have had conversations on the topic independently from this study.

Analysis was done using a constructivist grounded theory approach as suggested by Charmaz (Savin-Baden and Howell Major 2013), unlikely to achieve saturation. This approach was selected so that the researcher could use broad starting points to lead the conversations and gain insight on the topics studied. A total of eight interviews were conducted, one with two participants from the same company. It was led as an interview rather than a focus group. This may be seen as a limited sample but it was expected that theoretical sufficiency (Dey 1999) could be reached with at least six participants, through in-depth interviews and rigorous and careful simultaneous analysis. The number of potential participants was limited due to the deliberate target sampling of a rarefied group of individuals, while the researcher was under time constraints meaning that theoretical sampling with new participants was not used. Modifying the grounded theory to enable follow-up interviews with some participants was considered but not thought necessary following analysis.

The participants are all white males. This was not a deliberate choice but is representative of structural engineering leaders currently.

3.2.2 Interviews

The interviews were designed to be semi-structured, following an interview schedule (Appendix A.1) with main topics and sub-questions but with the possibility to vary from it in response to the participant's comments or reactions. The interview schedule helped ensuring that the same topics were explored with each participant but with flexibility to explore different aspects in more depth with different participants depending on their opinions and background. The main topics were as follows:

1. What construction project are you currently working on?
2. What do you understand by the phrase 'digital design'?
3. Which areas in the construction industry could benefit from further research/have been left out so far?
4. What do you think is the role of university eduction in adopting digital design tools in the construction industry?

Open questions were used when possible in an attempt to gain more depth in the conversation. The first theme was general and designed for the participant to get comfortable, talking about a familiar topic, namely the projects that they are working on and their career. The second topic was 'digital design' in general and specifically how it is currently used in the AEC industry, including relevant subjects such as Building Information Modelling (BIM), sustainability or interoperability. The third topic was on the future of digital technologies in industry, whether an uptake should occur and if so how. The last topic discussed in the interviews was the role of university education in promoting digital design tools in the AEC industry and the link between industry and academic research. At the end, each participant was offered the possibility to revisit anything that had been said or to suggest other ideas worth discussing. The conclusions of this qualitative study are based on the opinions, perceptions and feelings expressed by the interviewees.

The interview schedule was also used for time keeping as each interview was scheduled to last around one hour. They lasted from 45 to 76 minutes with an average of 61 minutes. Some interviews were under time constraints due to participants' other commitments. All topics were covered with each participant. The interviews were all conducted face-to-face in meeting rooms or shared space at the participants' offices. The researcher aimed not to introduce prior conceptions or personal opinions when asking questions. All interviews were conducted within two months with varying periods of time between each, from a

few hours to two weeks. Before any interview, the participants were sent an information sheet and a participant consent form (Appendices A.2, A.3) that they signed before the interview. Participants did not have access to the questions prior to the interviews, they were only aware of the topic investigated as can be seen in the information sheet.

3.2.3 Analysis

Each interview was recorded using a digital voice recorder, with the participant's consent. Commercial transcribers were used to obtain transcription of the recordings after checking each for clarity (first interview with GoTranscript, all subsequent ones with Rev) due to time constraints. Transcription was ordered rapidly after each interview, proofread against the voice recording and corrected accordingly by the researcher to stay immersed in the contents. Transcription was done verbatim, which includes hesitations, pauses and false starts in writing, in order to stay as close to the original exchange as possible. The data was anonymised after transcription of the interviews. After this point, participants could not withdraw from the study anymore as highlighted in the information sheet and consent form.

Once all interviews were conducted, transcribed and verified, the researcher read for the second time all the interviews in a different order, without annotating the data but taking notes of the themes and concepts and other considerations that had arose in the conversations. The interviews were read a third time and codified based on the concepts established from the previous reading or newly identified. The interviews were read a fourth time where additional conceptions were highlighted and codified. The interviews were printed and annotated by hand. Analysis was done following constant comparison as explained by Savin-Baden and Howell Major (2013) which is a common analytical method of grounded theory. An Excel spreadsheet was used to help keep track of the data for the constant comparison, in addition to the hand notes. Theoretical sufficiency appeared to be reached with nine participants as no new concepts were discovered in the last interview. Each participant has been assigned a random number so that quotes can be clustered to give an overview of the views and opinions of each anonymised participants in § 3.3.

3.2.4 Ethical considerations

The interviews were conducted after obtaining ethical approval from the Education Ethics Review Process (EERP) from Imperial College London. A copy of the approved application can be found in Appendix A.4. As highlighted in the application, the

participants are not students nor are they hierarchically inferior to the researcher, so potential power issues were minimal. A neutral email was used to recruit potential participants with a maximum repetition of three emails to be sent if no response was obtained, in order to reduce potential coercion from the recruitment process. Participants were offered no incentive for their input in the study. The researcher conducted the interviews herself as her knowledge in the area of interest could enable greater depth in the conversations, outweighing the risk of inducing bias in the interviewing of the participants, provided that the researcher was mindful not to express personal opinions. Data is stored securely according to Imperial College London regulations.

A potential ethical problem related to this particular study is that the researcher is in part funded by Robert Bird Group (RBG). They did not initiate this study, the analysis was done independently from them and they do not have access no any data collected. Participants were made aware of this partnership prior to interviews. It was decided that someone from RBG may be interviewed as it is one of the leading structural engineering consultancies but the participant would be treated as any other participant. Another difference from standard ethics applications is that participants were asked whether they wanted to be acknowledged. This allows thanking the participants for their contribution to the study. It was also recognised that these acknowledgements can potentially increase the legitimacy of the study when presented to an expert audience. Two participants wished not to be acknowledged, all others agreed to be acknowledged as was done at the beginning of this Chapter. All comments and views were anonymised after transcription of the interviews and in this thesis, as highlighted in the ethics application, participant information sheet and consent form.

3.3 Results and discussion

A large amount of data was collected during the interview process. It is not possible to discuss all the findings uncovered in this Chapter, however the main concepts are presented. Quotes from the interview transcripts are used to emphasise points and highlight when participants particularly agreed or disagreed on ideas. Quotes may have had minor changes for anonymity, conciseness and clarity, such as removing false starts or hesitations or projects names that could be related back to particular participants.

First an overview of the concepts is introduced, with definitions of the relevant terms and actors. This includes what is understood by digital design and computational engineering, what is the place of structural engineers with the new computing power available and what skills they are expected to have, as well as the place of the AEC

industry in the wider picture. Next the need for change in industry along with its incentives and resistance are presented. In the last part, the existing and potential applications of these digital technologies in industry are discussed. This encompasses direct tools such as machine learning or BIM and less definite concepts, for instance interoperability, communication or sustainability.

A lot of the concepts discussed are interconnected. The ideas have been separated for clarity and conciseness but the links between them are highlighted when possible. The order followed here does not match the order the questions are presented in the interview schedule as it is not necessarily the order they were asked in the interviews. Some concepts developed here are not direct answers to questions asked, which acted as broad starting points from which ideas emerged. The author may give pre-conceived opinions here but these opinions were not shared with the participants and the questions were asked as neutrally as possible in order to not introduce bias.

3.3.1 Overview: definition of terms and actors

Implicit concepts related to digital technologies in the AEC industry were discussed by the participants. Some participants explained that there can be abuse of language when discussing topics such as 'digital' so they are clarified. The relationship between engineers and computational tools is then explored, followed by the analysis of expected skills in structural engineers. Finally, the difference in uptake of computational tools between AEC and other industries is discussed.

The participants are all structural engineers now evolving in senior roles in leading firms. They have a variety of backgrounds and commonly have worked on projects of diverse scale and cost. They include tall buildings, stadia, bridges as well as smaller projects such as zoo enclosures or artistic exhibitions. The concepts discussed in this Chapter therefore apply to such projects. As highlighted previously, all participants have a direct interest in computational engineering in their career.

3.3.1.1 Digital design and computational engineering

A question asked to all participants was their definition of digital design. This is a common term used when using computers for various applications but from literature it can encompass many things so clarification was sought out. Most participants agreed that digital design is a wide concept, an "overall term" (P01). Some suggested that digital design has been used for "[...] 30 years, 40 years" (P04), since computers exist, "anything

that you couldn't substitute with a piece of paper and hand calculation" (P09). Another idea expressed is that currently, something else is meant by digital design:

> I think that what we mean by 'digital design' now is often understood to be something that involves BIM? Or drawing things in Revit or Tekla or the other BIM packages? So that is one of the things that people mean. [...] One of the other things that people mean is something which is generative or parametric or used in computational techniques to generate geometry or generate the representation of structural [...] Also, you might use automation techniques to do sizing [...] you might also do some geometrical optimisation, generating structural form [...] trying new shapes and seeing how they perform structurally. So digital design means a lot of different things. (P02)

A participant suggested that there is no clear definition:

> [...] it's extremely broad. And different people have very different ideas of what it is, and actually that's one of the biggest problems because when we try and have conversations about it, people come at it from different perspectives. [...] everyone's very keen to demonstrate their own level of understanding about it. So, you get caught in these conversations where people have very different perceptions of what you mean by the phrase. (P08)

Other participants said that the word digital is "overused" (P05) in industry in the UK. Two participants suggest that 'computational engineering' or 'computational design' is a better alternative with a clear definition:

> It's simply applying computational methods and approaches to solve complex engineering problems. (P05)

> When I talk about computational design, what I tend to mean by that [is] algorithms used as a design tool. [...] so not just taking computers and then trying to replicate drawing by hand but on a computer, but actually using the intelligence and the computing power of that machine to help with the design process in a slightly more integrated way. (P01)

'Computational engineering' therefore appears as a better definition for most applications within the scope of this study than 'digital' technologies. This is in agreement with literature where Ibem and Laryea (2014) describes digital technologies as including 'capturing technologies' such as keyboards, mice or image scanners, 'processing technologies' such as software, or 'communication technologies' such as e-mail or document management. Travush (2018) also suggests that the definition of digital technologies has changed over time. On the other hand, a similar definition to that proposed above of

computational engineering is encountered in literature: "the discipline concerned with the use of computational methods and devices to simulate physical events and engineering systems" (Babuska and Oden 2004). Based on these conclusions, the author has tried to be more accurate on the language use in this Chapter and other research. Computational engineering or design is still a very broad topic encompassing many applications, but it seems appropriate given the scope of the study and the lack of a better denomination.

3.3.1.2 Engineers and computational tools

The participants were also asked whether computational tools are replacing engineers. This question was asked multiple times to the author when presenting the engineering research in conferences. The intuitive author's answer would be that it is not but rather augmenting what engineers can do. Participants mostly agreed with this idea.

One participant suggested that it was replacing engineers before moderating his comment: "replacing means that we don't evolve as engineers ourselves" (P04). All participants agreed that computational engineering creates a change in the role of structural engineer. A couple of participants added that it may replace people who are not embracing that change:

> I think it's replacing the drudgery part of engineering. I do a lot of time sheets, is that part of engineering? [...] So if you're doing a load take-down of a column and then doing a column calculation, maybe the first time you do it that's engineering. If you're doing it for the hundredth time, that's not engineering. That's just churning the handle. So yes, these will replace those parts of it. [...] There'll be a place for people that are creative [...] inventive, innovative, and designers. There won't be a place for people that want to hide behind number-crunchers and calculations. (P06)

The overall feeling was that the benefit of using computational engineering is not replacing people but enabling them to do more, be more creative and reach better designs:

> [...] you're either reducing the number of people you need to do something, or you're doing more. (P03)

> We can use computers to replace people but that's not actually where the value really lies, because if you can instead of replacing people, augment what they're doing and make what they're doing better and more powerful and let them use their intelligence and do the things that those human beings are really good at, but combine that with the things that computers are really

> good at then you get so much more value out of that instead of just trying to automate the whole thing and kick people out. (P01)
>
> Every time there's been a revolution, there have been replacement or a sense of a different typology of works, but there's a constant improvement and 'complexification'. (P07)

This change in the role of a structural engineer then brings the questions of the skills that they should have, which is discussed next.

3.3.1.3 Computational and structural design skills

Two concepts can be investigated here. The place of 'classic' technical skills for structural engineers can be questioned if their role is changing. In parallel, with computing tools gaining a greater role in the industry, the level of coding and computing skills required is also of interest.

The first question is essentially answered by the previous part in the sense that since computational tools are not replacing engineers but enhancing their capabilities, classical structural engineering skills are still critical for a structural engineer. Multiple participants mentioned the importance of deep understanding, of not treating the computational tools as black boxes:

> [...] enables your creativity, enables your efficiency that you wouldn't otherwise have got. And it can make a better engineer. But you should never disconnect entirely from the way systems work. [...] If you had no knowledge about what's gonna happen, then you can't navigate that, so it's very dangerous, and structural engineering doesn't kill in ones and twos, it kills in thousands or hundreds, so it's very important that we keep that base knowledge going as designers and that we don't just use black boxes, but we can use these visual tools to increase the rate of turnover of ideas and to increase the insight in structural engineering and shorten the time it takes to get a good insight. (P06)

One problem that was highlighted here by a few participants is how to maintain these technical skills when computers are doing more and more of the analysis. A example cited by two participants is load take-down calculations, which in the past could be seen as a "rite of passage for young engineers [...] [to] understand the principles of that" (P01) by doing the calculations by hand. It is however a problem reasonably easy to automate and that knowledge could be lost if systematically done by computers. As quoted in § 3.3.1.2,

the solution suggested by most participants would be to differentiate between what is engineering work and what is not, and therefore in the case of load take-down, to do it once or even at regular intervals to keep the understanding but let the more efficient tools do it the rest of the time. Another suggestion made was also to continuously "interrogate models, [...] understand what analysis is giving us [...]" (P06). The importance of 'softer' skills was also discussed by some participants. Communication with peers and other disciplines, creative thinking, hand sketching for example are skills that could be found in structural engineers in the past and are still essential in addition to technical and computational skills.

To answer the second question, design skills and computational design skills can be compared. All participants agreed to different levels that there are differences between the two. Most participants described computational design skills as one tool amongst other tools that a structural engineer should have, a "subset of design skills" (P03). Computational design skills meant different things to the participants: the use of the computational design tools and the creation of these tools. As already explained, using computational tools is deemed necessary. The question then became whether these tools should be developed by structural engineers or third parties. There was a range of opinions expressed but the dominating viewpoint was that it depends on the application and that software engineering is itself a "mature industry" (P09). The example of finite element modelling (FEM) was used:

> It very much came from academia initially as a theory [and] got picked up by industry. Industry developed finite element engines and tools in-house as tools to use on projects. [...] And then, you get to a point where outside software houses start doing it. They catch up. [...] They're putting far more investment into the development of the tools. They overtake in terms of the capabilities of them. And then industry flips and says, "Right. Okay, my in-house tools, they're good for some things, I'm still gonna keep them because they have benefits, but actually I'm gonna buy an outside package because it comes with all the support and et cetera." And that's definitely what's happened with finite element [...] (P08)

Most participants agreed that it would be beneficial if engineers create the tools themselves but that software engineers may be required when developing more robust systems:

> We have very few centrally funded actual code developers [...] their roles are basically to make sure that the framework supports the rest of the engineering community, being able to develop it on it. So they were almost at the meta framework level and helping all of the engineers write code [...] We want the

> domain specific knowledge to go into the code from the domain specific experts. So we actually want them to up-skill and engage with the code development. So that their knowledge is being codified basically. (P05)

> The person doing the coding and the person who has the problem, if they're the same person, then it streamlines the whole process and it makes the whole thing easier. (P01)

This idea was however moderated by multiple participants by the fact that not everybody needs to have the same capabilities when working in a team and that great results can be achieved when people inside a team all have the same baseline understanding but are experts in different areas, which includes technical and computational skills. The last idea raised with respect to computational skills is "knowing what you don't know" (P08) and understanding the limits of programming, understanding when something is wrong.

The place of programming in the AEC industry has been discussed here. Next the place of this industry in light of computational engineering compared with other industries will be examined.

3.3.1.4 Construction and other industries

The AEC industry can be seen as one of the least digitalised industry (Manyika et al. 2015) and the participants agreed with that perception. The conclusions that can be drawn from the interviews on that topic is that there are multiple reasons to that. On one hand, construction is a mature industry, "one of our oldest industries" (P06), with a "game of marginal gains" (P08) which means that innovation is not encouraged. By comparison, the 'tech' industry is relatively new, with high margins and a great ability to invest and research. These marginal gains are also due to the fact that the industry is extremely fragmented unlike the automotive industry for example where there are significantly fewer competitors in each country. Additionally, in industries like automotive or information technology (IT), one actor is usually responsible for everything in the product design and production, unlike in construction where a great number of disciplines and companies are involved in the delivery of each project. The AEC industry is also a very risk-averse industry due to impact it could have when things go wrong, which makes it resistant to change. The resistance factors to the digitalisation of industry will be further developed in § 3.3.2. Another reason is the will for every project to be unique, the lack of data sharing in the industry and the fact that it is extremely physically intensive:

> In construction you are designing a new thing every single time. So you haven't got the same opportunity to finesse your process, and just keep using

> it because you do have to have a slightly different process each time for your different architectural grants, and different site, et cetera. And even if you're doing very standard buildings, you still have to do it slightly differently each time. (P03)

While one participant suggested that the aeronautical industry would make for a better comparison and that they "don't see the disruption there. You don't see Boeing, or Airbus about to despair and worrying about being taken over by Google" (P09), other participants suggested that disruption is likely: "every other industry has been digitalised, we're not going to be the ones that aren't" (P01). Another participant said that "pure economics will drive the uptake if nothing else does" (P08) to remain competitive. The conclusion in this case was that the best outcome for the industry would be to "disrupt ourselves as a business" (P06). This topic is more a prediction on the future rather than a definite concept but the dominating viewpoint reached is that given the positive impact that computational tools could have on the industry, it is in its interest to make better use of them. Incentives for change in the industry are discussed in § 3.3.2.

An overview of computational engineering in the AEC industry has been drawn. Structural engineers can create and make use of computational tools alongside their creative and technical skills to reach more innovative, efficient designs. The AEC industry is however slow at taking up these new technologies even though they can bring great benefits. Incentives and resistance to change are discussed in the next section.

3.3.2 Incentives and resistance to change

The use of computational engineering in the AEC industry was deemed beneficial by all participants and some participants suggested that an uptake will be necessary for the health of the industry. In the previous section, a comparison with other industries was drawn, highlighting that the AEC industry is behind, for various reasons, in terms of computational engineering.

The resistance to change in this aspect, such as low investment capacity, have been mentioned and are explored in more depth in this part. The incentives and actions for change at various levels are also analysed. This includes projects that could have not been completed without computational design, collaboration in the industry and company and personal initiatives. The role of university education and research in this change is then analysed.

3.3.2.1 Competitive market, clients and generational gap

As mentioned in § 3.3.1.4, there are multiple reasons for the low digitalisation of industry so far. Some reasons are inherent to this industry, such as the uniqueness and scale of the projects. However, there are some factors that seem to be actively resisting change and these are analysed here.

Two sources of resistance to change were mentioned by almost every participant: the fragmentation of the industry with low margins and therefore low capacity to invest in new technologies, and the lack of initiatives from managerial positions and clients. The first part is illustrated in § 3.3.1.4. Some participants answered to this lack of investment potential with the financial benefits that can be drawn from developing and using computational tools:

> You throw out something like a flat-slab raising job. [...] If [engineers] put the digital tools on it, you certainly recognise that they make it much quicker. And they do it not just quicker, but better, faster, cheaper. So then you say, "Well, hang on a second. If people just stopped and switched, the time to switch actually gets paid for in what I think is about three months." And three months is a standard part for project [...] (P06)

The investment therefore seems to be possible despite the low margins in the industry, at least for simple, repetitive tasks, or even for more complex problems. The applications of these technologies are further discussed in § 3.3.3. The participants work in leading firms for the uptake of computational technologies in the AEC industry. Several of these companies have understood this concept and have started developing and using more computational tools. Their initiatives are analysed in § 3.3.2.2. However, this is not uniformly the case across all consultancies in industry yet. This may be linked to the second source of resistance mentioned by the participants: the lack of incentives from clients and management coupled with the need to demonstrate that designs satisfy relevant guidelines and regulations.

First, participants have highlighted a generational gap:

> The moment you say something that no one's heard of, the immediate response you get from most senior people is, they'll just mock it down and they'll talk you down. [...] We're talking about Karamba and how powerful it could be. But it's actually not Karamba itself, the comment was "Imagine going to the building control and the council and say, 'I've used Karamba.' " And everyone would just laugh at you. This is a really good example of a reaction of a huge

> generational gap. Because people think that this is just a bunch of toys that the kids play with. (P04)

> The main resistance I think is that middle band [...] it's the middle to upper management that tend to be blocking this stuff. [...] I think, as this wave of younger people who are more digitally oriented do come in, that gap will start to close a bit more. [...] I'm now part that band of middle and upper management that has traditionally been pushing back against this stuff and now I'm pushing it forwards. And yes, certainly here, I haven't had that much push back against it. But yes, I've certainly talked to older members of the industry who have been like, "Oh, we designed everything much better before these computers came in. All these young kids don't know what they're talking about." (P01)

> Now the problem is that the people come into the workplace with pretty good skills in those areas, but the people running the projects [...] don't know how to mobilise those skills to improve the effectiveness of the projects, because they're not familiar enough with what they can do. [...] The education is really needed in the project leaders more than it's needed in the graduates, I think. (P03)

This resistance might therefore disappear with time, as new leaders have higher computational skills and more trust in the tools is developed, following the example of the companies of some of the participants. The other side of this problem are actors outside of the consultancies, such as clients or even governments. Indeed, "clients and contractors are trying to compress program and save money" (P07), which may not give space for technology development. AEC is a risk-averse industry for good reason given its scale but a participant highlighted the negative impact it has on fee levels:

> The problem is the factors of safety in construction, and from a consultant's point of view, if we worked leaner and sharper, we would kill more people, and people would pay more for engineering. It's a kind of self-fulfilling thing. So over-regulate it, kill less people, I know it's cruel, but actually, they can afford to push us down to the point where fee levels are bonkers. (P06)

Some participants on the other hand highlighted the positive impact that clients and higher powers could have:

> People going out to try and win projects and then the client would say to them, "So what are you doing on the digital side of things?" [...] And then, there was a bit of a gap there. (P01)

> I think governments, they're doing a lot, but they could do a lot more to promote the digital compliance and efficiency in this industry. (P07)

The impact governments and regulating bodies could have are discussed more in regards of environmental sustainability in § 3.3.3.8. Another point noted by some participants is that not every one has the same computational literacy in industry, for example with contractors requiring printed drawings rather than 3D models and thus slowing down digitalisation of industry. It could be concluded that consultancies have the power to increase the uptake of computational tools in the right framework, when "innovation [...] [is] facilitated, enabled from the top, and encouraged from the top" (P08), without substantial investment, but that the change needs to operate in the whole procurement chain to reach the best results.

3.3.2.2 Company incentives

Leading consultancies have started investing in and using computational tools in the UK and abroad. Some participants work in some of these companies and described what works well and what could be done better. Most participants who discussed this topic suggested the importance of embedding computational experts in all the teams of the consultancies and up-skilling people across the industry for a durable digitalisation, as opposed to having one specialist team solving computational problems for others but not spreading the computational skills. On one hand, engineers then have to spend some time developing these tools rather than directly working on billable projects. Also, this may require additional training to be delivered in-house:

> We've been to every single office doing lots of training courses and things and basically up-skilling people to this world of computational engineering. Almost just upgrading their computational literacy or what they were able to do before touch typing on the computer or building models manually. We take that up a step and they can use visual programming. (P05)

> [...] using the people that are becoming expert users and deploying them around the business to train more people. (P06)

This could be problematic given the low margins in consultancies. But benefits are then observed from companies investing in computational literacy and tools development:

> We justified it, A, on the fact that the projects we were doing were making money. B, on the fact that we were improving efficiency overall and then, C,

> on the reputation benefits, although we didn't like to rely on that too much. (P01)

The other aspect introduced by the participants is that companies can use the personal interest of its employees, which does not require any investment:

> [...] a collective of people, whose common goal and motivation is basically to solve problems and solve ever more complicated problems. But doing it in a way that we're starting to get more and more joined up. [...] We really started organising ourselves and formalising writing code and scripts on projects. Everyone was doing it in isolation. Bits and pieces all over the place. Amazing things going on. And we basically said, let's stop doing all of that in isolation. (P05)

It was actually highlighted by various participants that what led them to having their digital oriented role was a personal interest in coding or computer science. This emphasises the idea that the uptake of these technologies is possible in the AEC industry when it is enabled by senior staff.

3.3.2.3 Project driven initiatives

Another area enabling the uptake of computational tools is complex projects. Multiple participants have worked on projects where computational engineering was essential for successful delivery. Sport structures and long-span projects have been cited as one area where computational tools are used for analysis, complex geometry definition and optimisation. Applications of computational tools are developed in § 3.3.3 but these unique, complex projects allowed introduction and gaining of trust in these technologies. Projects mentioned by participants include the Gherkin in London, UK for sizing optimisation or the Opera House in Sydney, Australia for complex geometry definition. More recent examples include the Morpheus building in Macau, China that required extensive parametric techniques to define the geometry and connections. Interestingly, four participants are or were at some point involved in the Temple Expiatory de la Sagrada Familia in Barcelona, Spain, where historically dynamic relaxation and now computational technologies have had a most important place on the project. It was described by one of the participants as "an absolute textbook example of how things should be working". Such projects are iconic and may have had a role in the participants' career in reaching such leadership positions in computational engineering in construction. Project driven computational initiatives can therefore help lead the path for an uptake of these tools as

they justify the cost. Even on more standard projects, participants agreed that it is easier to justify the investment in computational tools when it is directly applied to a project:

> Quite often it's about taking a tool and generalising it after the project has been done if you've got a bit of money that you can put in [...] it's often quite difficult to justify setting up a new tool in a very general way at the outset because you don't yet know whether it's gonna be useful, or whether it's going to really pull in benefits. So, you quite often develop it, or use it and say, "That was fantastic on that project. That really delivered value. Now we're gonna take it and see if we can make it a bit more general." (P08)

A participant also highlighted the importance of developing and maintaining only what is needed, therefore minimising unnecessary expenditures:

> You don't need to create an interoperability between two platforms that supports the entire IFC file schema. We just at the moment really need to be able to pass beams and columns or whatever. So by building what you need, we can maintain what we need. (P05)

Participants were also asked if when using computational tools for a particular project, engineers managed to expand them to apply them on other projects. A few participants explained that this is can be a struggle as people tend to get caught in the next projects and do not necessarily have the time and incentives to turn the tools into something more robust and user-friendly. Other participants argued that improving the tools can be financially beneficial and that some companies, having identified these benefits, are taking steps to encourage work on more generalised tools that can benefit the whole company.

3.3.2.4 Collaboration in industry and open sourcing

Another concept mentioned by multiple participants to increase digitalisation of industry is through collaboration and open sourcing, at least on problems that are not pertaining to structural engineering. Interoperability is one of these problems and is discussed in itself in § 3.3.3.6 but the impact that collaboration can have is the focus here:

> I think that probably the right way for the industry to go is to recognise that there's not so much competitive advantage anymore in all individually developing the exact same thing, and there's a bit more collaboration that's possible to try and solve the problems that we all have. (P01)
>
> [*Open source*] we hope is something that will move the entire industry up a level. So instead of competing with each other for the most simple problems,

> why don't we all just solve the simple problems together and have a common platform? And the industry then can start moving forward together, to solve much more interesting and complex problems. (P05)

> When things are open source, the collective intelligence just moves it along at an incredible pace [...] Our industry is so closed down. [...] There's much more value in your experience than it is to a particular tool or particular bit of software to do something. [...] You need all the other things that we talked about. The experience, the ability to manage information. The ability to take decisions based on what's possible, what's buildable, fabricate-able and so on. It's a fairly safe environment, the construction industry is a fairly safe environment for us to be open source, actually. (P04)

The last part of this quote relates back to § 3.3.1.2 when it was perceived that computational tools are not replacing structural engineers and the importance of engineers' knowledge. Several companies, some of which some of the participants work in, are communicating more and more on the digital areas that they are looking into and release some of their tools. Recently, Buro Happold released the Buildings and Habitats object Model (BHoM) (Buro Happold 2018), a computational development project open sourcing material on interoperability and other topics. The hope is for other companies to participate and move the conversation along. Other examples include Thornton Tomasetti releasing TT Toolbox (Thornton Tomasetti 2013), sharing common computational tools used in the company for industry benefit.

It therefore seems that open sourcing some knowledge and collaboration in industry may be necessary for the uptake of computational tools with the aim of solving complex, meaningful engineering problems despite the competitiveness of the industry which was put forward by other participants saying that collaboration is not realistic:

> If funding was there to push some digital initiative, I'm sure we and many others would welcome that. But we would probably often try and put, we would be focusing on our own interests rather than the wider profession's interests, probably. Our instinct will be to try and get a competitive edge through what we're doing rather than try and do something for the benefit of the whole profession. (P03)

3.3.2.5 Role of education

Incentives and resistance to the digitalisation of the AEC industry have been discussed from a company, client and government perspective. Participants were asked if university

education could also have an impact. This is particularly relevant as a change in the role of structural engineers, with different skills needed, is happening as discussed in § 3.3.1.3. All participants agreed on the importance of technical skills and of getting a deep understanding of the fundamentals of engineering. Even though some analysis can be done by computers, it is crucial to understand what is happening and be able to exert judgement. The way to introduce more computational capabilities could therefore be to change the way the technical knowledge is taught rather than change the contents. Some participants suggested for example less repetition of hand calculations and better understanding of software operation. This reflects what is happening in some universities, when academic researchers with interests in teaching, such as the author's supervisor, try to implement new teaching methods or new design threads to better prepare students for their evolving engineering role (Stratford 2016; Phillips 2017a,b).

Most participants agreed that when it comes to computational capabilities, what is important is not the use of particular software but again the understanding of coding, the limits of programming, the underlying principles:

> If you don't understand, though, then you wouldn't know how to use the computer. People without understanding are not going to be safe, and they're not going to be creative. And we need to learn understanding of structural action. You need to know the basis of how the computer is doing that sum that you- and you also need to know how to be able to take those tools and make them do new things, which the writers of those tools never thought of. So you need to be able to use them and manipulate them and getting to the nuts and bolts of it, changing it around so it does what you want it to do. So you need to know the fundamentals. And you ought to know how to do the software engineering and data engineering that you need for that. So a grasp of the technical aspects of how it works and how the software thing works, it's very important to be able to produce an output in a digital way and do it in a powerful way. (P02)

Following the idea of increasing computational teaching, some participants, who see value in computational knowledge development before reaching industry, compared structural engineering with architecture:

> Every engineer has to be now educated to understand the digital tools and the digital workflows. In their very basic shape and form. Architects are way ahead of engineers in that field. (P04)

Some participants found the average level of computational literacy of graduates insufficient and wished for greater knowledge:

> Computer science, nowadays especially, is the enabler so I think that should be really pushed a lot more down. Even nowadays, I don't think it's still enough. It's still relegated to the backside, something optional. (P07)

Other participants thought that computational skills should be kept minimal in university, suggesting that interest in these areas should be more personal:

> An appreciation of what you do and don't do in software engineering would be quite useful. But I think that's as far as I would go. People pick up coding nowadays, and they have that as part of their degree already. I had it as part of my degree. [...] Kids are learning it at school, and if they're gonna go into any engineering related industry and not realise that they're going to have to know how to write a line of code, then they're in trouble, basically. But I don't think that's really necessarily the responsibility of the syllabus to completely correct. A way into that world, and some help getting going, fine. But, we're not delivering software engineers. (P09)

In this case, companies would then have to train people in using software in a way that interests them. It would seem that this depends on the company model but all participants agreed that computational skills are necessary although at different levels.

Even though not directly relevant to computational engineering, other skills that could be developed in university or earlier were mentioned by participants. These include management skills and "understanding the industry and how to operate within" (P07). Creativity was discussed as some participants said that it should be enhanced in university whilst others thought that it is a team-based activity, happening with people of various disciplines such as architects and mechanical, electrical and plumbing (MEP) engineers which is therefore not very reproducible in university. A participant moderated that thought:

> One thing that I really like from engineers that come from Europe and further afield places, is that they tend to do degrees which are a bit more of a mix of architecture and engineering. Which is good I think because it teaches you, even if you're going to be an engineer, how to think like an architect and how to understand things that they care about, and vice versa. I think at the moment, in the U.K., both education and industry are a little bit too siloed. (P01)

This idea of more fluid knowledge between various disciplines of construction is further developed in § 3.3.3.7.

All participants agreed on the need for computational skills to be taught in universities but at different levels. They agreed on the importance of finding the right balance between technical and computational skills. They have different expectations regarding other skills. This was not discussed in the same depth with each participant due to time constraints during the interviews and no clear conclusion should be drawn here on which direction university education should develop in. An ongoing conversation between universities and industry, which multiple participants mentioned having, is potentially a good method to improve the syllabus to match the changing role of structural engineers. A participant also highlighted the importance of not only teaching necessary knowledge in a "business looking to make a profit" (P08) aspect but also that universities should have some freedom in what is taught. This feeling was also extended to academic research, which is developed next.

3.3.2.6 Role of academic research

When discussing the relationship between academic research and structural engineering in industry, all participants identified a noticeable gap between the two and mostly agreed that this gap is healthy as academia and industry have different aims and motivations. One participant moderated his thoughts:

> Most of construction, structural engineering is making sure something's built safely... not trying to do anything particularly unusual. And in that world, I think it would be inefficient to get too involved in research. I think the place for the research is in making sure that the design guidance is good, and reflects the latest research. But it's the design guidance that the engineers practising should be turning to, not the actual academics themselves by and large, because it's just a more efficient way of doing things, I think. [...] Definitely if I was trying to argue, which I ought to be, because it's where my heart is. If I was trying to argue for better design, and creative design, and moving industry forwards and things, then I would be arguing for better links with research, yes. So perhaps that should be my answer. (P03)

Other participants agreed with that perception that research is important regarding innovations though breakthroughs do not necessarily arise when industry has a strong input but rather when "researching in some of the less obvious stuff" (P08).

Interestingly, multiple participants are involved in research projects with collaborations between universities and industry at various levels. One of these projects is Build-Opt, where three universities and seven companies or organisation work in collaboration. The author's research is also funded in part by industry who have had a strong input in the engineering research. These two collaboration are computationally oriented, as are many other initiatives between academia and industry. FEM is another example of innovation coming from academia then used by industry, as explained in § 3.3.1.3. It therefore appears that academic research may have a role in the uptake of computational engineering in industry, with and without collaboration between the two. Dialogue is however necessary as they may have different motivations and objectives:

> [*Talking about academic research in structural form optimisation*] But then when you actually start to put that into practice, there's all these other things that come into that. [...] From the pure mathematics, you'd end up with one beam which is this big, connecting into another one which is that big and things like that, and you just can't manufacture that and it won't work at that node. So what you also need to build into that optimisation is things around buildability and in making sure that those connections are smooth and that it all makes sense. Also, if every member is different sizes, then that's not something that's going to be very easy to manufacture for some time, until we can 3D print everything. [...] There's the theoretical optimum and then there's the practical optimum which actually builds in all these other different considerations. (P01)

When aiming to apply academic research tools to industry problems or vice versa, dialogue and sharing knowledge therefore seems important to move in the same direction.

The AEC industry is one with many actors, spanning across a number of disciplines. Digitalisation, which is more advanced in other industries, can have many benefits in construction. Despite the low margins of industry, innovations are still possible and do not necessarily require substantial investments. Companies can choose to promote these incentives, and projects where the use of computational tools was indispensable can help in this initiative. For the change to be durable, universities have a role to play, at the educational level and to some extent with research. The last part of this analysis is on the applications of computational tools in the AEC industry.

3.3.3 Use of computational design and technologies in practice

Some applications of computational tools in structural engineering have been mentioned previously and are discussed further in this part. Computational design can be used on practical engineering applications, such as complex geometry definition or structural analysis. They can also have an impact on less definite areas, such as communication between people and disciplines or sustainability.

3.3.3.1 Complex geometry, optimisation and parametric design

Seven participants directly talked about complex geometry definition to illustrate the use of computational engineering. It is one of the initial areas where computers could be used not just to reproduce what could be done by hand, such as drawings, but to enable the construction of structures that could not be defined otherwise:

> Historically they've had a very good impact in solving complex geometry so far I think, because without digital tools, we wouldn't have been able to solve those problems generally. So optimising complex shapes into the brick wall units. (P07)

Complex geometries that the participants have worked on include long-span projects, complex roofs, curved structures and grid shells where rationalisation for repetition is used so that the structure is buildable. As discussed in § 3.3.2.3, such projects can drive the uptake of computational tools:

> So, when I was looking at long-span structures and projects, we were looking at- Still am looking at them, but we were looking at things that you couldn't do any other way. You had to have some digital tools to simply handle the complex geometries, the analysis, the stuff that we have to do for something like a stadium roof is an incredibly complicated thing, beautiful thing, but it's high risk, and it needed to be done right, and some of the architectural and also the engineering intents, we've got our complex geometries and we need all skills to be able to handle and manipulate the data. (P06)

Parametric design is one of the tools that can be used to work on complex geometries. It can help integrate the geometry, rationalise it, search a greater design space for efficiency of the structure or other objective functions. Form-finding is a parametric design technique to define geometry and is older than computers with dynamic relaxation for example, which was used by Antoni Gaudí to model the Sagrada Familia. At the time, such

techniques required space and time and computers now allow for an easier application, the search of a greater design space than could be done manually and to integrate geometry definition with other aspects such as analysis or drawing production. Engineers can easily see the impact of one parameter or the other on their structure, which can lead to better designs when combined with their experience and knowledge. Some participants mentioned the risk of pushing the complexity too far and designing structures purely because computers allow engineers and architects to do it but without physical sense, leading to inefficient and unnecessary structures:

> [*Talking about architects*] they keep pushing. And they will always, this is the job of the architect. They'll keep pushing to make things more complex and more unique and more 'it's never been done before'. [...] There are examples where that was pushed too far. [...] Of course, digital tools, all these things are empowering us. But we have to have a very sober look at when do they help us and when do they actually are in our way. (P04)

Parametric design and optimisation can be used on many aspects of a structure other than geometry. Day light optimisation, member sizing, material reduction, strain minimisation, heating efficiency are some of these applications.

Complex geometries, parametric design and optimisation is perhaps the most obvious area where computational engineering can be used to build structures that could not be designed otherwise. Analysis, of complex geometries and of more simple structures, is also an evident application of computational engineering and is discussed next.

3.3.3.2 Analysis

Participants were asked whether analysis is part of digital design. They all agreed that analysis is and has been for a long time a key part of a structural engineer's job and that it is definitely part of the design process:

> [*Talking about analysis*] It's a key part of digital design and structural engineering. Analysis is intimately entwined with the design process, because what we tend to do is think of something and see and do analysis and see whether you can justify that by calculation. And we might then refine our design and check it again, or whatever, but it's usually a case of imagine, analyse, check, re-imagine. (P02)

They also agreed that computational tools can have a great power when applied to structural analysis and that analysis was one of their first applications:

> Analysis I guess has been something that's been digital from a fairly early stage. The Snowdon Aviary has got the most fantastic piece of historic analysis, where they did a very early version of a structural analysis using matrix methods that computers do as a standard, and have done for a long time. [...] There was a problem to solve, which was this statically determinate problem with about 20 nodes in it. And so they could write out all the equations, and then get a computer to solve the big metrics, and that's what they did. It was right at the beginning of computer software analysis. So the power of computers to analyse things in that way has been enormous, and essential to engineering for a long time, for two generations. It's been around for much longer than digital drawing has been around. (P03)

They emphasised the importance of using the correct software, solver or method for the right task, which is linked to interoperability, developed in § 3.3.3.6. The idea is that simpler methods can be used to solved complex problems, thus reaching faster analysis and reducing the carbon footprint of computer use. This requires engineers to use their understanding of structural mechanics and of computational tools to enhance both. That concurs with the ideas developed in § 3.3.1 that engineers need to still exert technical judgement, particularly when using computational tools for analysis, and that it is important to balance the two knowledge areas:

> Analysis is one of these things, it comes with two edges. It comes with, the digital tools we can use are really good to help us enable good designs, but they also, if deployed incorrectly, can take away some of the art of engineering [...] Some things go when you get more powerful tools, but other things emerge. So you can get to an answer much quicker, you can then look at more answers, you can start to see patterns emerging [...] So, you've gotta get the balance right, so we can't totally trust the machines, and we can certainly learn some of the principle of structural engineering, and the fundamental structural engineering and how to apply them, and every now and then we're gonna have to do some things by hand, just to keep our eye in. And that's still an important part. (P06)

One participant suggested that computational tools can bring a change of ownership of analysis as they allow for faster and more accessible analysis methods:

> It's maybe making analysis less part of what engineers do but more part of what architects do, in the sense that the analysis that we're doing as engineers is taking a bit less time so we're a bit freer to focus more on the more creative side of things rather than just sitting there doing ten thousand hand calcs.

> Whereas architects who were doing more of the creative type of stuff, it's making the more detailed analysis that typically engineers would do, bit more accessible to them. There's a lot of architects nowadays who are doing more of their own daylight studies and all kinds of environmental studies and things like that on their own without kind of necessarily having an engineer telling them what to do. (P01)

Analysis is intrinsically part of structural engineering and computational tools can be used to facilitate it and solve complex problems. Some analysis problems can be automated, and productivity can be augmented by making analysis faster. This is discussed next.

3.3.3.3 Automation, productivity and data

Automation can be used in various areas by structural engineers. It can be used on simple structural problems, such as load take-down which is discussed in § 3.3.1. Other areas mentioned by the participants where automation can be used include member sizing and analysis. Automation can also help search the greater design space available thanks to parametric design. Automation is not replacing engineers but helping them reach better design. It can also increase their productivity:

> [*Talking about a project*] If we were going to design that by hand in the traditional way, it would take four people four months to do that. [...] What that speed was actually about wasn't just essentially doing it 12 times faster and then saying, "Right, let's go home." It was about being able to respond more quickly to design changes and being able to be a bit more nimble and a bit more responsive to architect queries and client queries and things like that. So, we didn't just do that once and then give up, we essentially did that same thing. But over and over again, so we could actually, try out new things a lot quicker and ultimately, end up with a better design that way. So I think the main output of this, at least from our perspective is increasing the quality of designs because then it does free you up so much more to actually investigate things and try things out, and it gives you the space to breathe a bit so you're not just, right, decide something, all right, okay, that's the start of the project and now we'll just carry on and hope that works. (P01)

Some participants also discussed automation of non-engineering tasks, which is part of the change of the structural engineer role as discussed in § 3.3.1.2. Participants agreed

that automation of some parts of the design and of the activities that engineers have to do would enable them to have more creativity and reach more efficient structures.

Artificial intelligence (AI) and machine learning more particularly were also discussed by the participants. They mostly agreed that it is not ready yet for structural engineering problems:

> I don't see ways in which we are going to use artificial intelligence very soon. Artificial intelligence learns by, you show it pictures of cars and tell them what sort of car it is and then it gets to be able to guess what type of car it is. Because it decomposes the picture and it learns the rules itself by being told, all right, this is imperative from the directions so it can then- I don't see a parallel in structural engineering for that just at the moment. (P02)

> If you had some model image, and some machine learning, and you fed in all the previous contractors' jobs and you said, go away and work out all of the constraints there, and then come back with what the appropriate construction method for this particular contractor is for this particular job, and then tell me what the right structural form is, you might be able to but, that's- No, we're nowhere near that. (P08)

Several participants however said that research was being undertaken in that direction in their respective company:

> Machine learning is another area we're looking at which is about executive data, and that is about us looking at how we can start to use the resources of knowledge we have inside our business to make better decisions or make checks and get to concept design without doing any rudimentary analysis, we can actually get it to tell us what the likely answer is. We're always gonna check it, but we can always get there quicker. (P06)

Data is necessary for such applications, which the AEC industry is not particularly good at storing and sharing. BIM could help in that regard. Storing data for various purposes was mentioned by most participants. An area where automation, data and potentially machine learning can be used is in building occupation and building response. One participant highlighted the high factor of safety in industry and how we do not always know if a building just stand ups and performs as expected or if there is a different magnitude in the factor of safety. Monitoring of buildings and data analysis could help inform future designs and potentially help increase margins. One participant talked about the environmental sustainability problems of machine learning which is discussed in § 3.3.3.8.

Data collection and management is an area of interest according to the participants, as is automation and machine learning in the longer term. Physical applications of computational tools are discussed next.

3.3.3.4 Modular manufacturing, robotics and 3D printing

Modular manufacturing is constructing using predefined and prefabricated parts that are brought to site and assembled. It is not necessarily related to computational engineering but some participants discussed it as an area of interest for a number of reasons. It can simplify the design phase through automation by discretising member sizes, leading to faster design. It can also reduce construction time, for example by removing in-situ concrete casting. Modular buildings can mean buildings that can be taken down easily and with pieces that can be reused more easily on other projects, thus increasing the environmental sustainability. One participant saw the negative side of off-site manufacturing:

> [...] pre-casting things automatically in concrete. And you invest all this technology into something, and you're then stuck with the problem that somebody's gotta want to build things your way. As a contractor, you've actually got to get into the design process quite early in order to make the building design efficient for your system. But the client doesn't want you to do that, because the client wants a fully resolved design that they can then competitively tender going at competitive price. So actually designers loose fit necessarily for commercial reasons for the clients. And therefore doesn't go much of a benefit of somebody's particular clever system. (P03)

Other participants argued that computational tools and better machines can help to make off-site manufacturing more adaptable and customisable, thus reducing the problem of offering limited design choice and increasing the value. Some also suggested that computational tools can allow engineers and other stakeholders to get in the design process earlier, facilitating the dialogue and informing the design, so modular construction can be better used.

Another technology mentioned by some participants is robotics. Robotics can be used for the fabrication of the modular parts for steel production or for computer numerical control (CNC) for example which can cut custom elements before shipping them to site. Robotics could also be used on site. In light of modular construction, participants discussed robots bolting steel at heights and assembling pieces together to increase workers' safety. A participant mentioned using robots for building maintenance. Other

participants discussed drones, for tolerance checks during construction or for material spraying on domes. This leads on to 3D printing or additive manufacturing. It can enable manufacture of parts that could not be done in any traditional way and can create extremely efficient structures, where material is added only where it needs to be to sustain loads for example. Three participants directly talked about it. One did not see its application to the AEC industry currently:

> That technique may well be bringing to light, it's so beautiful, it uses a tiny amount of steel, but the steel is, the quality of material that you get in the 3D printing process seems so much lower than steel can be, if it's built in other ways. But it seems wasteful in a way, the 3D printing process is dependent on the material they're printing, aren't they, they print that plastic, whatever it is that they do, very nicely, but you can't just print anything, it has to be something that comes out of a nozzle and sets, sort of, structurally. Whereas 3D printing concrete, concrete takes a day or so to get hard [...] (P02)

The other two participants were more optimistic with the future it could have:

> The sheik in Dubai wants to have, I think it's 25 percent of all construction by 2025 3D printed? That was the aspiration? Ain't gonna happen, but I think the aspiration's there, so we could start to investigate that. (P06)
>
> I think one thing that's interesting to see where it ends up is on the digital manufacturing front, so things like 3D printing, like the MX3D bridge. [...] So, stuff like that is really interesting. [...] So, at the moment, this is very niche and it's not really ready for full-scale use and things like that, but I feel like there's going to be tipping point somewhere, where it suddenly becomes more economic to manufacture things in that way. (P01)

The MX3D bridge is the first 3D printed metal bridge from a collaboration between industry and academia, aimed to be installed in Amsterdam (Buchanan and Gardner 2019).

It therefore appears that there are many areas for digital manufacturing in the AEC industries. Some, like modular construction, are currently more used that other newer ones, like 3D printing or drone use. The participants had different opinions on the various uses but it would seem that there is a growing appetite for these tools at least in some parts of the industry.

3.3.3.5 Building Information Modelling

BIM is often associated with digitalisation of the AEC industry. For example, in the Digital Construction Week in London, which is described on their website as "the only event series in the UK dedicated to digital construction, engineering, design, manufacturing and operation" (Digital Construction Week 2019) which is an event that many industry stakeholders attend and participate in, BIM is an important topic and two out of eight seminar streams are focussed on it. Participants were asked whether BIM is part of the design process and some participants discussed it in light of computational engineering.

Participants agreed that the BIM is an inevitable part of industry but that it is not necessarily part of the design process in itself. Multiple participants suggested that it acts as the back end of the design process:

> I don't think BIM is part of the design process. I think BIM is a way of organising the output of a design process. So it's like a filing system in a way. (P03)

> BIM, I personally see it as a container where inevitably, your design process, where it materialises, it becomes something that you can then start to assess and cost and fabricate. Then, the BIM is the container. Actually, it's probably the back end of the digital process, so that's why our efforts are a lot into connecting our digital frameworks to the BIM side. That in order for us to be able to transfer all that database information into BIM platform without having to reinvent the wheel and recreate it. That's what I think of BIM in the end, it's a live footprint of your design stage and, if we're talking about construction, is the master construction model, if it's after construction, it is your final model, they can then maintain your building and know in the future where you're building was made [...] (P07)

> On every project, we start with huge enthusiasm saying, "Okay, we're really going to use Revit now from start and everything." Why? Because it's easier. Because everyone, every client expects you to deliver in Revit. The way we think about Revit or any other BIM, but let's say Revit is a bit of a standard, is just a huge database. It contains the geometric information, but also it contains a specification, schedules and everything that you need. Everything you need at the bid stage, doing construction and so on. So, clearly, having high level of information in Revit is very beneficial to the project and to the client. It makes the process flow better, it's more efficient. It's faster, therefore

> less room for mistakes. Great idea, great concept and obviously widely used on many projects. (P04)

That participant however highlighted the limitations of Revit and of BIM more generally, as did almost all other participants. Revit is mentioned as the most common BIM software but BIM as a process is the real topic.

> The reality is that we've never really used Revit for anything, but to copy paste the final geometry of the model on the last day before submission. And as much as this is supposed to be embarrassing for us as an industry, there is a standard and there is even legislative and contractual requirements for consultants to work and to submit the information in Revit. This rarely happens on complex and special projects. Because the software just cannot handle it. (P04)

Similarly to the word digital being inaccurately used in industry, some participants identified that the term BIM is often mixed with computational engineering which is a distinct process:

> People now are saying that they're doing digital design. They're just building BIM models. They literally are just building BIM models. [...] Computational engineering very specifically has a definition and an application and it can be applied to BIM. It can be applied to models. BIM itself is building information modelling. It's creating models of building with information attached. And so almost calling that what it is. [...] It's not using computational methods and approaches to solve complex problems. (P05)

BIM therefore appears to have its place in parallel to the design process. Several participants suggested that it could have a greater impact than it currently does if all stakeholders were using it properly. Participants argued that BIM in itself is not computational engineering but computational engineering could be applied to it, for example through having smart interoperability systems sharing only the necessary data between the "reality" represented by BIM and analysis, which is an "approximation of reality" (P06). Interoperability becomes essential here, as it is for using the correct software for each analysis problem.

3.3.3.6 Interoperability

Interoperability has been mentioned several time as an essential problem that industry faces on various levels. It was not part of the original set of questions but was brought

up by the first participant when asked if the researcher should cover any other topics at the end of the interview. Interoperability then became a topic discussed with every participant.

The main concept is interoperability between software. Using the correct software for each application but also only sharing the relevant data between software to keep the system efficient:

> It's important because fundamentally each package of software that we use is good. And most of them have started out because they're good at one particular thing, and they're still probably the best at that particular thing. And often what we're looking to do is to take that bit they're particularly good at, and take the bit somebody else is particularly good at and put them together. [...] The really nice workflows are the ones where you don't end up sharing everything, but you identify what you need, and you just take that little bit out. (P09)

Multiple participants suggested that software companies are not particularly helpful with that even though institutions such as the Institution of Structural Engineers is having a dialogue with them. Some companies may fear that people stop using their software entirely if they can do some parts elsewhere. A participant gave the example of a software company that goes in the direction of interoperability:

> They have an integrator that lets you go from Robot to Tekla structural designer. [...] And they're saying "we are going to create a product that's really, really good at doing this. We're not going to try and pretend that we're going to be brilliant at every single part of structural engineering, we're going to be really good at this. So come in and out as easy as possible to use our software." And I really hope and think that the industry should go in that direction. Where the software companies are creating a tool that does one thing, or a series of things really well. Not try and solve every problem. And then using a suite of different platforms to solve the meta problem. (P05)

When software companies are not as helpful, structural engineers have to find solutions even though it is not directly a structural engineering problem. All participants talked about interoperability and most mentioned using in-house codes to solve these problems. Software that allows for interoperability and easy coding and customisation are gaining in popularity. Many participants talked about their use of Rhinoceros 3D/Grasshopper 3D (RH/GH), not to solve every problem, but as a platform linking to other software. Participants said that the RH/GH is user-friendly, robust as a software but more

importantly easy to extend, develop plug-ins for, with a mostly open-source community around it. Similarly to engineering firms making interoperability solvers open source as discussed in § 3.3.2.4, this helps moving the conversation along and solving ever more complex problems.

Another side of the problem that was discussed is retrospective compatibility, reading now files that were created in older software versions or in software that do not exist anymore. This may be a problem in the future as physical drawings can always be read but as more and more information is in digital form, it will be important to still be able to access it in the future. This aspect was not discussed further but one participant suggested that geometry will always be geometry and that as technology advances, it should be possible to extract the relevant data and access it.

Interoperability is an important problem of computational engineering even if it is not direct structural engineering. Companies are solving these problems and could move faster by sharing solutions since they are all working on similar problems individually. Interoperability can also help link BIM and analysis softwares. Another side of interoperability that will be explored next is how it can facilitate communication between various disciplines in the AEC industry.

3.3.3.7 Communication

The increase of computational tools in the AEC industry can facilitate the dialogue between its different stakeholders. As discussed previously, it can introduce a change of ownership of some activities, for example with architects conducting more analysis and engineers engaging more in the creation side. Participants also suggested that facilitating the dialogue can also lead to more efficient, informed and integrated designs. Engineers can have an input earlier on in the design process, more options can be investigated and flexibility can be kept for longer in the design process.

Computational tools that help increase communication include visual software such as RH/GH that is more and more used by architects and that can provide a common language platform between them and engineers. Other tools discussed include augmented reality (AR) and virtual reality (VR). These are areas that several companies are investigating, according to some participants. These tools can help with communication across disciplines, for example with architects or clients, to get a sense of the design in real scale. Some participants also suggested that it can also improve site logistics. Visualisation tools can also be used for construction sequencing.

A participant talked about improved communication in a different light:

> More recently we've recognised as well that there is some other fundamental learnings and philosophies across disciplines that will help. So structural engineers and MEP engineers, their brains work in fundamentally different ways as we found. [...] It's not about changing the structural engineer into an MEP engineer or vice versa. It's about finding those fundamental building blocks or gaps in the way people think about things. And just improving those a bit so that then together when you get into the domain specific conversations, there's like a really concrete, common foundational language that you can talk, and it moves the conversation and the coordination on so much more quickly. (P05)

This is not necessarily linked to computational engineering but using similar digital platforms can help share knowledge between disciplines and potentially reach better designs. Use of computational tools can also allow conversations to continue throughout design or even construction. The process can become less linear, exploring gaps in the way different disciplines look at design.

Improved communication inside structural engineering and across AEC disciplines could be beneficial to the whole industry. Interoperability, open sourcing and use of visualisation tools are all steps in this direction and parts of the industry seem to be interested to take that further. The last part that will be explored is various sustainability aspects of the AEC industry and the potential impact of computational tools.

3.3.3.8 Sustainability

Participants were asked if computational tools could have a positive impact on the sustainability of the AEC industry. It is responsible for a third of global greenhouse gas emissions and more than 40% of global energy used (UNEP SBCI 2009) and participants discussed how they could be reduced. Environmental sustainability was the main topic here. Social sustainability is however also a topic that comes up regularly when engineers discuss the impact of computational engineering can have on society. One participant discussed it and it highlighted the positive impacts computational engineering could have in many areas:

> [*Talking about data collection*] Maybe one day, crunching through these numbers and finding out some relationships, some opportunities for making things better, etcetera. It's already happening, right? Infrastructure and

> city planning. There's a lot of information from a sociological point of view available, statistical data and so on. All that stuff has to be intermingled with the data in buildings. What really happens to the local residents in terms of well-being when you build a tower next to their house, in the neighbourhood. And this happens in London. London is a good example, because London has never been really designed to be a high-rise city. And, but it's turning into one. So, there is a good example of the social and cultural impact of these tall structures. All they do in their shape, and they impact local- on the well-being, on the environment. You know, these are complex topics and complex systems. But digital tools are really the only way. (P04)

Regarding environmental sustainability, participants suggested that a number of things could be done without the need of computational design. Material choices is one example, including the use of timber or improved concrete with less cement. Computational tools were described by some participants as an enabler to reduce embodied carbon in industry if pointed in the right direction but that there has to be a will to accomplish that. Given the low margins of the industry and clients often selecting the lowest offer, more sustainable options that cost more will not be selected unless obligated by law or governing bodies. Participants argued that the technology is there but unused due to lack of incentives. Using these tools does not mean more efficient designs with reduced embodied carbon unless the person using them wants to. Governments therefore seem to have a role to play if the carbon emissions targets set in various conventions, such as those of the 2015 United Nations Climate Change Conference in Paris (COP 21) in 2015 (Center for Climate and Energy Solutions 2015), are to be reached.

Participants however did identify areas where computational tools could have a beneficial impact. Better communication between the stakeholders could help engineers inform the design process and select the most appropriate structure for a particular application. Faster analysis tools can also help in that prospect. The definition of a good measure of sustainability would be necessary then to compare options:

> I think far more impactful would be digital design tools which can give you feedback at feasibility stage. At the decision making end of things, about whether this is a good idea, full stop, to do this scheme. [...] These are far broader questions. It's like, do we need a tunnel or a bridge, or do we need to give everyone a bike, or what is the solution here? There's no one tool that's gonna give you that answer. If it's very easy for us to get a good answer for how much carbon will be involved in a scheme [...] and get a decent number out, painlessly, and that informs that process, then that's useful. But

> the important thing is that process at the beginning, and comparing those numbers across a range of really broad options. (P09)

Another area mentioned by multiple participants that is already being implemented is material reduction on new project, which directly leads to reduced embodied carbon. Participants highlighted that it is not necessarily the area where big savings can be made but it can be done now and improve what would be built anyway:

> Obviously minimising waste, minimising material use, are two key things. Minimising material use through efficient design. Digital optimisation is a very good way of getting efficiencies in big complicated structures like tall buildings. If you're good at optimisation you can take a serious amount of material out. (P03)

> Digital tools will make us more efficient and have made us more efficient, so they can usually knock off anywhere between 10 and 15 percent, if you didn't use them, you could get out straight away. So that's just a straight material saving typically, whether that's in rebar quantities, whether that's in foundation sizing, just by doing our job a little better, we can start to get those things down. (P06)

Participants also discussed operational carbon of buildings which could be reduced but a lot of decisions to enable these reductions are made during design. This is again linked to engineers informing the design earlier on, for example so that the relevant stakeholders can improve energy and heating strategies. This is potentially quite commonly investigated already according to one participant:

> We're concentrating on energy and renewables and solar panels and wind farms, things like that, and that's well understood, and reducing the energy consumption, that's well understood. (P06)

This matches literature with a lot information on reducing operational carbon of buildings (De Wolf et al. 2017).

The last area investigated here is the impact of a greater use of computational tools on carbon emissions. Only one participant discussed it but it is a non-negligible factor to consider:

> It's like, yes, machine learning is the absolute, it will solve anything because you can train it to understand anything. [...] It is the ultimate sledge hammer if you like. But why bother creating all of that data and doing all of that work if we know what the solution is. [...] [In] an MIT article quite recently

> studying the environmental impact of machine learning. So I don't know if you know, but to power the computers to train these networks is not insignificant. And the article is talking about to train enough neural network, takes six lifetimes of a petrol driven car in terms of carbon footprint. [...] It's just a complete brute force approach and no one or very few people are taking a step back and saying, "Cool, let's continue to develop this capability of machine learning, but should we be a bit more organised about what we're using it for and why." And how we're working together on more of it to reduce the footprint on the planet because no one really is thinking about that right now. It will probably be too late by the time people start thinking about that. But taking a step all the way back then to the structure engineering. What that means is, for example, [...] like for a cable net roof structure. There's one answer. It's very quick. Maybe average structural engineer or other structural engineers when faced with the cable net structure for the first time would reach for finite elements or dynamic relaxation. Probably dynamic relaxation and not realising actually that you can get to the solution or 99% of the solution very, very quickly with one equation or one matrix. [...] Then you can choose whatever you want based on the building topology or the structure topology. Ultimately then going into finite elements or dynamic relaxation either for the very, very fine end analysis and as a second check to your initial equilibrate methods. (P05)

Computational tools have a carbon footprint that should be considered when developing them. Again communication may help to not solve the same problem multiple times, with multiple carbon intensive digital tools. Also, keeping the engineering knowledge is important to inform on the use of the correct method to solve a problem. This highlights the complexity of environmental sustainability and the number of factors to account for. As suggested by the participant, it could be beneficial to take a step back from computational tools sometimes as simple methods could be used. Again, there is no real guidelines to account for this carbon footprint and a good measure seems necessary. In this area too governments and institutions may have a role to play.

3.4 Conclusions and reflections

Interviews with architecture, engineering and construction (AEC) industry leaders working in structural consultancies of various sizes allowed deep insights on digitalisation of industry. Digital design is widely used to describe many applications. Computational engineering or computational design has been identified as a more appropriate term for

most topics covered by this qualitative study. The AEC industry has not embraced digitalisation as other industries may have. Some reasons for this are inherent to construction and cannot be changed, such as the uniqueness and the scale of the projects or the fragmentation of industry. However, industry is likely to have to embrace these new technologies to stay competitive and some factors against it are not as permanent. The uptake of computational tools in structural engineering consultancies and in the whole industry requires leaders, senior staff to enable it and to encourage it. Until recently, they provided more resistance than incentives to change but this is evolving. One of the reasons is that more computationally literate engineers are getting in leadership positions. The low margins in industry are also given as a reason against change and investment in computational tools, though increasing computational design does not necessarily require substantial investments and can lead to sizeable benefits, one of which could be increasing these low margins. Application on complex projects is one way of justifying investing in new technologies. However, further investment to develop the tools for wider applications is still lacking. Computational tools can also increase the rate of turnover of ideas and increase productivity. Moreover, engineers may already be developing computational tools through their own initiative so companies could benefit from that in the correct framework without great investments. Collaboration between structural engineering consultancies and other disciplines could help solve some of the simpler problems that everyone is looking at and move the conversation onto more complex problems such as climate change. This could help open up the AEC industry to computational engineering.

Other benefits include more efficient designs and engineers able to spend more time on creative tasks. Indeed, the increase of computational design is leading to a change in the role of structural engineers. Computers are not replacing them. It is important that engineers keep the technical knowledge of the fundamentals of structural engineering, as well as the communication skills that are necessary to convey ideas, but computational skills are also becoming essential. Combining these skills efficiently can reach great results. Engineers should not only be able to use computational tools but also modify or create new ones, tailored to their need. Keeping the domain specific knowledge to create the tools is important. Engineers however work in teams and best results can be achieved with a mixture of expertise areas. This change in skills expected in structural engineers asks the question of the role of university education. It is still essential for graduates to have a deep understanding of structural mechanics and analysis. Whilst the contents are not necessarily expected to change, the teaching methods could become more computationally oriented. Another side to universities is research. There is a healthy gap between academic research and industry and with this freedom, the former can lead to great innovations. Better communication between the two is not necessary but could be beneficial to improve structural design.

Computational design and technologies can be applied to a range of areas in the AEC industry. Historically, they have been used for the geometric definition of complex structures definition and constructability. Engineers have also been using computational tools for analysis since the 1960s (Plevris and Tsiatas 2018), first for complex structures but they are now also applied to automate simpler analysis. Automation can also be applied to tasks that are not structural engineering but that still are part of an engineer's role. Optimisation and parametric design are other tools than can allow for better, faster design depending on many functions, augmenting what engineers can do and the design space that they are looking at. Machine learning has potential but is currently more difficult to use in the AEC industry. It is necessary that engineers use these tools in combination with their technical knowledge and that they exert judgement at all times so that designs are safe but also answer real needs. It is also critical that engineers use the right software for each problem for efficiency, and interoperability is therefore essential. Some software companies are moving towards easier interoperability but in the meantime, engineers are solving these problems through in-house codes. They are making use of software that allows for easy customisation and development. For this reason and for its robustness, Rhinoceros 3D/Grasshopper 3D (RH/GH) is often used as a platform linking the relevant analysis software. Building information modelling (BIM) was initially seen as digital design and thought of being able to solve interoperability problems but it is actually limited and acts more as the back end of design where information is stored.

Other technologies are also picked up by industry, such as modular design. These technologies are not necessarily dependent on computational tools but they can help make it more flexible and customisable. It can lead to faster design and construction and reuse of materials, thus reducing embodied carbon in industry. Advanced robotics for off-site manufacturing and on-site use, such as 3D printing or drones, have a place in industry which could be growing. Computational tools can also facilitate communication between the different disciplines of the AEC industry. Improved communication combined with a shared base knowledge could help solve more complex problems and reach more efficient, integrated designs.

As mentioned, the AEC industry should aim to lower its carbon footprint. More efficient, lighter structures are one way to reduce embodied carbon by minimising material and waste immediately. A more effective solution to reduce embodied carbon would be to better evaluate alternatives at the feasibility stages but further research and a measure for sustainability would be necessary. However, clients going for the cheapest offer do not encourage companies to propose more sustainable but also more expensive alternatives. Governments may have a role to play in that as climate change is a real problem that requires action at country and global scale (UNEP SBCI 2009). The technology to produce

more sustainable structures is already here and is not dependent on computational design but there is a lack of commercial and regulatory drivers. Finally, a step back might be beneficial when using computational tools as they too can have a large carbon footprint.

Regarding the author's engineering research, some particular conclusions can be isolated. Even though material minimisation may not be the best way to reduce embodied carbon of buildings, it can still have a non-negligible impact and it can be applied now to all new buildings with tools such as the ones developed by the author. RH/GH is a good platform as it is used by many stakeholders in industry. The importance of using the appropriate software for analysis was highlighted, but the need for fast turnover was too. Companies are interested in increasing computational design use but engineers do not necessarily find the time to develop robust tools as they have to work on billable projects. Industry collaborating with academic research, establishing dialogue in order to share common goals, is one way to facilitate this uptake. This is what is being done by Robert Bird Group with the author's research.

Having completed this study, the author has noted some improvements in the methodology that could be made in future work. A wider spectrum of engineers could be interviewed, maybe from less computationally oriented companies, to give a perspective of the state of industry as a whole rather than of leading companies only even though the aim is to inform on the future of industry embracing more computational engineering. Interviewing engineers from companies based outside of the UK, such as Thornton Tomasetti, could also have given different, interesting ideas. SOM is another company with known interests in computational design and structural optimisation (Park and Holt 2010) and interviews with engineers involved in their research could be interesting. This could be done in the future with more time and budget but it is expected that similar conclusions would be reached. Improvements in the interviews could also have been made and were made as more interviews were conducted. When reading the transcripts, it appeared that some less interesting topics were sometimes investigated in depth whilst more meaningful comments were not always picked up by the interviewer and developed. This is something that potentially comes with practice and that requires deep attention for relatively long periods of time. Overall, theoretical sufficiency has been reached on most topics but better direction of the conversations could have made the process more efficient. The author also actively tried not to induce any bias when asking questions but despite that, it seems that participants may have given answers that they think the interviewer or their supervisor is expecting. This effect was minimal and unlikely considering the deliberate selection of the participants as individuals happy to give their opinion. The expertise of the author allowed for deeper conversations, outweighing this risk.

The aim of this qualitative study is not to provide specific guidance or conclusions on where the AEC industry needs to go in light of digitalisation. The hope was to provide a platform for leading engineers to share their thoughts and to gather knowledge that is not always easily accessible. It is informing the engineering research of the author but also much wider topics. Industry as a whole could benefit from more open conversation on these topics. This is not reflecting on the AEC industry as a whole, which is extremely fragmented, but on what a few, leading companies are interested in and on state-of-the-art technologies in industry.

Chapter 4

Concrete high-rise buildings: core optimisation

In this Chapter, the tool developed to optimise the core of concrete high-rise buildings is presented. The tool is tested on different case studies and discussed.

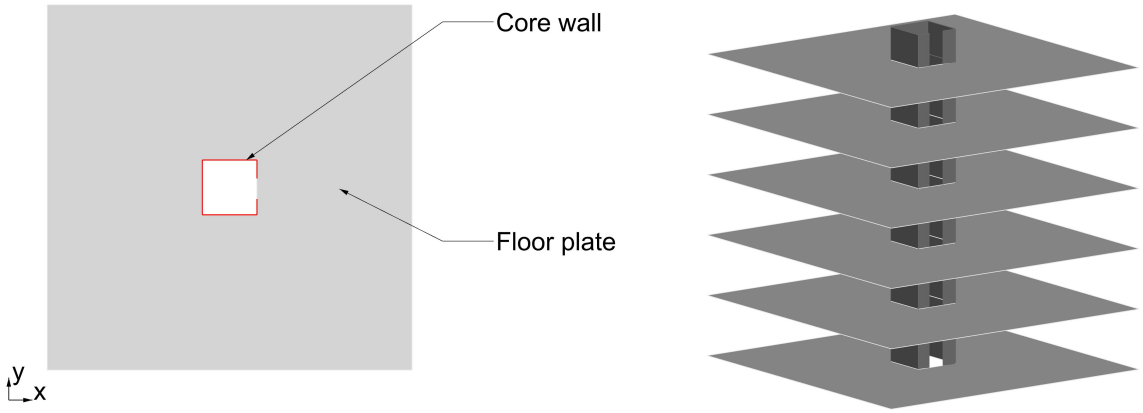
The author would like to thank Theodoros Mourtis from Robert Bird Group (RBG) for his advice during the development of the computational tool.

The tool is accessible to RBG engineers and it was reported that it was used on an ongoing project where a concrete core system was added to a 14-storey building in a relatively late design stage. The engineer estimated that using the tool enabled saving around 15 h of work. This was achieved using the tool on one project with a limited design space. If the tool was used on more projects with more core arrangement options, it could lead to a substantial number of hours that could be used to reach more creative or efficient designs.

4.1 Introduction

Vertical walls are a standard construction element that has multiple applications. They include isolation from the environment, acoustics, fire protection but also structural stability. They can be separated in two categories: non-structural walls, which includes partitions and cladding, and structural walls, which transfer in-plane forces to each other.

The latter can resist in-plane vertical, in-plane horizontal, out-of-plane horizontal forces or a combination of them (Gardner 2015). Tall buildings are an increasingly common structural form and are of interest here. They are subjected to high wind loads, which can be asusmed horizontal. There are various ways for such buildings to resist wind loads, and one of them is through shear walls. The role of shear walls is to resist in-plane horizontal forces (Gardner 2015). In parallel, tall buildings require lifts, staircases, toilets and other services, which are often located in at least one core. A core is illustrated in Figure 4.1. Shear walls can be arranged in a core, in which case it can have two functions: resisting lateral loads, typically wind, and housing communal services. This is a common set up for tall buildings and is the topic of this Chapter.



(a) Plan view. **(b)** Elevated view.

Figure 4.1: Illustration of a simple core arrangement.

Given their importance, a computational tool aimed at analysing structural cores has been developed. It was done in collaboration with industry to integrate the 'rules of thumb' used by structural engineers to reduce the design space, to ensure constructability awareness and to develop a tool that could be applied in practice. The core layout is often driven by architects and it is for engineers to analyse and check it. In early design stages, they may go through a relatively high number of core arrangements. 'Core arrangements' is used in this Chapter to describe the various ways shear walls have been combined to resist wind loading for a project. The computational tool aims to help engineers compare how the various core arrangements available perform when subjected to wind loading. The tool has been developed in Rhinoceros 3D (RH) (Robert McNeel & Associates 2018) and Grasshopper 3D (GH) (Rutten 2016) as it is widely used by architects and increasingly used by engineers, allowing for modelling, analysis and facilitated communication between key stakeholders. The tool can be used in multiple ways and at different design stages. Finite element analysis (FEA) of the core is done using

the GH plug-in Karamba (Preisinger 2013). Wall deflections and stresses can be visualised to easily compare the different core arrangements and the user can see the impact that changing wall thicknesses or other variables has. The tool additionally allows automating optimisation of core arrangements, minimising the mass, which is done using genetic algorithms (GA) through the GH component Galapagos. As discussed in Chapter 2, Ramboll has developed an automation tool exploring and sizing tall buildings (Jeffries 2018). It is possible that other companies have similar tools internally. However, it does not seem that the tool developed by Ramboll conducts analysis of the systems and it seems that it is mostly based on engineering 'rules of thumb'. The computational tool developed here is aimed at different applications, allowing more detailed design and analysis.

The methods used to create the tool are described. The tool has been tested and validated on various cases, which are presented. This is followed by concluding remarks and discussion on this core optimisation computational tool.

4.2 Methods

The tool has been developed with some requirements. The first requirement is for the tool to be user-friendly and to be usable on standard workstations. A software easily accessible in a structural consultancy office was necessary. The software Rhinoceros 3D/Grasshopper 3D (RH/GH) is a suitable option. It is a popular software amongst architects and is increasingly used by leading engineers as highlighted in Chapters 2 and 3. The tool only uses a limited number of GH plug-ins so that it can be used easily by different people. It does require the FEA plug-in Karamba which is not a free plug-in but is noticeably cheaper than other FEA packages. Further details on the software are given in § 4.2.1. Using Karamba fulfils the need for fast turnover in projects highlighted in Chapter 3. The tool has been developed thinking of the end user at all times. Another requirement for the tool is to enable the user to explore a wider design space than would be possible by hand or without parametric design but not to create a black box where an optimal solution is outputted without knowing exactly how. The tool is aimed to be used by structural engineers and to make use of their understanding of structural mechanics and their technical experience, increasing the use of computational design without replacing engineers, as discussed in Chapter 3. The requirement is also for the tool to be versatile enough that it can be applied to many projects and therefore be useful whilst still bringing enough depth and information on all the projects.

With these requirements in mind and with an aim to lower the embodied carbon in the core of concrete high-rise buildings, the tool has been developed. Information on the

software selected is provided. The problem formulation is detailed and the proposed optimiser is explained. An overview of the GH definition created for the tool with explanations of the key steps is provided in Appendix B.1.

4.2.1 Software information

The computational tools, discussed in Chapters 4 to 6, required to be developed in a suitable environment. Based on the conclusions from Chapters 2 and 3, the software RH/GH appeared as a suitable platform to develop the tools. RH is an accessible computer-aided design and drafting software. GH is a visual programming language that is part of RH that enables parametric design. A user-generated script in GH is called a definition. The tools have been developed in Rhinoceros 3D 6 and in Grasshopper 3D 1.0.0007. RH/GH is widely used by architects and increasingly used by engineers. One of the advantages for both professions is that developing tools in the same software environment can facilitate the dialogue between them in the design process. Another advantage of the software is that it is user-friendly, and can be used to output visual results. It is easy to extend and develop the software, which has a strong community and open-source influence.

The computational tools use particular aspects of RH/GH which are explained here. Galapagos is an evolutionary solver built in GH that enables GA and simulated annealing optimisation. It is a GH component that requires a genome, which is the variables of the optimisation in the form of GH sliders. Galapagos modifies the value of these sliders during the optimisation. Galapagos also requires a 'fitness' which is the objective function of the optimisation. Galapagos can aim to minimise or maximise the function. It accepts only one objective function. The user can set other parameters such as the population size in GA when running an optimisation.

Custom Python, Visual Basic and C# components can be created easily in GH and are used in the tools. One of the applications is to create of a modified Gene Pool component. Gene Pool is a GH component made of multiple sliders. Originally, the Gene Pool component does not take any input like other components do and the user manually selects the number of sliders in the component, the minimum and maximum values and the number of decimal places. A custom C# component has been created to automatically modify this Gene Pool component based on upstream information which is useful when there are a high, varying number of variables to be given to Galapagos.

Karamba is a parametric structural modelling plug-in of GH that enables FEA. Version 1.2.2 is used in the tools. Karamba has a free version with limited features. The tools

require the pro version which requires a fee of 1150 euros for a perpetual commercial license. This cost is significantly lower than other established finite element (FE) solvers such as Abaqus or Ansys. For shell elements, Karamba uses three-noded flat elements resembling TRIC-elements (Argyris et al. 1997, 2000) with linear shape function and one integration point, neglecting transverse shear deformation. The beam element definition is not explicitely provided in the documentation and is further discussed in Appendix C. Beam elements are two-noded and account for shear deformations. They are by default connected rigidly at end points, with six degrees of freedom per node (Preisinger 2016). The size of elements in Karamba is referred to as mesh resolution. By default, beam elements are not discretised in the analysis. Karamba also has a sizing optimiser that is used for beam elements in Chapter 6. By default, the load bearing capacity of the beam is considered, and limits on deflections can be used. In the tool, the sections are optimised for minimal mass. The optimisation follows these steps:

1. From the initial section, section forces are calculated at various points along the beam.
2. The first sufficient cross-section from the same cross-section family to reach a utilisation ratio less than 1 according to BS EN 1993-1-1:2005 (2005) is selected.
3. If no change happens in step 2 or if the maximum number of iterations is reached, the optimisation stops. Otherwise, the new section is selected and the iteration goes back to step 1.

If deflections are limited, they are checked once safety against structural failure is ensured. The design procedure can account for normal and shear forces, biaxial bending, torsion, buckling and lateral torsional buckling as well as maximum displacement (Preisinger 2016).

4.2.2 Problem formulation

4.2.2.1 Design variables and parameters

The optimisation can include up to five variables from various structural elements that are represented in Figures 4.2 and 4.3:

- The primary walls thickness t_p. Primary walls are the outside walls of the core(s).
- The secondary walls thickness t_s. Secondary walls are internal walls of the core(s) that are expected to have an impact against wind loading.

- The lintels depth d_{lintel}. Lintels are coupling beams in primary walls where there are openings (doors for lifts or staircases).
- The shear walls length l_{shear}. Shear walls are other walls provided additionally to the core walls to reduce deflections and torsion in the core arrangement and the building system overall.
- The shear walls thickness t_{shear}.

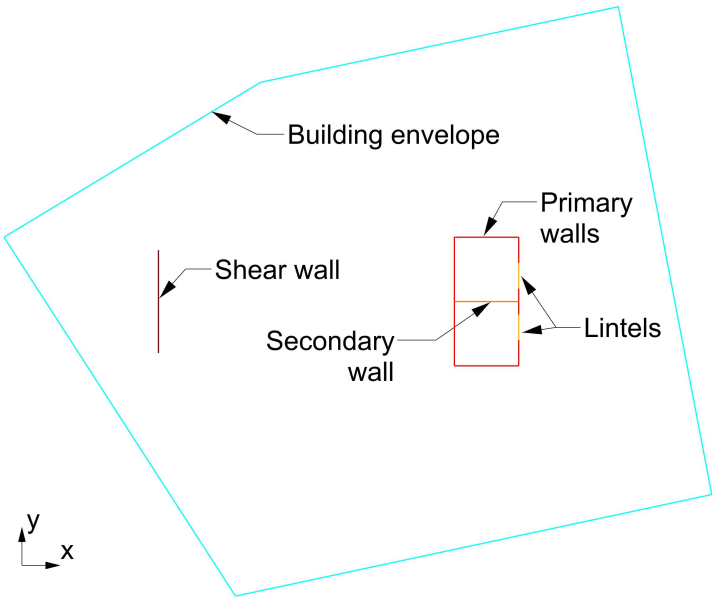
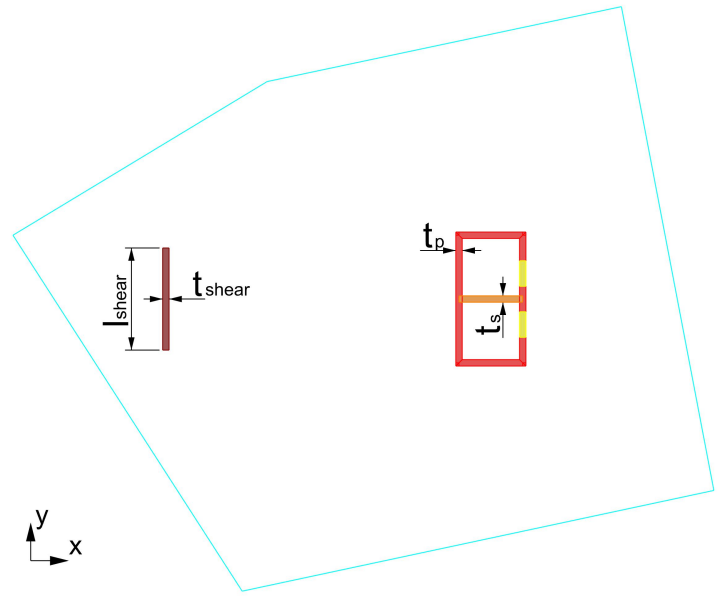


Figure 4.2: Sample plan view of the various structural elements that can be part of the optimisation process.

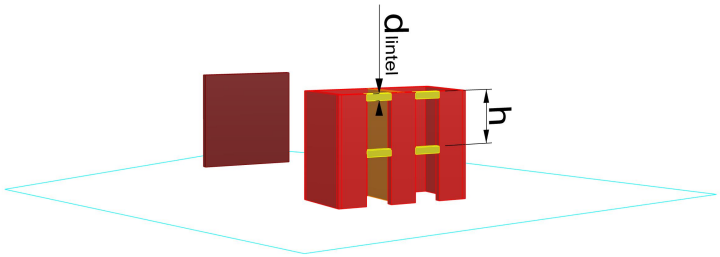
The user can select which of these parameters are to be used as variables and the remaining ones can be fixed and act as regular parameters. When using GA, the design space therefore decreases with a smaller number of variables. Whilst the automated optimisation can be run with up to five variables at once, the initial idea was to run multiple optimisations with only one or two variables each time, to see the impact each has on the structure. Engineers can therefore use their technical knowledge and experience in combination with the tool to explore the design space efficiently. It should be noted that in order to keep the tool efficient in time, simplifications have been made. One of them is that all the walls identified as primary have the same thickness and this is the case for the five variables. This was identified as a reasonable assumption to make, similar to what would be done in a design office. Additional simplifications are discussed in § 4.2.3.1.

The user can set a number of other parameters. These include:

- Any parameter previously mentioned that is not acting as a variable.



(a) Plan view.



(b) Elevated view

Figure 4.3: Detailed views of the structural elements that can be part of the optimisation process.

- The number of floors N.
- The height of each floor h, constant across the height of the building H.
- The wind direction, described in § 4.2.2.2.
- The slab load, described in § 4.2.2.2.
- The decrease of the primary and shear walls thickness with height: following what is commonly done for concrete cores, the thickness can be decreased in up to two steps of similar height by a reduction to be fixed by the user as long as the smallest thickness is greater than 0.2 m (this value can be changed by the user). For example, if there are 20 storeys and the thickness is to be decreased in two steps of 0.1 m with a starting thickness of 0.5 m, the first seven storeys starting from the ground floor will have a thickness of 0.5 m, the next seven storeys will have a thickness of 0.4 m and the last six storeys will have a thickness of 0.3 m.

- The lintel stiffness reduction factor: this is a simplification that can be done so that the lintels do not attract more shear than they would as the penetrations cause cracks to appear in the lintels, thus having a reduced stiffness compared to the walls (Fraser et al. 2008).

4.2.2.2 Loading

As the main role of concrete cores is to provide stability against horizontal loading, wind loading checks are the driving factor in the design of cores. As the tool is to be used early in the design process at the concept stage, a simplified envelope of the building can be used (Fraser et al. 2008). The tool is not suitable for more in depth calculations with a complex building envelope. The wind loading is also simplified for efficiency and to be applicable to a range of problems. Therefore more detailed analysis may be required for buildings taller than 30 storeys or with more complex building envelopes as the wind loading simplifications described below may not be applicable anymore (Deng et al. 2019).

In reality, the wind load acts on the building façade and is transferred to the core system through the slabs that act as diaphragms, creating a horizontal load on the core at the slab level and potentially torsion if the shear centre of the core is not concurrent with the shear centre of the building envelope. Beam elements are more efficient in FEA with Karamba than shell elements because of the reduced number of degrees of freedom per element. Because one of the goals is to have a efficient tool, simplifications were made to loading. Figure 4.4 shows the loading conditions.

For any direction of wind, the projected length L of the façade onto which the wind is acting is found. The simplified point load P in kN acting on the core at the level of every slab is:

$$P = L \times h \times w \tag{4.1}$$

where w is a nominal distributed load of 1.0 kN/m^2 to represent wind loading. The load at the roof level is halved because of contributing area, called tributary area, of the projected wall to each slab. The height of the tributary area used to calculate the load applied to each storey is equal to the storey height h but theoretically goes from the middle of the storey below to the middle of the storey above the slab, meaning that at the top the load is halved. The load is arbitrarily applied at the geometric centre, or centroid, of the building envelope which is not expected to coincide with the shear centre of the core system. The centroid has been selected for convenience rather that necessity and any other point could be used to transfer external loads in this model. This point is linked to

points on the core system edge by stiff beams which is shown in Figure 4.5. The walls are extruded with height and modelled as shell elements as discussed in § 4.2.1 and § 4.2.3.4.

In order to have an accurate loading scenario despite the simplification explained above, a moment can be also applied at the plate centroid. This occurs when the centre of the projected façade line onto which the wind acts is different than the centroid of the building envelope, which may occur when the envelope is irregular for example. The moment is therefore:

$$M = P \times e \tag{4.2}$$

where e is the eccentricity between the point of application of the load, the plate centroid, and the centre of the projected line of the façade as illustrated in Figure 4.4.

An alternative loading is possible to check the maximum deflection of the overall slab rather than of the core arrangement, which could be critical, or if frequency analysis is required. The tool was not developed to optimise the structure including dynamics but engineers may wish to check frequencies and modes in further design checks. This is explained further in § 4.2.3.1 but the loading condition is shown here. In order to conduct frequency analysis, mass needs to be provided. The slabs are therefore modelled as shells with a generic thickness of 0.250 m, which can be modified by the user. This is shown in Figure 4.6. Live and dead loads can be applied as uniformly distributed loads (UDL) onto the slabs. In this case, the stiff beams linking the centroid of the section to the primary and shear walls are not modelled. The wind load is then applied directly on the edge of the slab as a point load in the chosen directly in the middle of the projected façade line, as shown in Figure 4.7.

Because the load is not applied in line with the centroid but in the middle of the projected façade, there is no need to apply the extra moment M. A point load is used rather than a UDL on the slab edge for simplification as the point load magnitude is already calculated in the other load case. It was seen as a reasonable simplification given that dynamics are not the object of the tool and that the point load being applied in an accurate location should provide sufficient results at the stages the tool is aimed for. When using the tool on case studies in § 4.3, this loading scenario is only used to compare results with the use of rigid beams as frequency and mode checks are outside the scope of the tool.

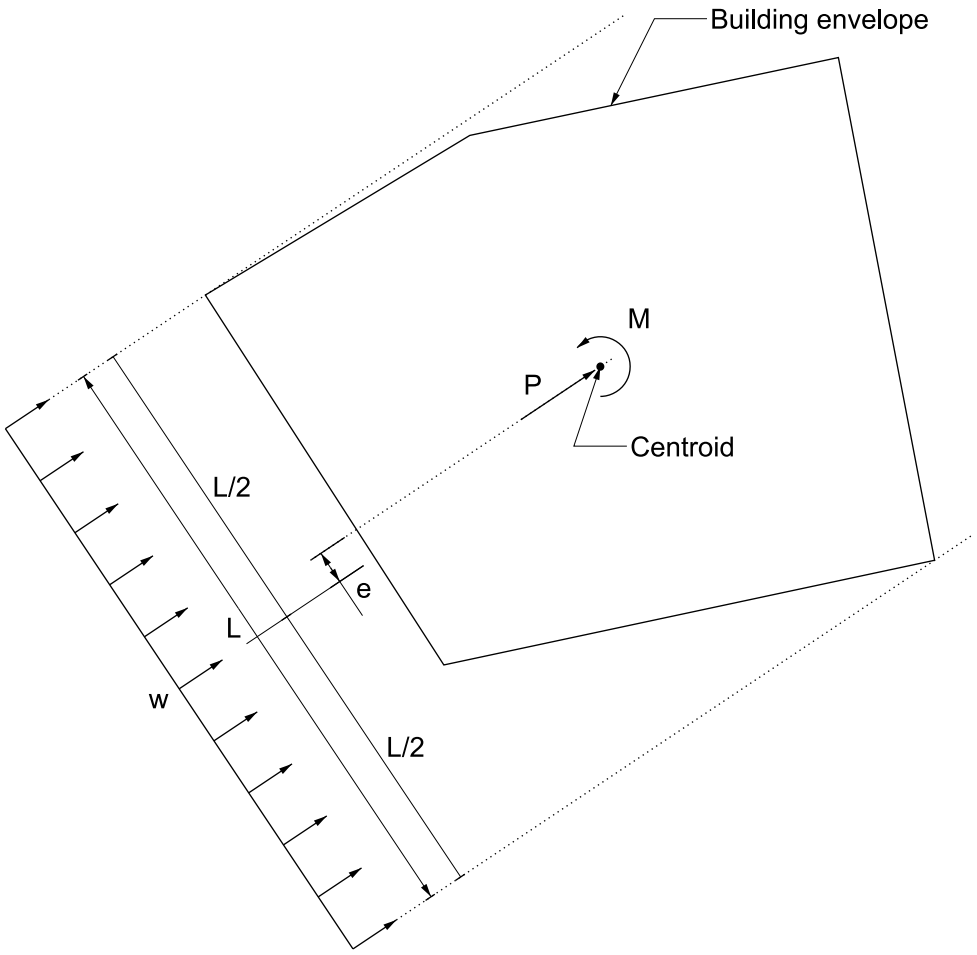


Figure 4.4: Illustration of the loading conditions used by the computational tool.

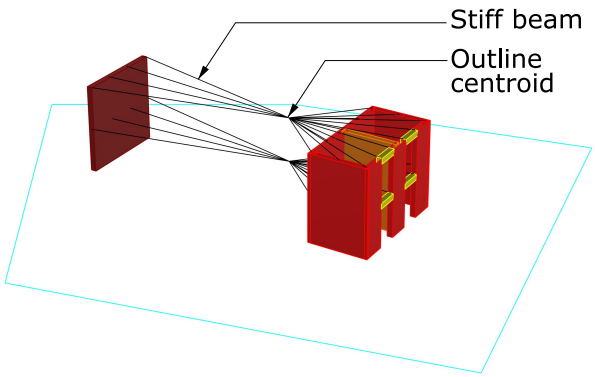


Figure 4.5: Illustration of the stiff beams connecting the slab centroid which is where the loads are applied to the shell elements modelling the primary and shear walls on two storeys in an elevated view.

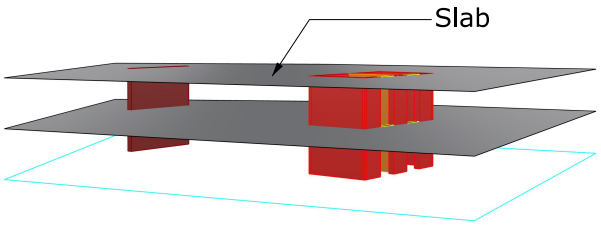


Figure 4.6: Illustration of slab modelling on two storeys in an elevated view.

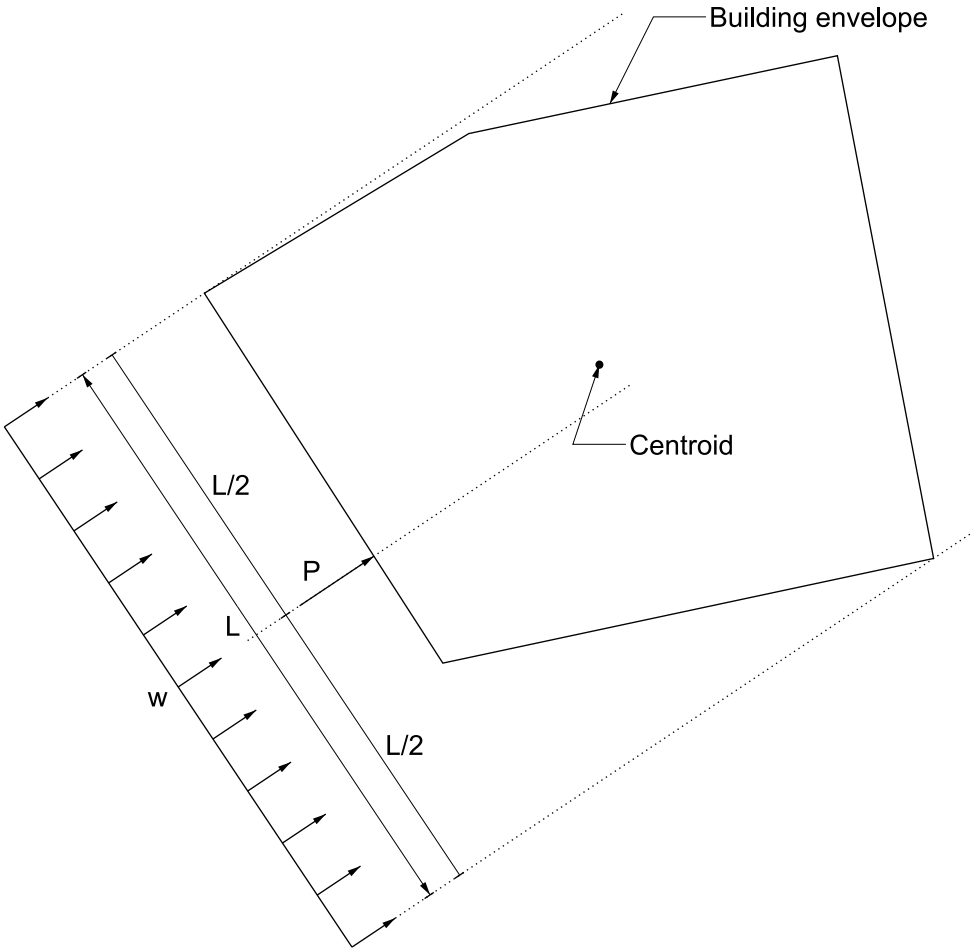


Figure 4.7: Illustration of loading conditions when modelling slabs.

4.2.2.3 Objective function

The overarching objective of the tool is to allow the user to easily compare the various core options available for a design. This comparison has not been automated but is facilitated by practical outputs such as the material volume or deflection plots. Each core arrangement available can be also optimised in an automated way and the objective function used for this is discussed here.

The objective function is to minimise the structural mass of the selected optimisation elements (core primary and secondary walls, shear walls, lintels). The optimisation is constrained by penalties that are added to the objective function to limit deflections, inter-storey drift and stresses.

The limit on deflections and inter-storey drift is set following BS EN 1992-1-1:2004 (2004) for serviceability limit state design as span / 500 but could be changed by the user. Deflections and rotation are often critical for concrete core stability systems (Fraser et al. 2008; Gardner 2015). Therefore, for any arrangement of the optimisation parameters, if deflections or drift are above this limit, a penalty significantly greater than the structural mass is added to the objective function, thus making this particular arrangement suboptimal. It should therefore be removed by the optimiser.

Stresses in the walls and in the lintels can be checked and added as a penalty to the objective function. The user can choose against what stress values to check to satisfy either serviceability or ultimate limit state design. For such designs, it is expected to get a small portion of cracking in the walls. The core is also modelled under wind loading only in the analysis whereas in reality it would be subjected to downwards live and dead loading, which may reduce tension on the side of the core exposed to the wind loading. For these reasons, the penalty added is proportional to the portion of the walls that fail compared to the overall surface and is small compared to the structural mass, as to not directly reject options where stresses are too high in only small parts of the walls. In this Chapter, the limits used are 2.5 MPa for the lintels stress and 10 MPa for the tensile stress and 23.5 MPa for the compressive stress in the walls.

The objective function with the added penalties can be expressed as follows:

$$\min \left(W_{material} + P_{defl} + P_{drift} + P_{stress} \right) \tag{4.3}$$

where $W_{material}$ is the structural mass of the selected optimisation elements with an order of magnitude O_W, P_{defl} is the added penalty when deflections δ are larger than the limit

δ_{max}:

$$P_{defl} = \begin{cases} 0 & \text{if } \delta \leq \delta_{max} \\ O_W \times 10^6 & \text{otherwise} \end{cases} \tag{4.4}$$

P_{drift} is the added penalty when inter-storey drift δ_{drift} are larger than the limit $\delta_{maxDrift}$:

$$P_{defl} = \begin{cases} 0 & \text{if } \delta_{drift} \leq \delta_{maxDrift} \\ O_W \times 10^6 & \text{otherwise} \end{cases} \tag{4.5}$$

and P_{stress} is the added penalty when the stress in each shell element σ_i is larger than the maximum allowable stress σ_{max} in the various structural elements:

$$P_{stress} = O_W \times \frac{\sum_{i=1}^{N} p_i}{N} \tag{4.6}$$

where N is the total number of shell elements and $\sum_{i=1}^{N} p_i$ is the number of elements breaching the stress limit where:

$$p_i = \begin{cases} 0 & \text{if } \sigma_i \leq \sigma_{max} \\ 1 & \text{otherwise} \end{cases} \tag{4.7}$$

4.2.2.4 Constraints

The variables have been constrained to reduce the design space to be searched in order to increase the speed of the optimisation. The constraints have been derived from 'rules of thumb' that are used by engineers in consultancies from conversations with RBG engineers whilst developing the tool. The constraints were set as follows:

- All wall thicknesses t: 0.2 m $\leq t \leq$ 1.0 m in 0.025 m increments. This comes from constructability awareness as wall thicknesses have been standardised for practicality and minimum reinforcement requirements. This means that each wall thickness variable has 32 possible values which are considered feasible.
- All walls set as primary are constrained to be the same thickness and it is also the case for all walls set as secondary or shear respectively. In reality there may be more variations in wall thicknesses but this determination has been selected to simplify the optimisation and keep it efficient and it aides constructrability as it reduces the chance of error. This tool is expected to be used upstream in the design process and fine-tuning could be conducted later on.
- The decrease of primary and shear wall thicknesses with height can be done in a maximum of two steps and with a decrease of 0.1 m per step as long as the thinnest

section is still ≥ 0.2 m. This is what is commonly done for tall concrete buildings and it can be changed by the user but cannot act as a variable in the automated optimisation as it is a common assumption and it keeps the optimisation efficient.

- The lintels depth d_{lintel}: 0.2 m $\leq d_{lintel} \leq$ 1.5 m in 0.025 m increments. All lintels throughout the building have the same depth as it is a common assumption and it reduces the design space. Again these constraints have been set for constructability considerations. It is expected that lintel depth would be driven by architectural requirements and can typically not be greater than the overall floor plate depth, it should therefore rarely act as a variable. The thickness of the lintels is set to be the same as the adjacent walls as would usually be done for construction.
- The shear wall length l_{shear}: modified by a scaling factor f_{shear} multiplied by the original length of the shear wall, $0.0 \leq f_{shear} \leq 3.0$ in 0.1 increments. All shear walls in a core option have been constrained to be modified by the same scaling factor for simplification, their original length is therefore important. This is a limitation deemed reasonable for the design stages that the tool is aimed at.

As for most parts of the tool, these constraints can easily be modified by the user depending on what is to be achieved so that the tool can be adapted for use on varied projects or to reduce the design space. The constraints settings have been chosen following these objectives.

4.2.3 Proposed optimiser

4.2.3.1 Modelling simplifications

The main aim of the tool is to rapidly and efficiently optimise the various core options available for a project in order to identify the most efficient one, based on multiple variables. It is expected that the tool is not going to result in large mass reductions but that it can allow engineers to investigate the options in short periods of time and therefore help make the design process more efficient, particularly when core design and overall structural design changes are made frequently in the early design stages. Frequency and mode checks of the structure should be conducted when designing cores at later stages. From conversations with engineers specialised in concrete core design in RBG, it was agreed that these checks would not be conducted in the design stages where the tool is intended to be used. Also, frequency analysis requires mass which can be achieved by modelling the slabs, requiring modelling them as shells. This would make the optimisation less practical as Karamba is more efficient in modelling beams than shells.

It was therefore deemed reasonable to ignore frequency checks in the optimisation of the core walls. Vertical loads are also ignored. This is a reasonable assumption as the aim is to identify the better performing core arrangement for lateral stability and while adding vertical loads may require resizing elements, it is not expected that it will modify the assessment of performance to resist wind loading. The slabs are however modelled in an alternative part of the definition with an appropriate load applied to them as discussed in § 4.2.2.2. This option has not been investigated for dynamic analysis as it is outside of the scope of the tool but further research and verification on this could be beneficial. However, it allows checking deflections of the overall structure rather than of the core arrangement only, which could be critical.

In order to keep the optimisation efficient in static analysis, beams are used to link the centroid of the plate to the nodes in plane of the primary and shear walls, mimicking the diaphragm action of the slabs. The loading is explained in § 4.2.2.2. Only the response of the horizontal stability system is investigated in this tool so it is a reasonable assumption. The stiff beams allow to transfer all loads applied in the centroid to the walls whilst preventing the walls from deflection in the floor plan. As the aim is to increase the stiffness of these dummy beams without creating real structural elements, the Young's modulus (E) and shear modulus (G) have been given very high values and the specific weight has been made negligible. This way, only the concrete core stability system resisting horizontal loading needs to be modelled with shell elements, increasing the efficiency of the tool.

4.2.3.2 User interface

In order to have an efficient and user-friendly optimiser, the required input information has been split between RH and GH. There are user information panels in the GH definition to help the user input the necessary information and to explain the main steps in the optimisation. In RH, the user can draw the outline, or envelope, of the building and the various information for each core option: primary, secondary and shear walls, and lintels. The outline of the building is constant with height, which is a reasonable assumption for the projects this tool is aimed at. For each core option, the user must also input specific points of interest where deflections should be checked if they are to be limited during the optimisation. Checks are automatically conducted for corners of the core arrangements. The information must be provided in layers and sublayers with specific names in order to be easily used in GH. To make this process easy, the tool can be used starting from an empty template with the layer system already set. This system is shown in Figure 4.8.

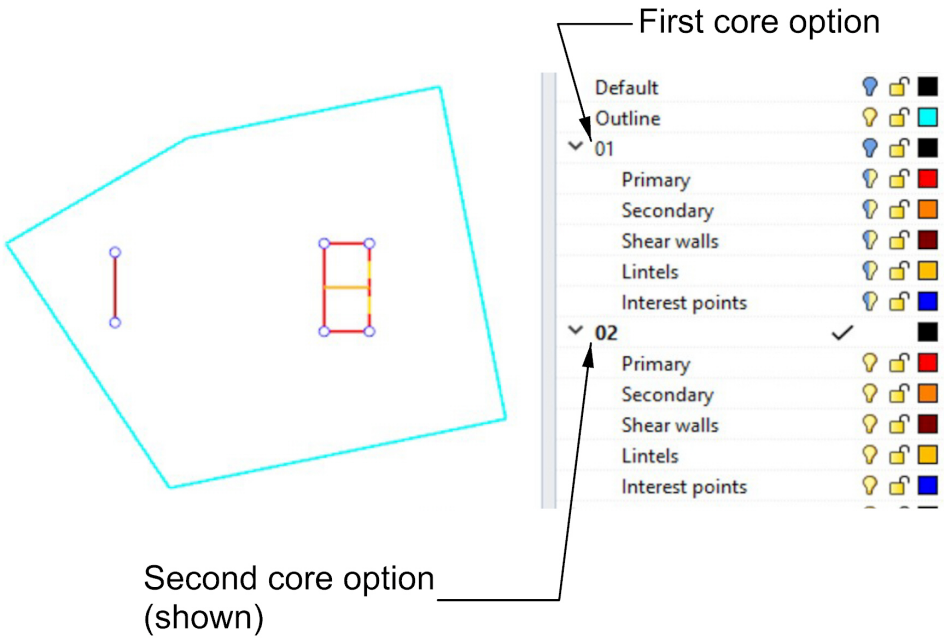


Figure 4.8: Organisation of the layers and sublayers in RH for user input.

The GH user interface is shown in Figure 4.9. First the user selects which core arrangement is to be analysed and/or optimised. The button is included to update the input from RH if the core arrangements have been modified. The next group is where the user can create the deflection and inter-storey drift plots at the point of greatest deflection either in the core arrangement or in the building outline. The third group is where the user can set the parameters. The first parameter is whether the primary and shear wall thicknesses decrease in height, in how many steps and by how much (§ 4.2.2.1). Next are the building parameters: number of floors and floor height. The following parameters to be set are loading and material. For the automated optimisation, the user should select the wind direction that leads to the highest displacement possible as to study the worst case scenario. The user can also observe how the structure behaves under various wind loading directions. The slab load can be defined if relevant (§ 4.2.2.2) as well as the concrete yield stress and a lintel stiffness reduction factor to account for cracking in the lintels due to shear. The last parameters to be set are stress and deflection limits. The last group is for the variable selection. The user can tick which parameters are to used as variables for the automated optimisation. The value showing on the corresponding slider in the VARIABLES box then becomes meaningless and the actual value appears in the panel named Optimised values. The properties that are not used as variables should be given a value on these first sliders.

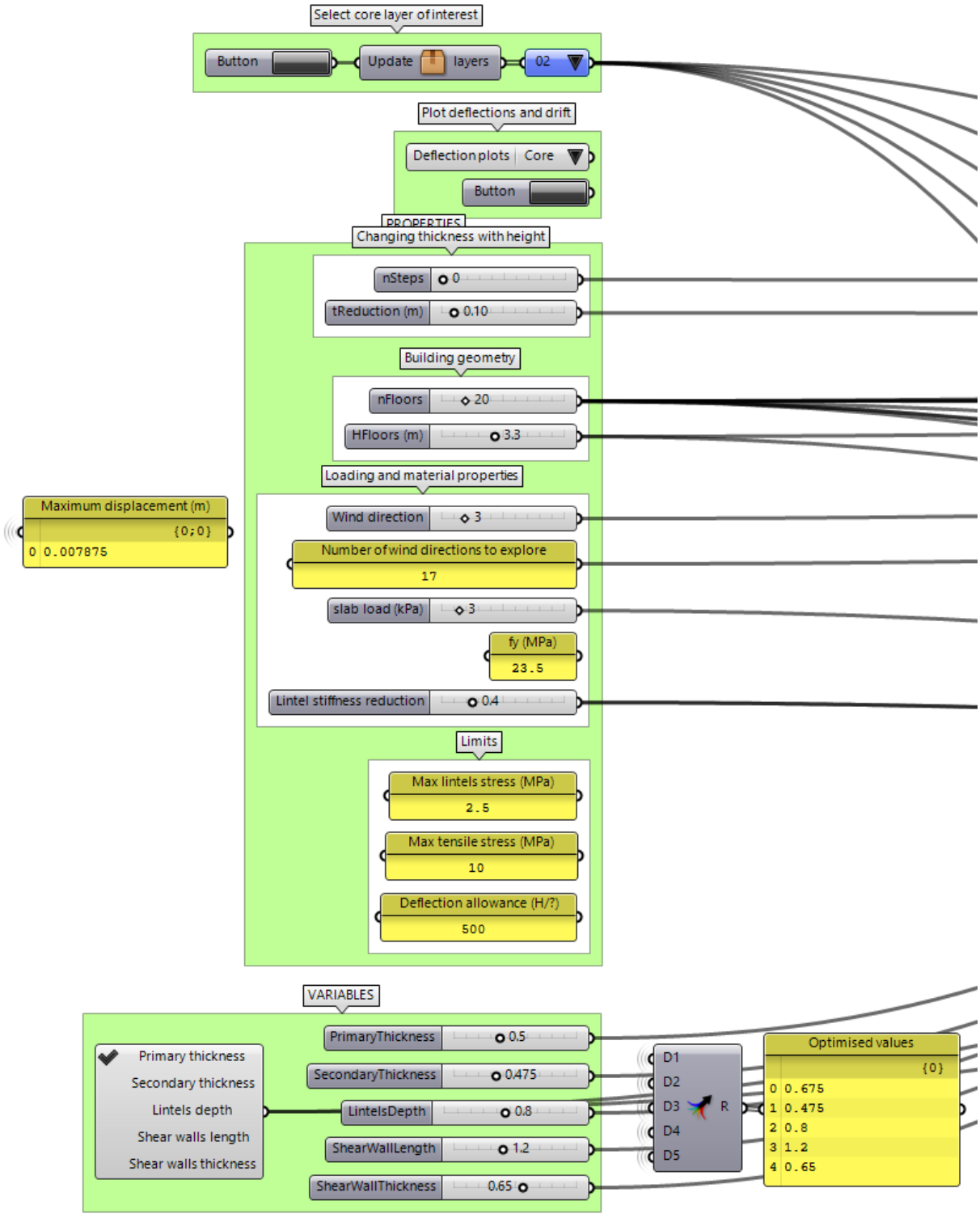


Figure 4.9: Input required from the user in the GH definition.

4.2.3.3 Optimisation process

As discussed in Chapter 2, GA implemented by Galapagos in GH are used to automatically conduct sizing optimisation of the core arrangement. A modified dynamic Gene Pool component, with the number of sliders informed by the variables selected by the user, is used as genome. The fitness function is given by the mass of the core arrangement with any stress and deflection penalties added. The GH definition follows these steps:

1. User to input relevant parameters in RH/GH, as detailed in § 4.2.3.2.
2. User to select variables of interest for the analysis.
3. Iteration:
   (a) Karamba used for static analysis followed by deflection and stress checks and the structural mass with relevant penalties is provided, as detailed in § 4.2.3.4.
   (b) Galapagos modifies the geometry with the variables through GA.
4. GA converges with optimised core arrangement.

As explained when discussing the objective function in § 4.2.2.3, this optimisation process is not the full objective of the tool. It is expected that the user would run this process multiple times with different variables to optimise each arrangement or manually optimise each arrangement. Then when all the core options available for a project are optimised, the user can easily compare them manually, through total mass of the core arrangement or using deflections. A custom Python code has been developed to plot the overall and x and y deflections at the point in the arrangement where they are the greatest, plot the inter-storey drifts and output the angle of rotation of the building. This feature can be particularly useful given that deflections and rotation are often critical in concrete core stability systems design. The plots are displayed in RH so that the user can easily see these plots and understand how the structure is behaving. Deflections, stresses, loads, reactions, utilisation and other data can also be plotted on the structure by Karamba.

4.2.3.4 Structural model definition

Karamba is used for structural modelling and analysis of each core. From the RH/GH input by the user, the core arrangement walls are extruded to the correct height. They are meshed and modelled as shell elements in Karamba, discussed in § 4.2.1, with the correct thickness and thickness variation with height if required. The mesh resolution

can be modified by the user. Primary and secondary walls share nodes to ensure contact between the shell elements. The lintels are added at the correct height and are modelled as beams with potential reduced stiffness according to the user input. Beam elements can be used to model the lintels in early design stages as they account for shear deformations as discussed in Appendix C and the stiffness reduction can be used to simulate the deformation at the junction of the walls and lintel beams (Fraser et al. 2008). The stiff beams are modelled with an arbitrary cross-section and the material properties described in § 4.2.3.1. Alternatively, the slabs can be modelled as discussed in § 4.2.2.2 and § 4.2.3.1. Each beam is modelled by a single element in Karamba.

The user can modify the wall material properties easily in the definition, however it is assumed that all walls have the same properties. Fully fixed supports are provided at zero height. It is reasonable to expect the core arrangement to behave as a vertical cantilever beam, however this can easily be modified by the user in the GH definition. The loading is applied as a point load and as potential moment due to eccentricity at the centroid of the plate at each floor level, linked to every in-plane node of the primary and shear walls through the stiff beams.

The model is then assembled and linear analysis is conducted by Karamba. The deflections and inter-storey drift of all the nodes that have been identified of interest are checked across the height of the core arrangement. Stresses in each element are checked against the provided limits.

4.3 Results

The tool has been tested on a range of case studies. The same material definition has been used for every model presented here. It is taken as reinforced concrete, with E of 34 GPa, G of 14.167 GPa, equivalent to a Poisson's ratio (ν) of 0.2, a specific weight of 25 kN/m^3 and a yield strength of 23.5 MPa. The lintel stiffness reduction factor is taken as 0.4. In FEA, materials are assumed linear elastic. A personal workstation (2 × Intel Xeon E5-2620 v3 2.40GHz 12 CPUs and RAM 64.0 GB) was used to run all models.

When needing to describe a particular face or side of a core arrangement, cardinal points are used, taking north point in the positive y direction of the plan view of the relevant arrangement. This is shown in Figure 4.10.

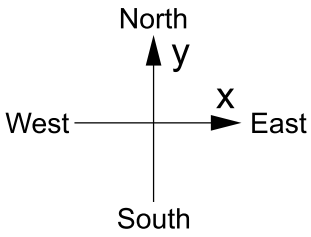


Figure 4.10: Illustration of cardinal point alignment with x and y axes.

4.3.1 Analytical validation

The first model presented is a simple square core with a closed section, used to verify the Karamba model against analytical calculations using simple centreline deflections and torsion when a moment is applied. The core used is 80.0 m high, with 20 storeys of four metres height each. The core is square hollow with each side being six metres measured along the centreline, with a wall thickness of 0.250 m. The point load or moment is applied through the centroid of the section, coinciding with its shear centre. Stiff beams go from the centroid to each node in plane of the core shell. When a point load is applied, it is applied in the x direction. This arrangement is represented in Figure 4.11. The model is tested under three loading scenarios, which are shown in Figure 4.12. The first is the most simple, with one point load applied at the top of the core. The second load case is more realistic, with a load applied at every storey. The last scenario is with a moment applied at the top of the core. The core dimensions were chosen to respect the assumptions of the simplified equations used for the analytical calculations, namely a slender beam as the deflection equations use Euler-Bernoulli assumptions, and a thin walled section to use the relevant torsion constant and rate of twist equations. The mesh resolution of the core shell elements and the number of stiff beams was varied to analyse the impact that they have on the accuracy of the results and on the analysis run time. The detailed analytical calculations are shown in Appendix D.1.

For the first case, shown in Figure 4.12a, a 1000 kN point load was applied at the top of the core. From centreline simplified hand calculations, the maximum deflection δ_{max} at the top of the wall can be obtained:

$$\delta_{\max} = \frac{PH^3}{3EI} \tag{4.8}$$

where I is the second moment of area, equal in the x and in the y direction for this cross-section with a value of 36.02 m^4. For this scenario, the maximum deflection at the top of the core is calculated to be 0.139 m.

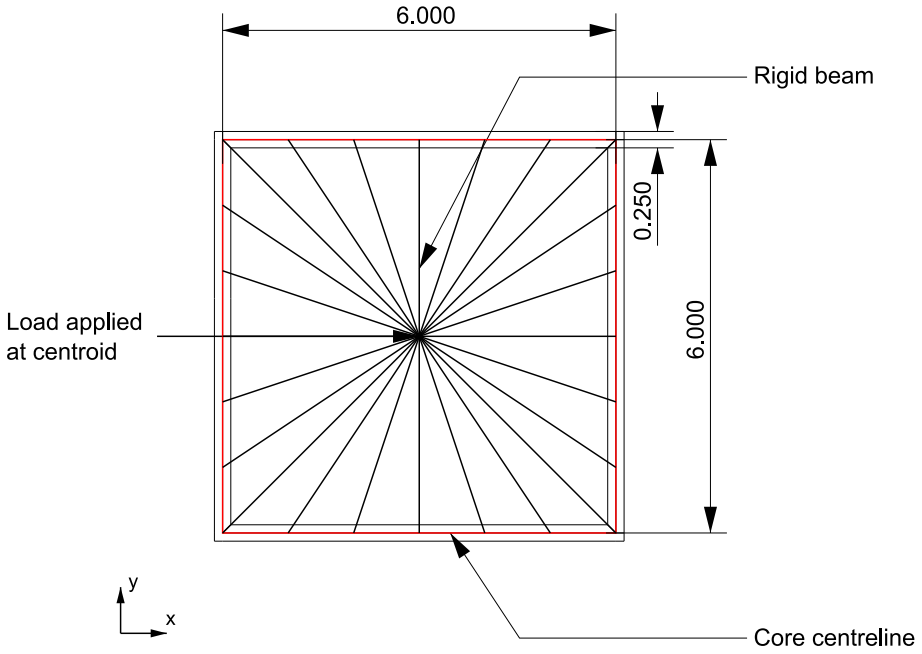


Figure 4.11: Plan view of core arrangement used for analytical validation of the RH/GH FE model. All units are in meters unless otherwise specified.

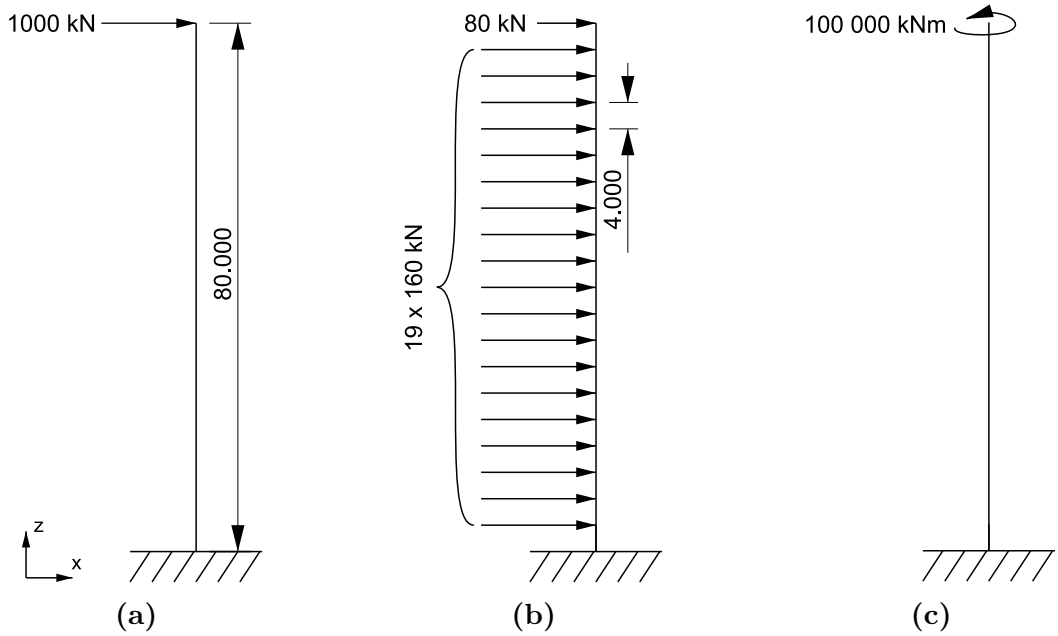


Figure 4.12: Loading scenarios tested in Karamba for analytical validation on simplified core elevation, represented by centreline: (a) one point load, (b) point load at every storey and (c) one moment. All units are in meters unless otherwise specified.

The percentage difference between the analytical solution and the mesh resolutions tested for different beam spacing is presented in Figure 4.13. The displacements obtained from Karamba used for the convergence plot are presented in Appendix D.2, Table D.1. The number of beams going from the centroid of the slab to each wall is represented by the approximate distance between two beams on the core wall. The result show that the driving accuracy factor is the mesh resolution and that the number of beams only has an impact on finer meshes. In Table 4.1a, the approximate time that the analysis component of Karamba takes to run when changing the wall thickness is given. In Table 4.1b, the number of mesh faces necessary to model the core with the prescribed mesh resolution is given. The run time of the Karamba component is approximately proportional to the number of mesh faces in the model. The data is presented for one beam distance for conciseness but the observation is true for any number of beams. This was expected as shells are computationally more demanding to model than beams. The run time of only one component is presented as it is the heaviest component in the definition when running the optimisation and makes a satisfactory surrogate to evaluate the speed of the definition. A suitable balance between results accuracy and run time is needed.

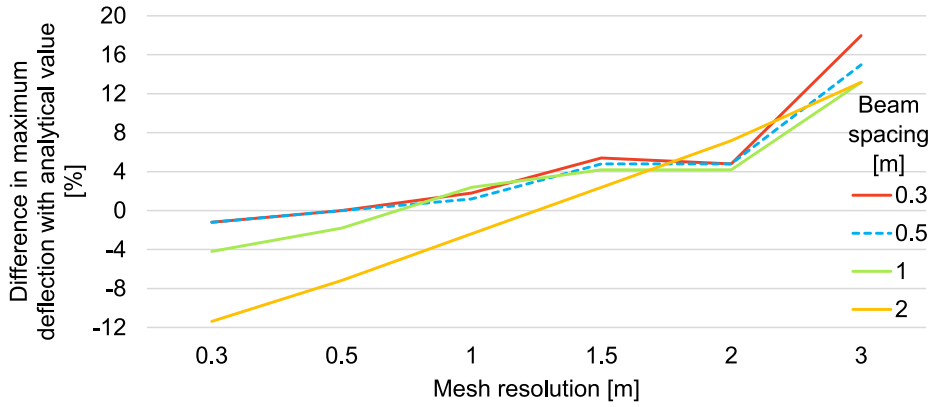


Figure 4.13: Convergence plots showing the percentage difference between the analytical maximum displacement and the maximum displacement obtained from Karamba for varying mesh resolution where each line was obtained from a different beam spacing for single point load.

A higher beam distance means fewer beams and appears to lead to greater difference in δ_{max} compared with analytical results. This could be due to the fact with fewer beams, it is more likely that the wall will deflect in plane, which is not desirable as the beams replace a diaphragm slab. Given that any number of beams leads to approximately the same run time, it is preferable to keep a low distance between them. Regarding the mesh resolution of the shell elements, when it is 3.0 m, the absolute error comparing with the hand calculations and with finer mesh resolution is greater than 12%, which is

		Mesh resolution (m)					
		0.3	0.5	1.0	1.5	2.0	3.0
Beam distance (m)	0.5	2300	900	250	130	100	70

(a) Approximate Karamba analysis component run time (ms).

		Mesh resolution (m)					
		0.3	0.5	1.0	1.5	2.0	3.0
Beam distance (m)	0.5	43800	15992	4200	1976	1192	616

(b) Number of mesh faces to model core walls.

Table 4.1: FE model size and run time for varying mesh resolution with 0.5 m beam spacing for single point load.

potentially unacceptable. The mesh resolution tends to converge when nearing 1.0 m or below, and matches analytical calculations. However the run times increase significantly. A mesh resolution at 1.0 m reaches a 2% or less difference with the analytical result and has a reasonably low run time. However, it is expected that with larger structures with more elements, the run time will increase. Depending on the design stage and tolerance, the user could choose a coarser mesh to increase the speed of the optimisation. A finer mesh can also give better results when conducting stress checks. Overall, based on the results presented in Figure 4.13 and Table 4.1, Karamba gives satisfactory results with a beam distance of 0.5 m and a mesh resolution of 1.0 m for the shell elements which are recommended.

The second load case is shown in Figure 4.12b with multiple point loads applied along the height of the core. This is a more accurate loading scenario for a core subjected to wind loading. The floor height is taken as 4.0 m and the load on the top floor (the roof) is half of every other load. The load values are taken as 160 kN on internal storeys and 80 kN on the roof. For a slender cantilever beam subjected to multiple point loads, the maximum deflection at the end is (The Steel Construciton Institute 2012):

$$\delta_{\max} = \sum_{a=1}^{N} \left(\frac{P(h \times a)^2}{6EI} \times (3(h \times N) - h \times a) \right) \tag{4.9}$$

where a is the storey number, N is the total number of storeys, $h \times a$ is the storey height multiplied by the storey number, equal to the height at which the load is applied for each slab, and $h \times N$ is the height of the core. For a storey height of 4.0 m with 20 storeys, the total maximum deflection at the top of the core is calculated to be 0.167 m. For such a simple loading condition, hand calculations are already proving tedious and time consuming compared with using computational power.

The percentage difference between the analytical solution and the mesh resolutions tested for different beam spacing is presented in Figure 4.14. The displacements obtained from Karamba used for the convergence plot are presented in Appendix D.2, Table D.2. The mesh resolution and beam distance have similar impacts on the results to those shown in Figure 4.13. The run time presented in Table 4.2a is however different than previously as a mesh resolution coarser than 1.0 m does not lead to a substantial run time reduction compared to Table 4.1a. This is again proportional to the number of mesh faces presented in Table 4.2b which does not decrease significantly either when the mesh resolution is coarser than 1.0 m. This behaviour is due to the loading beams being present at each floor, creating nodes in the core wall mesh, forcing smaller mesh faces than the resolution. This confirms the idea that the run time of the analysis component of Karamba, and of the definition in general, is approximately proportional to the number of mesh faces. It also shows that the run time is not significantly reduced for a mesh resolution higher than 1.0 m, which therefore should be used unless the beam distance is also increased. However, as can be seen in Figure 4.14, a higher beam distance leads to a larger difference so the user should be cautious when doing so. A beam distance of 0.5 m and a mesh resolution of 1.0 m is still advised and reaches satisfactory results. Analytical calculations use approximations, which is likely to explain why the convergence study in the two cases does not converge to 0% difference between analytical calculations and Karamba results but around -2%.

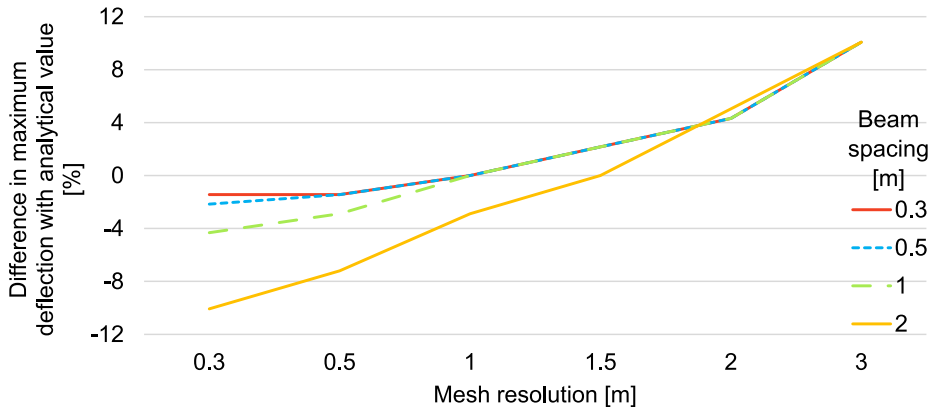


Figure 4.14: Convergence plots showing the percentage difference between the analytical maximum displacement and the maximum displacement obtained from Karamba for varying mesh resolution where each line was obtained from a different beam spacing for multiple point loads.

The third loading scenario presented is with a $1{\times}10^5$ kNm twisting moment applied at the centroid at the top of the core as shown in Figure 4.12c. This is to verify the behaviour of the core wall subjected to moment loading rather than point loads. The moment value

		Mesh resolution (m)					
		0.3	0.5	1.0	1.5	2.0	3.0
Beam distance (m)	0.5	2000	900	350	200	170	170

(a) Approximate Karamba analysis component run time (ms).

		Mesh resolution (m)					
		0.3	0.5	1.0	1.5	2.0	3.0
Beam distance (m)	0.5	41904	16000	5120	2928	2560	2080

(b) Number of mesh faces to model core walls.

Table 4.2: FE model size and run time for varying mesh resolution with 0.5 m beam spacing for multiple point loads.

is chosen to give results of a reasonable magnitude given that closed sections, which is how the core is modelled, are particularly resistant against twisting. The section can be taken as thin-walled because the wall thickness is significantly smaller than the width of the section. Given that the moment is applied at the centroid of the core, the maximum deflection at the top is:

$$\delta_{\max} = 2\sin\left(\frac{\phi_x}{2}\right) \times 3\sqrt{2} \tag{4.10}$$

where ϕ_x is the twist angle at the top of the core, equal to $\theta_x \times H$ at the top of the core where θ_x is the rate of twist of the cross-section subjected to a twisting moment T:

$$\theta_x = \frac{T}{GJ} \tag{4.11}$$

$$J = \frac{4A_c^2}{\oint \frac{1}{t(s)} ds} \tag{4.12}$$

where J is the torsion constant for a thin-walled closed section, which is the case for the section shown in Figure 4.11, A_c is the enclosed area, $\oint$ indicates the integration around the complete perimeter of the closed section, s is the perimeter position and $t(s)$ is the wall thickness at that point. For the cross-section shown in Figure 4.11, the torsion constant is 54 m^4. With a shear modulus G of 14.167 MPa, the twist angle at the top of the core ϕ_x is 1.05×10^{-2} rad or 0.599°. The maximum total deflection at the top of the core is therefore calculated to be 0.044 m.

In Appendix D.2, Table D.3 shows the detailed deflections obtained from Karamba. The analysis reaches similar results to the analytical displacement and angle with all mesh resolutions and beam spacings. The maximum displacements from Karamba vary from 0.043 m to 0.045 m, equal to a maximum absolute difference of 2% with the analytical

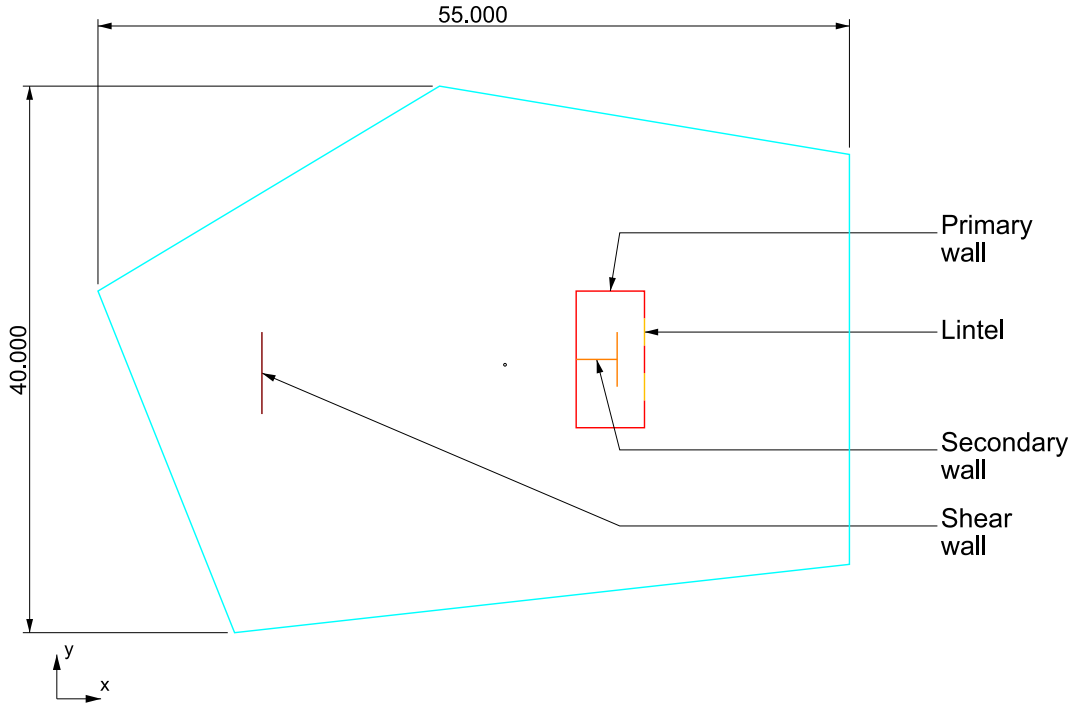
displacement. The corresponding twisting angle given by Karamba ranges between 0.597° and 0.604°, equal to less than 1% absolute difference with the analytical angle. The run times and number of mesh faces are not presented as they matched those presented in Tables 4.1a and 4.1b. This shows that the Karamba analysis outputs results that match analytical calculations for a closed section subjected to a twisting moment. It does not modify the conclusions made above on the choice of mesh resolution and beam spacing.

4.3.2 Numerical validation

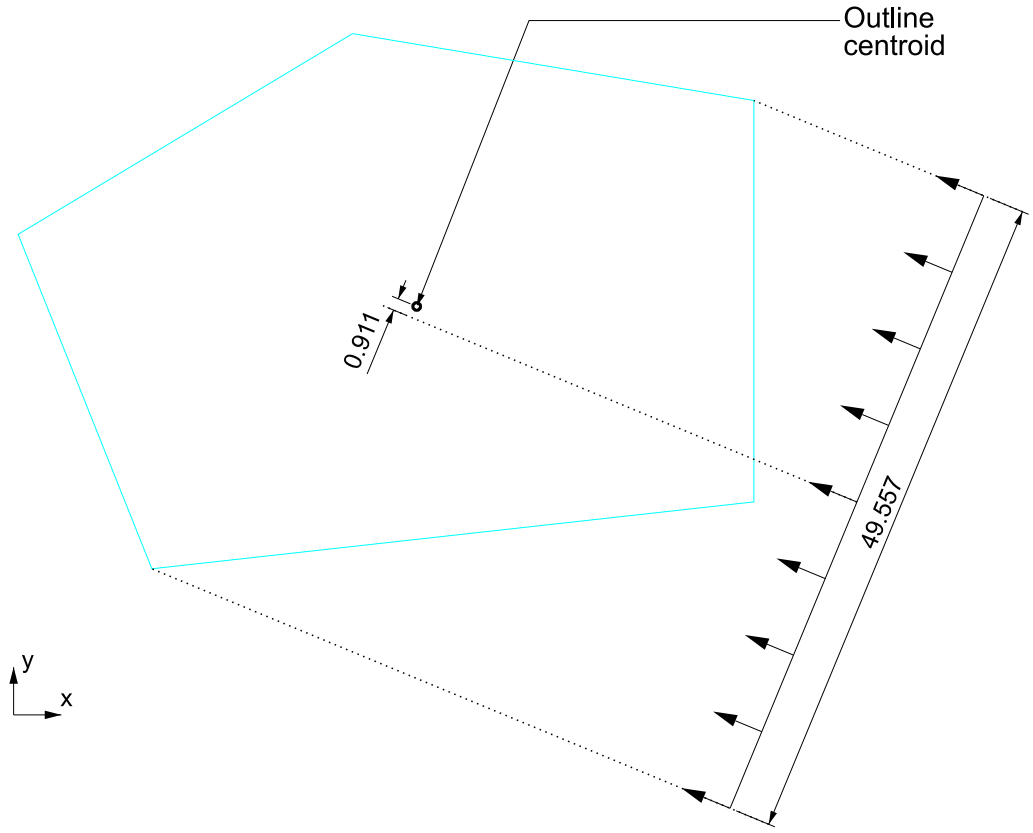
The second model presented is a more complex core arrangement with primary, secondary and shear walls and an irregular outline, presented in Figure 4.15a. The elevation profile selected is the same as the previous model: twenty storeys of 4.0 m height each, for a total height of 80.0 m. This core arrangement is used to numerically validate the Karamba results against a robust FE software, Abaqus (Dassault Systèmes 2013). The wind direction leading to the highest deflections in the core arrangement is shown in Figure 4.15b when a nominal 1.0 kN/m^2 distributed load is applied. The loading is therefore a 198.228 kN point load and a 180.586 kNm moment applied at the plate centroid of every storey, except on the roof level where it is halved. The core arrangement was optimised to minimise its mass, reaching the lowest limits for all the walls which therefore all have a thickness of 0.2 m. The lintels have a depth of 0.250 m. These dimensions are used in Karamba and in Abaqus.

In Karamba, the mesh resolution is taken as 1.0 m and the stiff beam spacing is 0.5 m. In Abaqus, the walls and lintels are modelled using homogeneous shell elements. General-purpose shell elements are used and two analyses are run, with 3-noded S3R elements for direct comparison and 4-noded S4R elements for further validation. These elements use linear shape functions with one integration point. The mesh resolution is taken as 1.0 m for the walls and as 0.250 m for the lintels. In Karamba, only triangular elements can be used for shells as discussed in § 4.2.1. The diaphragm action of the slabs is modelled using rigid bodies at each storey in Abaqus, using the Tie option to fix both lateral and rotational degrees of freedom. The point loads and moments are applied at each storey at the centroid of the outline which is modelled through a point that is part of the rigid body at each storey.

Figure 4.16 shows deflection plots with results from Karamba and Abaqus with triangular shell elements in the north end of the shear wall which is where the highest overall deflection of the core arrangement occurs. The deflection profiles are evidently similar, with a maximum absolute difference of 2% between the Abaqus and the Karamba



(a)



(b)

Figure 4.15: (a) Plan view and (b) loading conditions of the core arrangement used for the numerical validation of the RH/GH FE model. All units are in meters unless otherwise specified.

model. The Abaqus model with quadrilateral elements matches the Abaqus model with triangular elements within 0.5% difference in deflections. This confirms that the stiff beams used in Karamba as surrogates for the diaphragm action of the floor slabs are a reasonable simplification. Figure 4.17 shows the von Mises stresses of the outside surface in the Karamba model and both Abaqus models, plotted on the walls. Von Mises stresses are used as it is one of the only measures that can be used to obtained comparable plots in both solvers. The contour values from the two software match but the legend is reversed in Karamba compared with Abaqus and it was not possible to modify it. The maximum stress is higher in Karamba than in Abaqus, however this high stress value is only observed in a few shell faces in the north side of the shear wall near the floor. The results from the two software and with the two types of shell elements in Abaqus are again noticeably similar and comparing the stress values between the three models leads to less than 5% difference particularly for the highest stresses which occur on the north side of the primary wall. In Karamba, a static analysis was also performed modelling the full slabs instead of using stiff beams. The results obtained match within 1% those of Karamba with stiff beams. Modelling the slabs increases the run time of the analysis and is not expected to be used when the user modifies the model but can be used once the variables have been set to control the maximum deflection and rotation of the whole structure.

These results show that the FEA plug-in Karamba in GH reaches noticeably close results to those obtained with the more robust FEA package that is Abaqus. Both the analytical checks conducted with the previous model and the numerical checks show good agreement on deflections and stresses in Karamba. The computational tool developed is aimed to be used early in the design process and enables fast analysis of core arrangements, where the user is able to easily change the variables. This is not necessarily as easily and rapidly done in more robust FE packages. In Abaqus, the analysis run time is faster or similar to Karamba's, however the pre-processing necessary when modifying one of the variables before analysis is longer whilst this process is smoother and more intuitive in Karamba. The RH/GH interface is also more user-friendly. The computational tool also allows seeing the maximum deflection profile of the core arrangement and of the overall building easily by pressing one button with the custom Python component developed. Inter-storey drifts are also outputted, as seen in the next example. For these applications, the accuracy reached by this computational tool seems sufficient, given its benefits.

The computational tool has been validated both analytically and numerically. It is applied retrospectively to a case study.

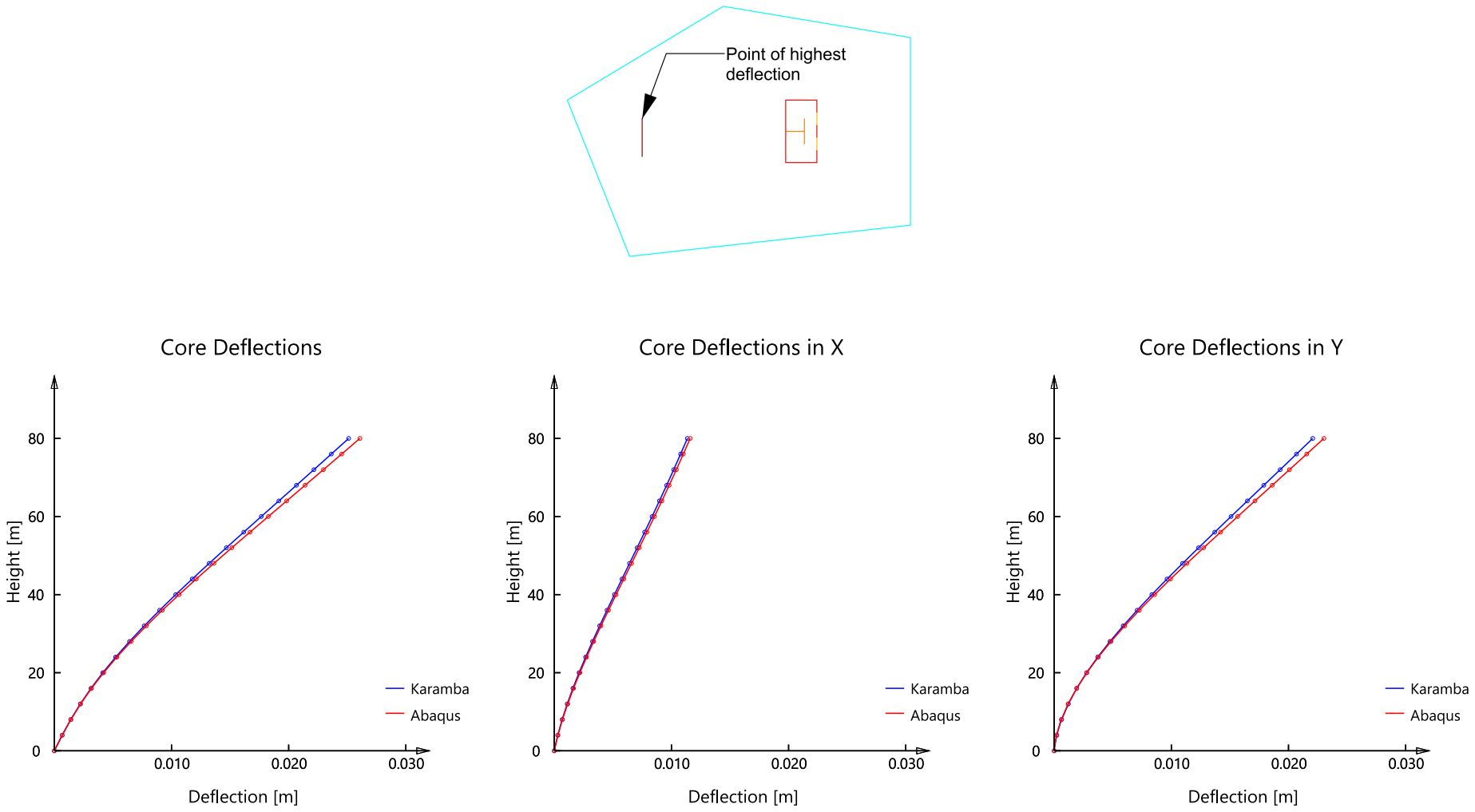
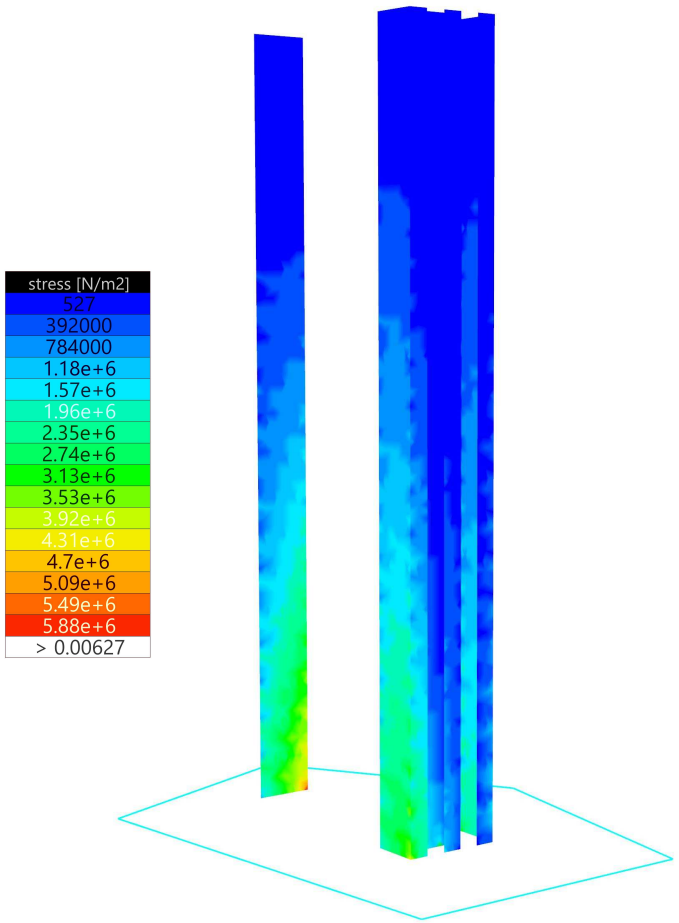
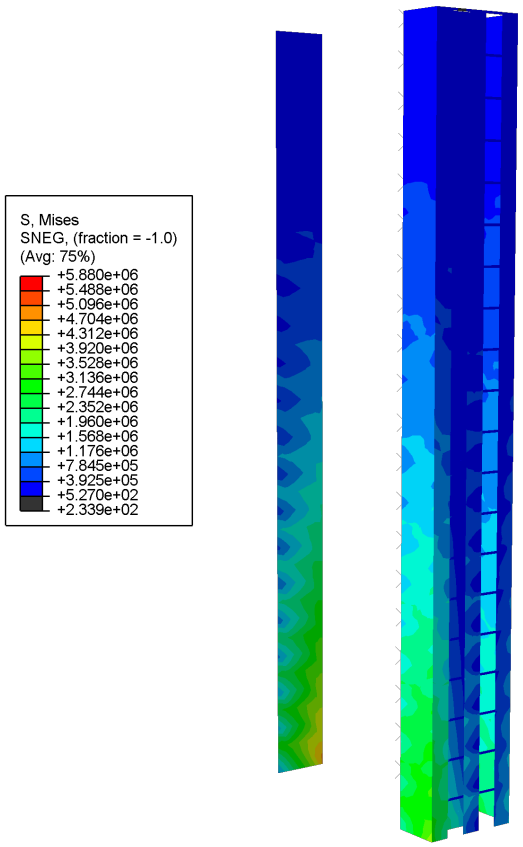


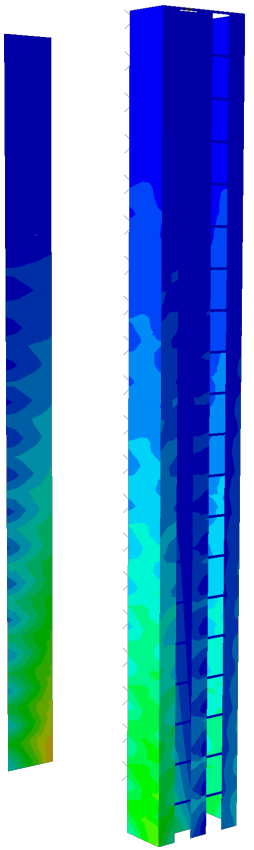
Figure 4.16: Deflection plots of the core arrangement used for the numerical validation of the RH/GH FE model from Karamba and Abaqus with triangular elements.



(a) Karamba results with triangular elements.



(b) Abaqus results with triangular elements.



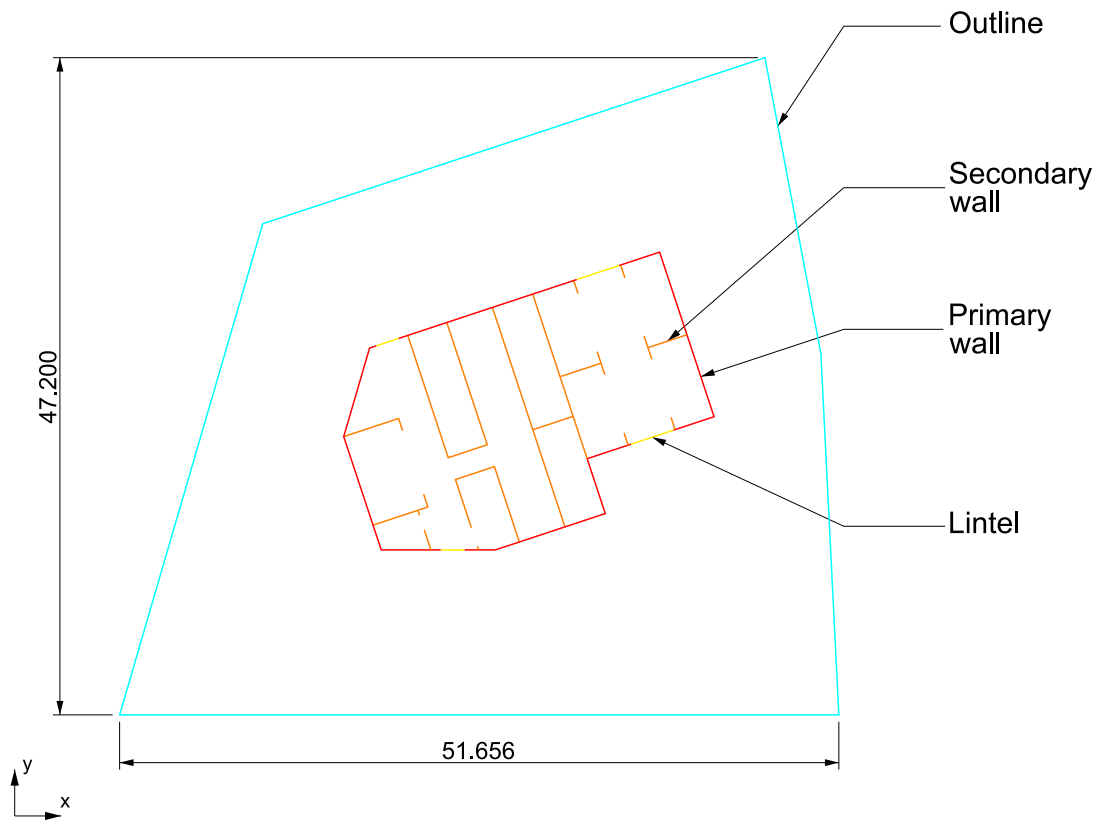
(c) Abaqus results with quadrilateral elements.

Figure 4.17: Von Mises stresses of the core arrangement used for the numerical validation of the RH/GH FE model. The Abaqus legend applies to both Abaqus models. The Karamba and Abaqus contour colours match but the Karamba legend is reversed compared with the Abaqus one.

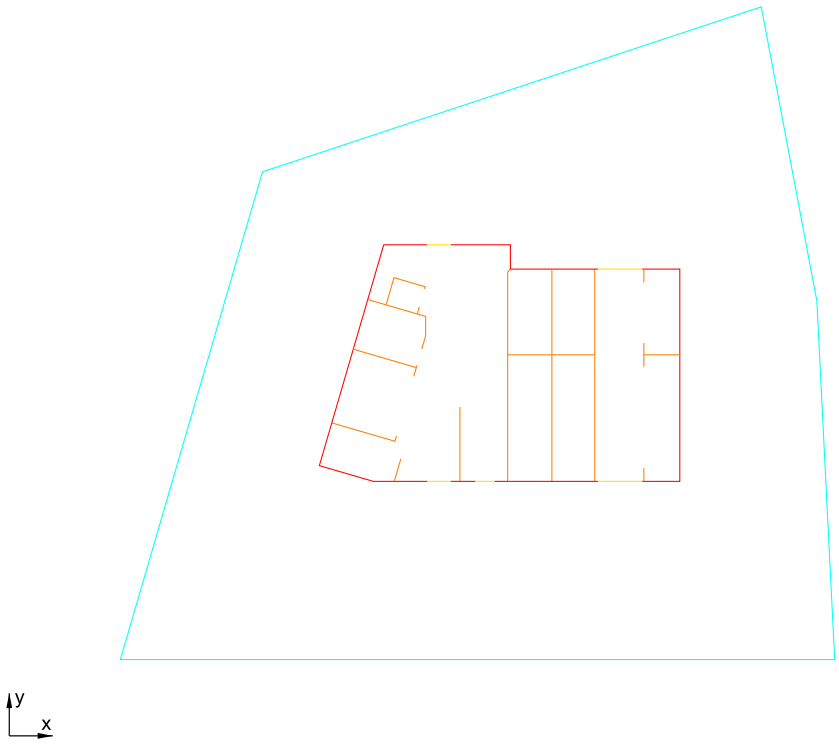
4.3.3 Retrospective case study

The core optimisation tool has been retrospectively used on a real project. It is an office and residential building with two core options. Drawings have been supplied by RBG. It is a 34-storey building with a floor-to-floor height of 4.0 m. The layout of the outline of the building and of the two core arrangements are presented in Figure 4.18. The main difference between the two core arrangements is the overall orientation where the first core arrangement shown in Figure 4.18a is aligned with the north face of the building envelope whilst the second core arrangement shown in Figure 4.18b is more aligned with the south face of the building envelope. Both arrangements have been simplified to only keep the secondary walls that are directly connected to the primary walls. This reduces the model size and is a reasonable assumption as secondary walls often are simple partitions unless they are needed to stiffen the core arrangement. Removing secondary walls is a conservative assumption. Both core arrangements only have primary and secondary walls and lintels, there are no shear walls. For both arrangements, the wind direction leading to the greatest maximum deflection is shown in Figure 4.19. This could be expected given that this direction leads to the highest projected length onto which the wind is applied and to a noticeable eccentricity. The loading is therefore 259 kN point load and 613 kNm moment applied at the plate centroid of every storey using a nominal wind load of 1.0 kN/m^2, except on the roof level where the loading is halved.

Galapagos was used on both arrangements, optimising the primary and secondary wall thicknesses simultaneously. The lintels depth is set at 0.250 m arbitrarily. After optimisation, the optimal value of the primary and secondary wall thicknesses is the lowest allowed, 0.2 m, for both core arrangements. The deflection and drift plots for each core arrangement are shown in Figures 4.20 and 4.21. They are both significantly below the limits. In both arrangements, less than 1% of the core walls mesh elements are above the stress limits and these are located at the bottom of the walls. The first principal stresses for both arrangements are shown in Figure 4.22. The overall maximum deflection is 0.103 m in the first arrangement and 0.082 m in the second arrangement. These results are coherent given the orientation of the core arrangements relative to the wind direction as the second arrangement should perform better in the given wind direction. The total mass of the first core arrangement is 11.03×10^6 kg whilst it is 10.83×10^6 kg for the second arrangement. This means that the maximum deflection is 25% lower in the second arrangement, which also has a mass 1% lower. It therefore seems a more suitable option even though the deflections of both arrangements are noticeably within the limits. The stresses in the second core arrangement are higher than in the first but they are significantly below the yield stress of concrete both in tension and in compression. The rotation of both core arrangements, shown in Figures 4.20 and 4.21, is negligible too. RBG



(a) Core arrangement 1.



(b) Core arrangement 2.

Figure 4.18: Plan view of the two core arrangements and the building outline for the case study. All units are in meters unless otherwise specified.

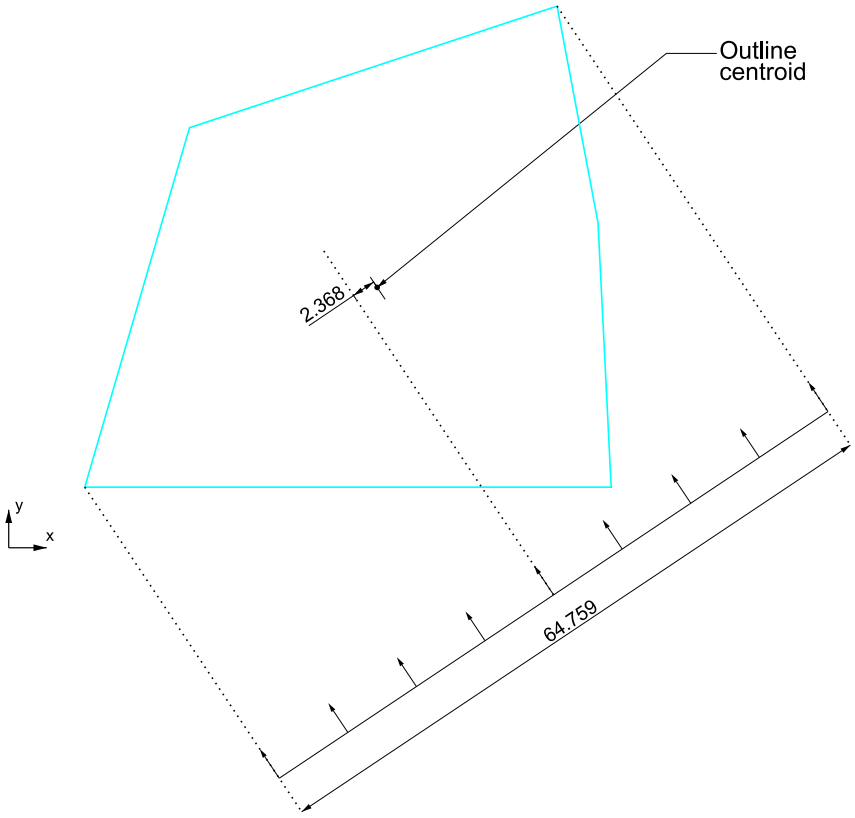


Figure 4.19: Loading conditions of the core arrangements of the case study. All units are in meters unless otherwise specified.

engineers reported that the first core arrangement had been used. They had identified that the second arrangement performed better but given that both arrangements are below deflection and stress limits, architectural considerations drove the final decision. They however reported that they were not able to optimise the wall thicknesses on both layouts because of time constraints and even though similar conclusions were reached on this particular project, the tool may enable engineers to easily explore the design space and make more informed decisions.

The size of these models is significantly greater than of the ones discussed in § 4.3.1 with approximately 50000 elements for a mesh resolution of 1.0 m, so around ten times more than for the analytical validation model. This means that the run time of the analysis component is longer, requiring around 2500 ms to run. Therefore, for each core arrangement, the run time of the optimisation with Galapagos is around three hours if all options of primary and secondary wall thicknesses are analysed. As discussed previously, this could be improved by increasing the mesh size but could lead to more unreliable results. However, it is not expected that using the Galapagos optimiser would reach substantial material savings as the design space is relatively constrained and core arrangements are often efficient when using standard design methods. The main aim of the

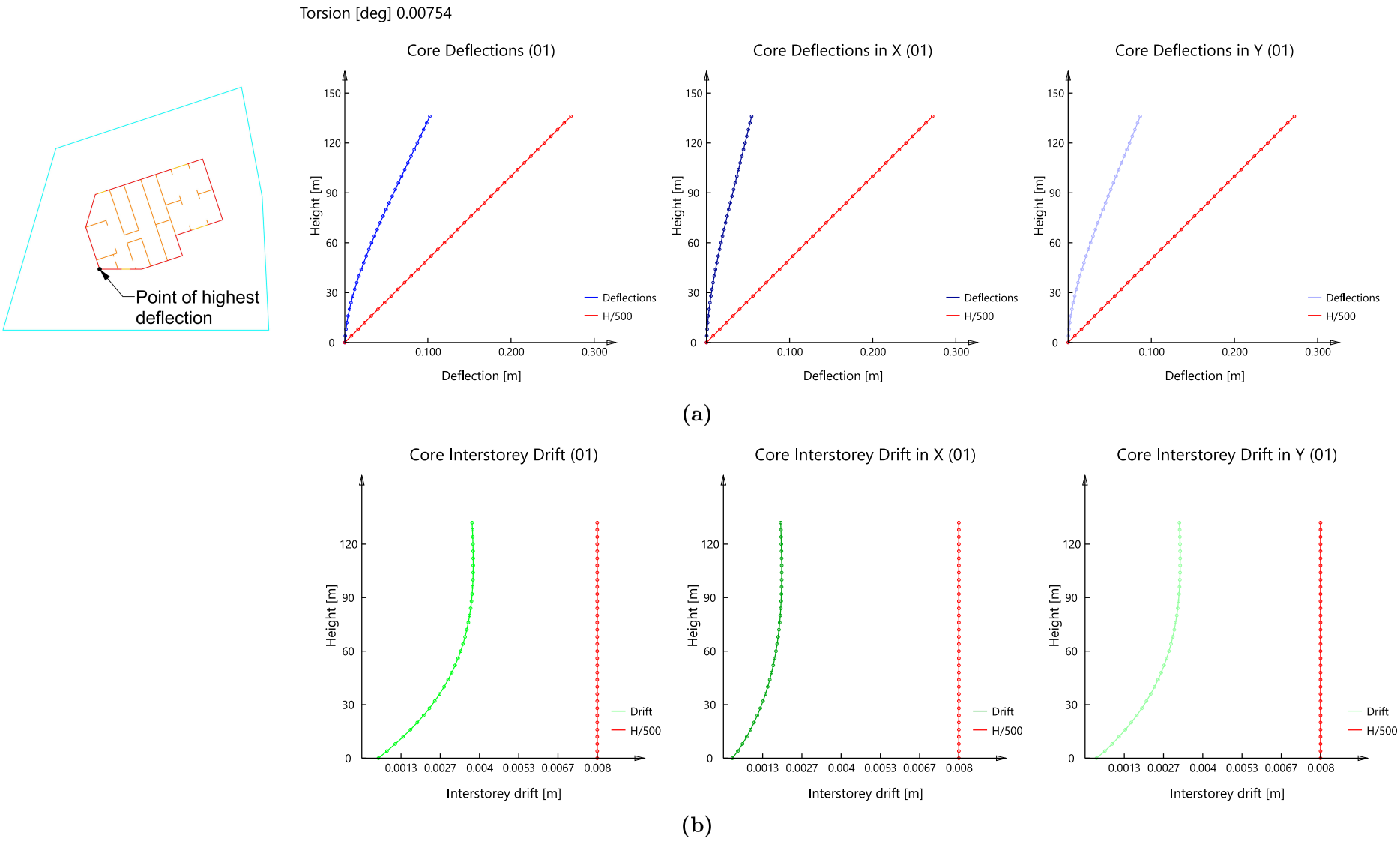


Figure 4.20: Maximum (a) deflection and (b) inter-storey drift plots for the case study's first core arrangement.

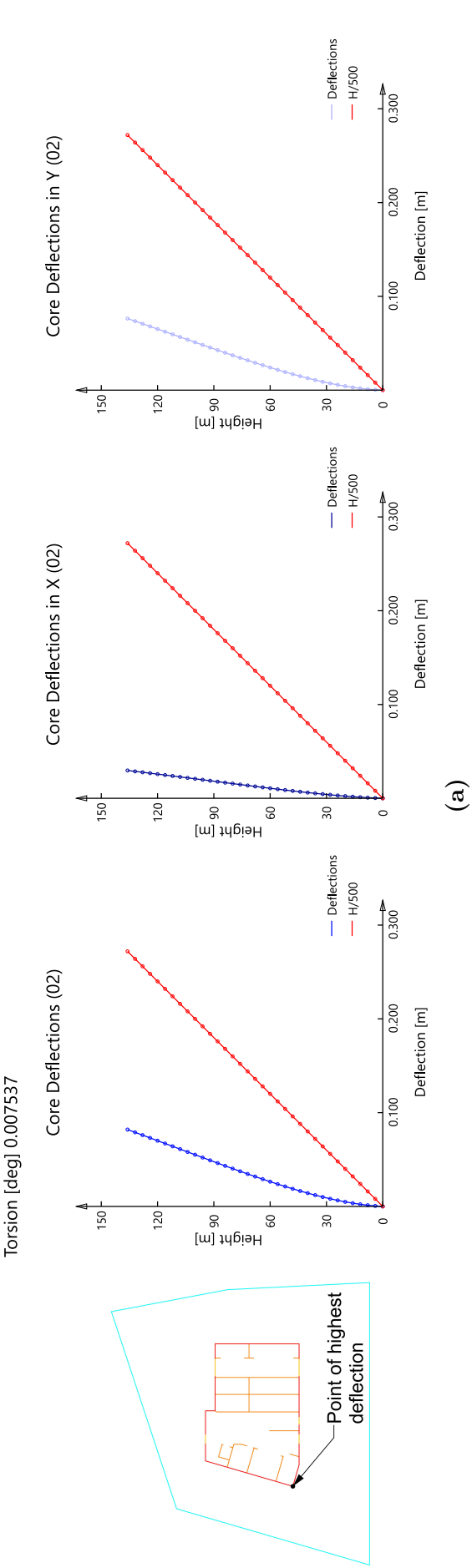
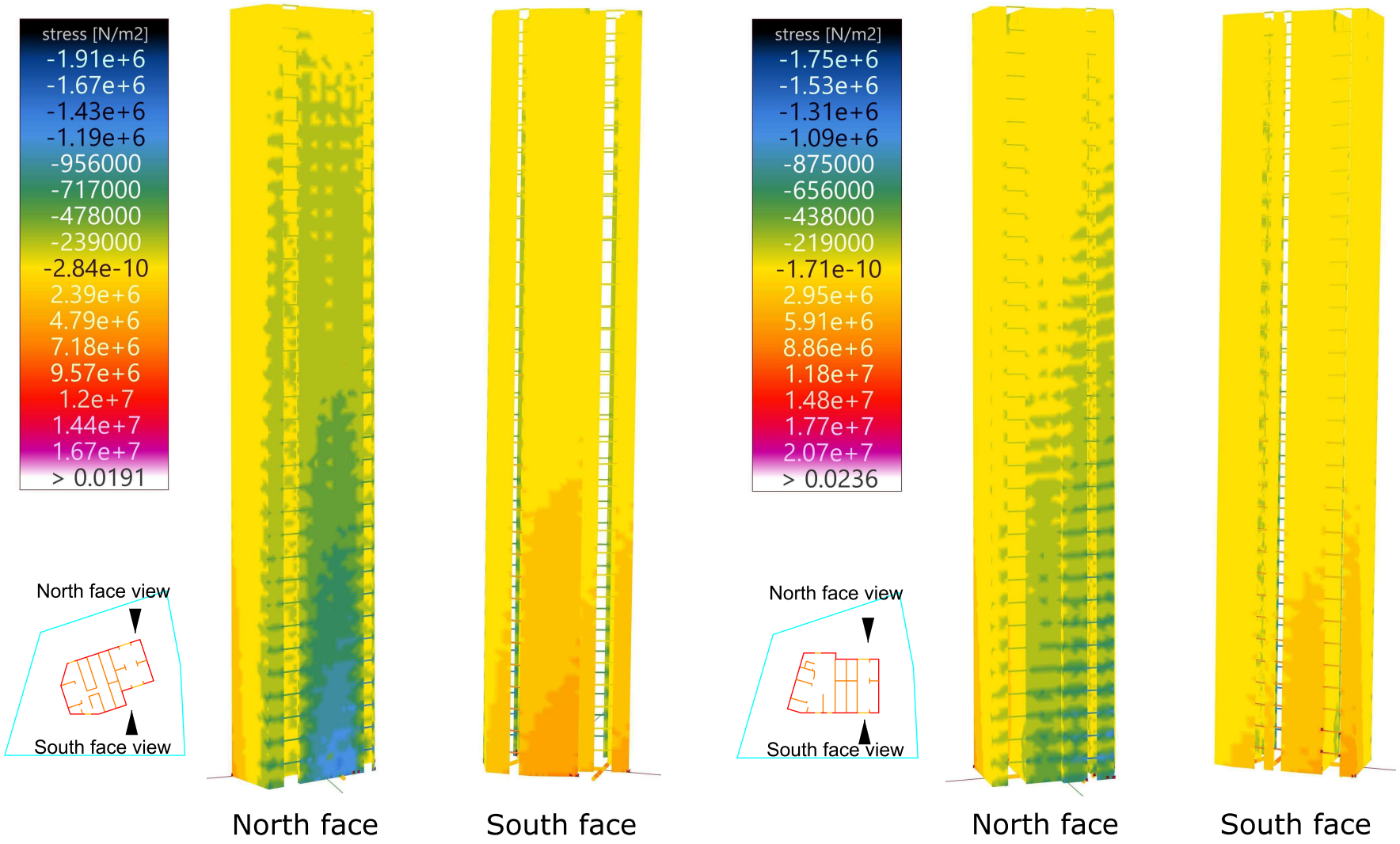


Figure 4.21: Maximum (a) deflection and (b) inter-storey drift plots for the case study's second core arrangement.



(a) First core arrangement.

(b) Second core arrangement.

Figure 4.22: First principal stresses in the two core arrangements of the retrospective case study.

tool is to easily assess the various core arrangements for a project in early stages through FEA. It allows the user to rapidly get feedback on the response of the arrangement under various wind loading conditions, to see the impact of changing one of the variables, check deflections and stresses. Given the automated optimisation run time, it is suggested to use it with a coarse mesh to get a reasonable starting point and then refine the mesh to manually investigate the design options. The main aim is for the user to use their technical expertise in combination with the tool to draw meaningful conclusions regarding the performance of core arrangements.

4.4 Conclusions and discussion

A computational tool aimed at facilitating the optimisation and analysis of concrete core stability systems has been developed. It has been developed in partnership with industry to integrate the 'rules of thumb' that would be used by engineers to increase the efficiency of the tool, reducing the design space available and ensuring constructability awareness in the design. The tool has been designed for engineers to use in conjunction with their technical knowledge to analyse and compare the various core arrangements that maybe available for a project in the early design stages. It has been developed in Rhinoceros 3D/Grasshopper 3D (RH/GH), ensuring its user-friendliness but also enabling finite element analysis (FEA) with the Grasshopper 3D (GH) plug-in Karamba. The user can compare the various arrangements subjected to wind loading with varying primary, secondary and shear walls thickness, shear walls length and lintels depth. Genetics algorithms (GA) can be used with the component Galapagos to automate the optimisation of a core arrangement, minimising its mass with deflection and stress checks, with one or multiple variables. Deflection and inter-storey drift plots can also easily be displayed in the RH/GH environment.

4.4.1 Assessment of the computational tool

The analysis part of the tool has been validated both analytically on a simple core arrangement and numerically on a more complex core arrangement using the FEA software Abaqus. In order to keep the GH definition efficient, stiff beams are used in Karamba to mimic the diaphragm action of the slabs. The results from Karamba reached satisfactory results on both cases with less than 2% difference for deflection calculations, which are often critical when assessing concrete core stability systems. Less than 5% difference was observed when comparing von Mises stresses in the walls from Karamba with Abaqus.

Given the scope of the tool, which is aimed to be used in the early design stages, and given that stresses are often not the critical check, these results seem reasonable. The run time of the analysis component of the tool is similar or longer than that of more robust FEA packages. However, the overall time necessary to modify and re-analyse the model is shorter and the interface is more intuitive. This may be important early in the design process when multiple core arrangements are available and architects may change the design regularly. The run time of the analysis and the accuracy of the tool are directly impacted by the mesh resolution used to model the walls. A finer mesh reaches results closer to analytical and numerical calculations but leads to a longer run time. Based on the case studies, a 1.0 m mesh resolution is suggested to reach sufficient accuracy in a reasonable time for buildings with a simple building envelope in early design stages. In more advanced design stages or with a complex building envelope, a finer mesh is recommended though the tool may not be suitable for such cases due to the simplifications made. The tool enables using FEA earlier in the design process than may be done with standard design methods whilst using engineering 'rules of thumbs' to output useful results. It allows exploring the design space efficiently. It was reported that the tool saved 15 h of work to compare a limited number of core arrangements on one ongoing project. The tool requires easily accessible software, can be used on standard workstations and the FEA software used is substantially cheaper than more robust alternatives.

4.4.2 Recommended use of the tool

The tool should be used early in the design process to optimise and compare core arrangements for a project. It can also be used in later stages. It can be used by engineers with different levels of computational literacy. Engineers can simply run and analyse models using the tool or modify it to adapt to their needs. A simplified building envelope can be used and the various core arrangements are drawn in Rhinoceros 3D. Once the necessary information is inputted in GH, the user can automate the optimisation of each arrangement using GA to minimise the mass. This is not the main aim of the tool as it can be long and it may not reach large improvements compared with standard design methods. If the automation is used, the user should first identify the wind direction leading to the highest deflection to optimise for the worst case scenario. It is then recommended to use the available variables independently to understand how each influences the system. A coarser mesh can be used to reduce the run time of the automated optimisation. In this case, the user can run the optimisation to get broad results and then adjust the variables manually with a finer mesh. Without the automated optimisation, the user can rapidly get feedback on how changing the variables impacts the core arrangement and the efficiency of the system to resist lateral loading and can optimise each arrangement manually. For

each core arrangement, it is recommended to check how the building performs under different wind directions so that each individual wall can resist the maximum force it can be subjected to (Fraser et al. 2008). Once each core arrangement has been optimised, manually or automatically, they can easily be compared to each other using the mass of each arrangement and deflection and inter-storey drift plots. The user can choose to model the slab as shells or as stiff beams. While modifying and optimising each arrangement, it is recommended to use the stiff beams to fasten the definition run time. However, once each arrangement is optimised, modelling of the full slabs can be used to check the maximum deflection of the overall structure. The wind loading has been simplified for the tool to be applicable to a range of projects. This loading simplification may not be sufficient to accurately analyse buildings taller than 30 storeys or with complex building envelope because of wind interactions.

4.4.3 Limitations and future work

The tool reaches satisfactory results for early design stages but more detailed analysis is required for more advanced design stages. The tool is designed to be applicable for a range of projects. It can be used for standard high-rises using concrete core stability systems which are common but care should be taken when modelling less standard structural forms.

The wind load has been simplified to a point load and moment as can be done in practice. This simplification does not capture suction that would happen on the leeward side of the building or other wind interactions on the façade. Sensitivity studies could be performed to assess the suitability of the simplification used in practice though that would require modelling the full building envelope, leading to a slower analysis. The tool could be used in addition to other plug-ins such as Ladybug[1] which enables more detailed wind rose analysis or other weather-related analyses in further design stages. The open-source community around RH/GH developing and sharing plug-ins is one of the reasons that the software was used to develop the tools. The wind loading simplification used may also not be applicable for complex building envelope or buildings higher than 30 to 40 storeys when wind interactions can be more complicated.

A single beam element is currently used to model lintels. Given that such elements account for shear deformation, this is reasonable for early design stages though more detailed modelling of the lintels, for exampled by shell elements with a fine mesh, could be necessary to truly to assess the action of the lintels and of the torsional stiffness of

[1] https://www.ladybug.tools

the system (Gardner 2015). The stiff beams used to mimic the diaphragm action of the slabs are also reasonable for early design stages though they may induce high stresses where they connect to the walls. Modelling theses beams differently, for example running parallel to the wall shell elements, could be done for comparison and further validation of the modelling assumptions.

Deflections and rotation are often critical when designing concrete core stability systems, which are covered by this computational tool. However, natural frequency of the system can also be critical (Fraser et al. 2008). Although it appeared outside of the scope of the tool, frequency and mode checks need to be conducted at later stages. The tool has been set up to allow for these checks by modelling the slabs and vertical loads, however this part of the analysis has not be validated and requires further work. P-delta effects can also be critical for tall buildings in which case modelling the vertical loads and considering geometry non-linearity would be necessary. Enabling frequency and mode checks and considering P-delta effects in the computational tool, if assessed and validated, could be beneficial for its versatility and for completeness. Interoperability between the tool and other software more appropriate for such analyses by sharing the correct data is an other option that could prove valuable.

Chapter 5

Concrete high-rise buildings: slab and column optimisation

In this Chapter, the tool developed for slab and column optimisation of concrete high-rise buildings is explained. The tool is tested on different case studies and discussed.

The author would like to thank Theodoros Mourtis and Daniel Woodcock from Robert Bird Group (RBG) for their advice during the development of this tool. Theodoros Mourtis had created a Grasshopper 3D (GH) (Rutten 2016) definition to optimise the column arrangement on the slab of a project internally in RBG (Mourtis 2017b). Through conversations with Theodoros and other engineers, the principles and aims were understood and used as the starting point of the tool discussed in this Chapter. The aim was to create a robust and comprehensive tool that could be used on varied projects, at different design stages, and with a user-friendly interface. The computational tool developed is currently available to engineers in RBG.

5.1 Introduction

Tall buildings are subjected to horizontal and vertical loads. In concrete high-rise buildings, the core system is typically responsible for lateral load stability, as discussed in Chapter 4. Floor systems are subjected to a number of vertical loads, usually downwards acting, and structural columns and walls are responsible for the vertical load take-down. Typically when designing such buildings, the core arrangement will be assessed and

defined first to ensure lateral stability which is usually critical, and vertical loads are then added to design the floor system and columns. Cores and shear walls can be particularly useful structural elements combining multiple functions, such as lateral and horizontal load resistance as well as environment isolation (Gardner 2015). Once the core arrangement is established, columns are the only structural elements that can be moved to optimise the floor system performance when subjected to vertical loads. There are a number of floor systems available for concrete high-rise buildings and their design is often highly impacted by the column arrangement, both for detailed design of the floor system and for constructability considerations. 'Column arrangement' is used to describe one combination of column location on a slab. In most regular concrete high-rise buildings, vertical structural elements, such as the columns, form a smaller part of the material volume of the building than the horizontal structural elements that are the floor plates (Taranath 2009). Also, the same floor system is used throughout the height of the building and therefore, material and embodied carbon savings that would be negligible in only one floor can become considerable when applied to each storey of a tall building. Flat slabs or plates, which are a popular solution in concrete high-rise buildings in the UK (Eleftheriadis et al. 2017a), are two-way, beamless, reinforced concrete floor systems (Taranath 2009). In this Chapter, the floor system is assumed to use reinforced concrete flat slabs and 'slabs' is used to describe the floor plates. Given the scope of the tool, it is possible that it could be used for other floor systems.

As discussed in Chapter 2, a number of research studies focus on vertical load take-down system optimisation in reinforced concrete buildings, including Sahab et al. (2005); Aldwaik and Adeli (2016); Eleftheriadis et al. (2017a). These studies focus on sizing optimisation and to some extent on structural arrangement optimisation. Because detailed design of slabs is impacted by the column arrangement, more noticeable materials savings can be achieved by structural arrangement optimisation of the columns rather than by sizing optimisation of the slabs or columns only. In literature, when column arrangement optimisation is conducted, the columns can be positioned anywhere in the slab or following a grid, to achieve maximum cost or material savings. However, in design consultancies, the column arrangement is often subjected to architectural constraints. These constraints are particularly important when there are partition walls, in residential buildings for example, in which case columns are commonly positioned inside these partitions. A computational tool has been developed to optimise column arrangement on floor slabs to minimise embodied carbon in slabs and columns. It has been developed in collaboration with industry to ensure that it can be applied on real projects when working with architectural constraints and to capture the 'rules of thumb' that are used by engineers to design such structural elements. The tool is aimed to be used in various design stages, from conceptual to more advanced. Detailed design of the slab including reinforcement is often conducted

in later stages, which is why the tool is focussed on column arrangement optimisation rather than sizing optimisation. It enables using the tool from the earliest stages of design. The tool has been developed in Rhinoceros 3D (RH) (Robert McNeel & Associates 2018) and GH, an easily accessible software widely used by architects and increasingly used by engineers. The tool models the slab and column arrangement, conducting finite element analysis (FEA) with the GH plug-in Karamba (Preisinger 2013), and optimises the column arrangement using genetic algorithms (GA) with the GH component Galapagos to minimise net or peak moment, net strain energy or maximum displacement which act as surrogate objective functions to minimising mass. This is discussed in § 5.2.1.3.

The methods used in the development of the tool are explained. The case studies used to test and assess the computational tool are presented. Concluding remarks and discussion are provided on this slab and column optimisation tool.

5.2 Methods

Similar guidelines to those presented in Chapter 4, § 4.2 have been followed during the development of this computational tool. They include versatility, robustness and user-friendliness. This tool has also been developed in Rhinoceros 3D/Grasshopper 3D (RH/GH).

Following these guidelines, a tool aimed at lowering the embodied carbon of slabs in concrete high-rise buildings has been developed. The problem formulation is discussed first, followed by the proposed optimiser. An overview of the GH definition with explanations of the key steps is provided in Appendix B.2.

5.2.1 Problem formulation

5.2.1.1 Design variables and parameters

The thickness of a slab and reinforcement provision in concrete high-rise buildings are dependent on the stresses and strains in the slab, which are in turn dependent on the location of the supports. Because the tool is aimed to be used in early conceptual design stages as well as more advanced stages, the only variables in the optimisation are the column positions rather than the detailed design of the slab and the reinforcement is not modelled. Usually in concrete residential buildings or possibly in office buildings when partitions are required, the architect defines partitions in the floor plan and the concrete

columns are located inside these partitions. Engineers may have freedom over their exact position in the partitions. In Figure 5.1, the variable lines are these partitions along which the columns can be located. In the optimisation process, the position of the columns in these partition lines is varied. The slab is modelled by shell elements.

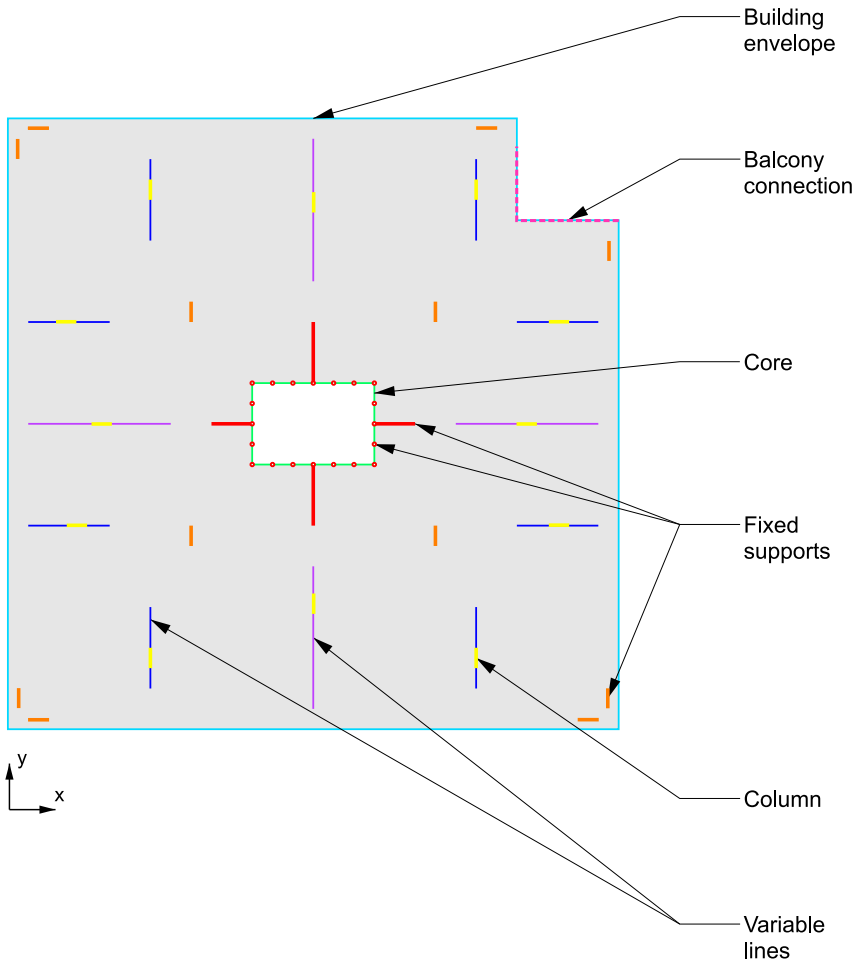


Figure 5.1: Sample plan view of the various structural elements that can be part of the optimisation process.

These variables act as the genome for Galapagos but can also be modified manually by the user to explore the design space. There are other parameters that can be set by the user:

- The slab external outline taken as the building envelope.
- The core or any other internal edge to the slab.
- The column size shown in Figure 5.2. The length l_{col} which is parallel to the partition wall can be drawn by the user in RH for each column, it can be set as a constant for all columns in the slab, or it can be computed during the optimisation based on axial force for ultimate load capacity. For the former case, multiple columns can

be drawn in each line and for the latter two cases, the number of columns in each partition can be varied by the optimiser. The thickness t_{col} has to be set by the user.

- Supports that have a fixed position. They can be drawn as lines, points or circles for circular columns. The length of rectangular columns with a fixed position can be computed by the tool based on axial force for ultimate load capacity. In this case, t_{col} is used for the thickness.
- Balconies can be added to integrate their load in the analysis as discussed in § 5.2.1.2.
- The slab thickness t_{slab}.
- The load values which include the slab self-weight, live and dead loads as well as a façade load that is applied on the slab external outline and a balcony load. Loading is explained in § 5.2.1.2.
- The material properties.
- Span limitations if the number of columns in each wall can vary.
- The number of floors in the structure. If the column length is computed in the analysis, it is done for the ground floor so that the maximum length is computed.

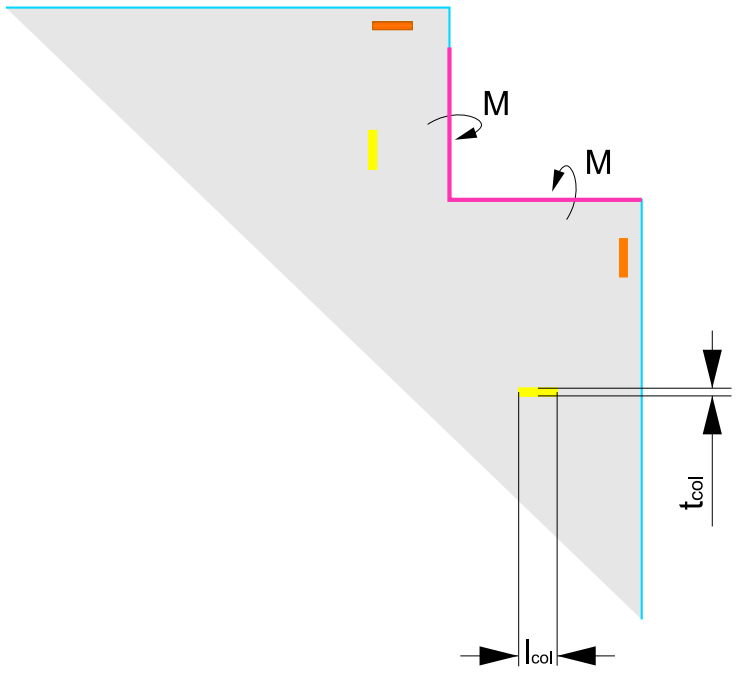


Figure 5.2: Plan view of the slab shown in Figure 5.1 zoomed around the balcony with additional information.

5.2.1.2 Loading

Columns are responsible for vertical load take-down in concrete high-rise buildings. Therefore the loads used in the tool are all vertical running in the negative z direction unless otherwise specified. Surface loads are distributed over the slab: self-weight, dead and live loads. Additional loads are distributed over the relevant sections of the perimeter of the slab: façade line load on the perimeter and balcony line load and moment where balconies are connected to the façade.

Depending on their connection to the main slab, balconies can induce both vertical loads and moments in the slab. However, the connection type may only be defined later in the design stage. Also, balconies can have various shapes. After discussions with engineers in RBG and given the scope of the study, it was agreed that it would be a reasonable simplification to only model rectangular balconies that have two edges connected to the slab, as illustrated in Figure 5.1. It is assumed that the connection is moment-taking and that there are no other supports to the balconies. The user needs to draw the line of contact between the balcony and the slab edge which should be two sides of the rectangular balcony. Based on these two edges and on the surface load to be applied on the balcony which can be specified by the user, the vertical line load in the negative z direction and the moment applied on the edge can be calculated. The moment of interest here can be represented using the right hand rule convention where the thumb is aligned with the slab outline pointing in the anti-clockwise direction. In the example of Figure 5.1, this means a moment in the negative x direction on the section of the balcony aligned with the x direction, and a moment in the positive y direction on the section of the balcony aligned with the y direction. This is illustrated in Figure 5.2.

5.2.1.3 Objective function

The overall aim of the tool is to reduce the embodied carbon of slabs and columns in concrete high-rise buildings. Minimising their mass is used as a surrogate to embodied carbon reduction. For columns, their size can be computed by the tool based on axial force capacity, meaning that their mass can be minimised. This is done through simple calculations during the analysis following BS EN 1992-1-1:2004 (2004). The objective function described here is that used to minimise the slab embodied carbon.

The tool should be used to conduct structural arrangement optimisation. Given its intended applications and to ensure efficiency, modelling the slab in detail with reinforcement is not suitable as it would be computationally demanding and there are softwares more appropriate for this task such as SAP2000. After discussions with

RBG engineers, five objective functions have been identified as potential surrogates to minimising the slab mass, either by reducing the slab thickness or the reinforcement. They are:

- Minimising the maximum bending moment in the slab M_{Peak} which is the difference between the maximum positive and maximum negative moment in the slab.
- Minimising the net moment in the slab M_{Net}, where the net moment is the sum of the absolute moment in two directions in all the elements of the slab.
- Minimising the net moment in the slab, considering minimum reinforcement M_{MinNet}. A minimum reinforcement of 12 mm rebars with 200 mm spacing with a 50 mm cover at the top and bottom of the slab spanning in two orthogonal directions has been selected after discussions with RBG engineers as this reinforcement is typically the minimum that is provided everywhere in a reinforced concrete slab. Using this reinforcement, a minimum moment resistance M_{min} of the slab can be calculated following BS EN 1992-1-1:2004 (2004). This means that there is no reinforcement mass reduction to be gained by minimising the moment in any shell element below this limit. Therefore the objective function is the sum of the absolute moment in all the elements of the slab, where any moment below M_{min} is taken as M_{min}.
- Minimising the maximum deflection of the slab d_{Max}.
- Minimising the total strain energy in the slab U_{Net} which is the sum of bending energy in all shell elements of the slab.

These objective functions have been identified as when designing slabs, bending strength and deflection are usually governing criteria to calculate the slab depth and reinforcement area (Brooker 2009). All these objective functions can lead to net moment or deflection reduction in the slab. This could lead to material reductions in the slab when conducting detailed design. Some objective functions are dependent on the number of elements, such as M_{Net} and U_{Net}. This is a limitation, however the number of elements is not expected to change when moving columns for a certain mesh refinement and these objective functions still enable comparing different column arrangements.

It was decided to keep the five objective functions independent rather than combine them in one or use a multi-objective optimiser such as the GH component Octopus (Vierlinger 2014) for two reasons. The first is that some objective functions are conflicting, such as minimising deflection and minimising bending moment. The second reason is that the aim of the tool is to enable engineers to search a greater design space than would be possible with standard design methods and to make decisions using this in conjunction

with their technical expertise, not to create a black box with an answer that is not readily and technically understandable. The results from using these objective functions separately allows assessment of both the strength and the stiffness of the plate.

Various penalties can be added to the objective function. Ultimate load capacity checks are conducted in the columns and if a column is subjected to an axial force greater than its capacity, a penalty significantly greater than the objective function value is added so that the solution is suboptimal and should be rejected by the optimiser. The magnitude of objective functions O_W that can be obtained range from 10^5 kNm for net moments to 10^{-3} m for deflections and the penalty magnitude is dependent on the objective function magnitude. A second penalty can be added to ensure that all columns have a similar utilisation for axial shortening considerations. The minimum and maximum axial utilisations of the columns are identified and if the difference between the two is greater than a value to be set by the user, by default of 0.4, a penalty proportionally small compared with the objective function is added as not to automatically reject the option but it allows to account for axial shortening. The last penalty is on column spacing. Given the objective functions available and when the number of columns can be modified in the optimisation, it is likely that the optimiser would tend to provide many columns next to each other in each partition wall. To avoid this, a minimum column spacing can be provided by the user. Additionally, if the ratio of column lengths in each partition line to the length of the partition line is greater than a benchmark value, a penalty proportionally small compared with the objective function can be added.

The objective function with the added penalties can be expressed as follows:

$$\min\left(f + P_{axial} + P_{shortening} + P_{spacing}\right) \tag{5.1}$$

where f is the selected objected function, P_{axial} is the added penalty when the axial force in a column N_{Ed} is larger than its capacity N_{Rd}:

$$P_{axial} = O_W \times 10^6 \times \sum_{n=1}^{N_{col}} p_i \tag{5.2}$$

where N_{col} is the number of columns and $\sum_{i=1}^{N_{col}} p_i$ is the number of times that the limit is breached where p_i is:

$$p_i = \begin{cases} 0 & \text{if } N_{Ed} \leq N_{Rd} \\ 1 & \text{otherwise} \end{cases} \tag{5.3}$$

$P_{shortening}$ is the added penalty when the difference between the minimum column utilisation $Util_{Min}$ and the maximum column utilisation $Util_{Max}$ is larger than the limit

$Util_{diff}$:

$$P_{shortening} = \begin{cases} 0 & \text{if } Util_{Max} - Util_{Min} \leq Util_{diff} \\ O_W \times 10^{-1} & \text{otherwise} \end{cases} \tag{5.4}$$

and $P_{spacing}$ is the added penalty when the ratio of the sum of column lengths in a partition line $l_{colTotal}$ to the length of that partition line l_{part} is larger than a benchmark value $spacing_{min}$ based on an average column length to be provided by the user, for each partition line:

$$P_{stress} = O_W \times 10^{-1} \sum_{i=1}^{N_{part}} r_i \tag{5.5}$$

where N_{part} is the total number of shell elements and $\sum_{i=1}^{N} r_i$ is the number of partition lines where the limit is breached where r_i is:

$$r_i = \begin{cases} 0 & \text{if } \frac{l_{colTotal}}{l_{part}} \leq spacing_{min} \\ O_W \times 10^{-1} & \text{otherwise} \end{cases} \tag{5.6}$$

5.2.2 Proposed optimiser

5.2.2.1 Modelling simplifications and assumptions

The objective of the tool is to search a wide design space with many design variables. Some simplifications are used in order to reduce the design space, making the optimisation more efficient, but also enabling constructability considerations to be accounted for. The main simplification is that the slab is given an arbitrary depth with no reinforcement modelled and therefore the slab is not modified during the optimisation but surrogate objective functions are used as discussed in § 5.2.1.3 which are expected to lead to material reductions in the slab. Simplifications regarding loading from the balcony have been discussed in § 5.2.1.2.

Another modelling simplification is that the columns can only be located in the partition walls. Full structural arrangement optimisation where columns can be located anywhere or where the grid orientation and spacing can be changed could reach greater embodied carbon reduction, however the tool is aimed to be used by structural engineers on real projects. From conversations with engineers in RBG, column arrangement in partition lines based on architectural decisions was identified as a more realistic and practical method as it is a common process that happens in consultancy offices.

Regarding structural arrangement and sizing of columns, the user has several options to choose from. The column sizing options are explained in § 5.2.1.1. If the column size is to be computed in the optimisation, two Karamba analyses need to run. A first analysis is run where each column is taken as a point support in order to compute its reaction force, which is used to compute the column length l_{col} based on ultimate load capacity. This is done in a custom Python component. A second analysis is then run with the derived value of l_{col}. This method in itself is a approximation to calculate the column length. Given the scope of the study, it was deemed appropriate as it can be a starting point for column design but is not aimed to be used for detailed design. The process of using two Karamba analyses increases the run time of the optimisation process as the Karamba analysis component is the most computationally demanding in the GH definition. To increase the speed of the optimisation, the user has the possibility to assign a constant column length to all columns, therefore requiring a single FEA and reducing the run time of each iteration of the optimisation. Because the tool is aimed to be versatile and applicable at various design stages, a third option is provided. If calculations of the column dimensions have been performed, the user can draw these columns in RH and the drawn l_{col} is used in the optimisation. This could be useful for projects in later design stages to check the column arrangement for example. Again, only one FEA is performed in this case, thus reducing the optimisation run time.

Regarding column arrangement, the user can choose to group the partition lines based on symmetry. If this option is selected, the columns will be positioned identically in all variable lines in the same group. This is illustrated in Figure 5.1 where the partition lines have been grouped in two layers: the dark blue ones and the purple ones. In this case, it allows going from twelve to two variables, reducing the design space significantly which can be useful when running multiple optimisations. Independently from this grouping option, the user can also define supports with fixed locations. This can be useful to model cores or shear walls which are also part of the load take-down system, but also to model columns with known locations either from engineers' expertise or architectural requirements, such as in slab corners. This allows removing additional variables to the optimisation, reducing the optimisation time and increasing the probability of finding the global optimum.

The columns are modelled as supports only, not as shell elements, to reduce the size of the model. Two points, located at each end of the column length-wise, and at the centre thickness-wise, are used. Given the scope of the tool, this is a reasonable assumption and enables capacity checks as discussed in § 5.2.1.3. Another simplification made is that t_{col} is constant for all columns. This is a reasonable simplification as it is often the case on projects for constructability considerations. The building envelope is assumed to be

constant with height so that the optimised column arrangement is valid for all storeys and needs to be computed only once, which is common for the structures that the tool is aimed at. The column arrangement is therefore assumed to also be constant with height, which often happens for constructability considerations and efficiency of the slab (Taranath 2009).

Finally, assumptions are made for the materials. When section capacity checks need to be conducted and given that detailed reinforcement is not considered as part of this study, a reinforcement area of 2% is assumed both in the columns for sizing and utilisation checks and in the slab for minimum moment resistance as discussed in § 5.2.1.3. The slab material properties can be set by the user. Based on conversations with RBG engineers, a 'rule of thumb' used is to reduce the Young's modulus (E) and the shear modulus (G) to 25% to account for long term time dependent effects such as concrete shrinkage or creep.

5.2.2.2 User interface

The user interface for this tool is similar to the concrete core optimisation tool presented in Chapter 4. The user is required to input information both in RH and in GH. A template is provided in RH to draw the elements in the relevant layers as their name is important for data importation in GH. The RH data required includes the building envelope, which is constant with height, the connection line between balconies and the building outline, and internal cores that form an edge to the platform. Supports of fixed location need to be drawn in RH and can be points, lines or circles for circular columns. Line supports can be added in a separate sublayer if their position is fixed but the user wishes to compute their length. The partition lines along which the columns can move should be drawn, and in separate layers if there is symmetry and the user wishes to run grouped optimisation. If the column number is fixed or if the user wishes to use an existing l_{col}, they should be drawn on top of the relevant partition line. The layer arrangement is shown in Figure 5.3.

In GH, additional information is required. The interface is shown in Figure 5.4. Three decisions need to be made:

- If l_{col} is computed in the analysis, drawn in RH or constant for all columns.
- If the column arrangement can be grouped by symmetry or is independent in each partition line.
- If the number of columns can vary in each partition line.

In the remainder of this Chapter, these decisions are described by the term 'optimisation decisions'. The option of varying the number of columns in each line cannot be used if the

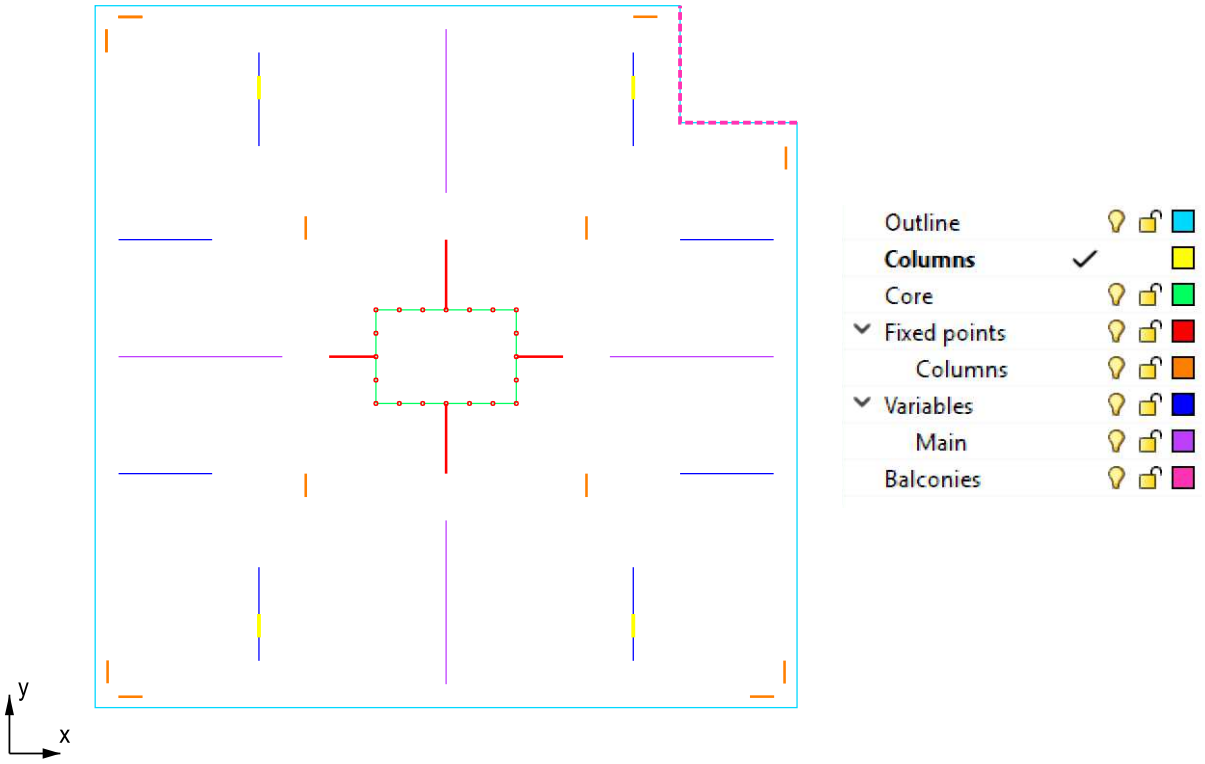


Figure 5.3: Organisation of the layers and sublayers in RH for user input.

column length is drawn in RH. This means that there are ten versions of the optimiser, increasing its versatility. The second group shown in Figure 5.4 is where data from RH is imported and where the user needs to specify column length limits if l_{col} is computed in the optimisation, set l_{col} if it is constant for all columns, and set t_{col}. The last group is for additional parameters. The user can set t_{slab} and all the loads to be applied in the analysis. The number of floors can be set if l_{col} is to be computed in the analysis. If the number of columns can vary in the optimisation, the minimum and maximum span allowed should be specified. Finally, yield stress values for concrete and reinforcement steel need to be provided for the slab and columns for sizing and moment capacity checks as discussed in § 5.2.2.1. In the GH definition, the user can also set the slab's material properties. Downstream in the definition, the user needs to select the objective function of interest.

5.2.2.3 Optimisation process

As discussed in Chapter 4, § 4.2.1, GA from the Galapagos component in GH is used for the optimisation. Modified Gene Pool components, automated by custom Python components so that the number of sliders varies based on the number of variables and on the optimisation decisions made by the user, are used as genome which is the name

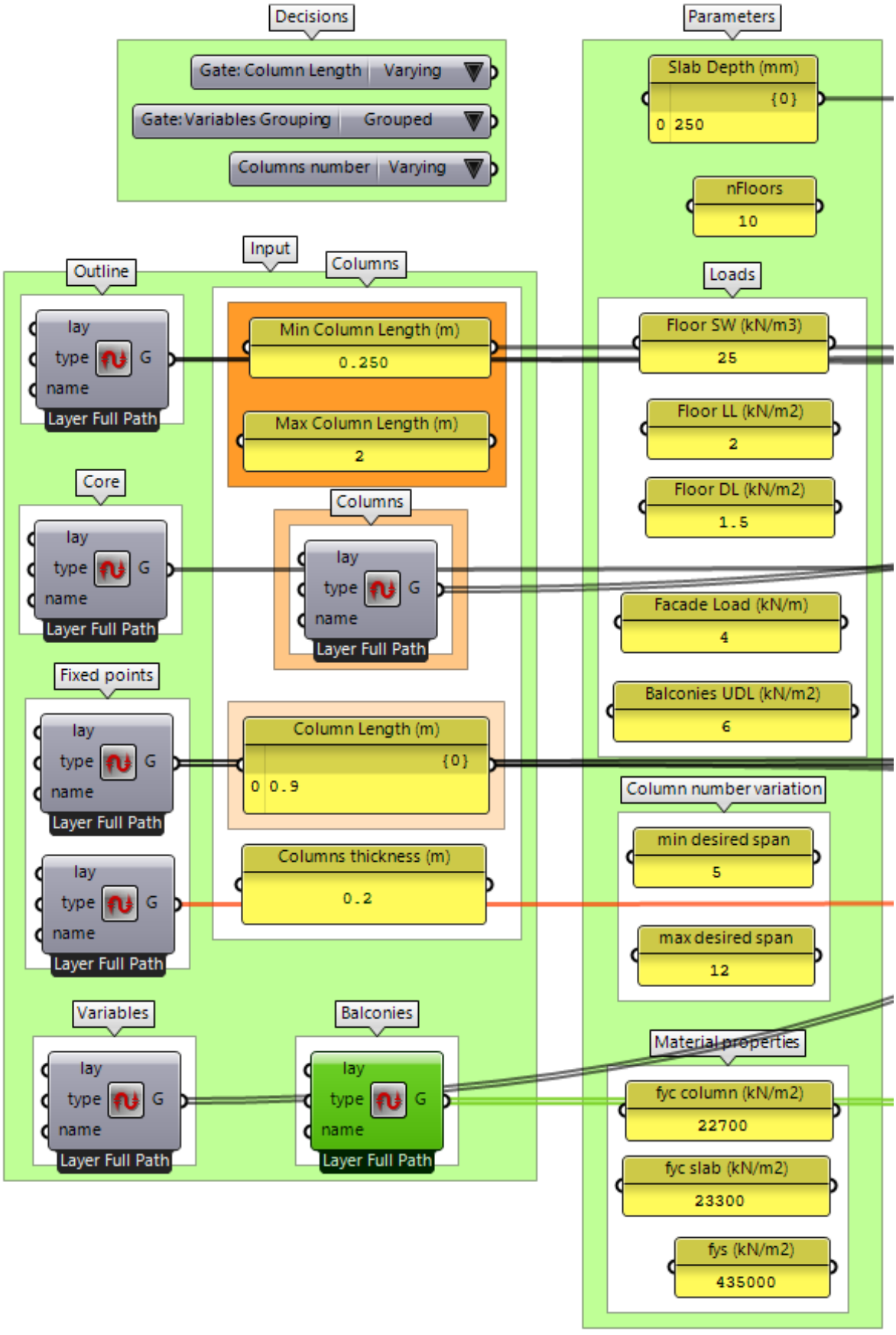


Figure 5.4: Input required from the user in the GH definition.

of variables used by Galapagos. The fitness function is given by the selected objective function with any penalty added. The optimisation process follows these steps:

1. User to input relevant parameters in RH/GH, as detailed in § 5.2.2.2.
2. User to make optimisation decisions and to select the objective function of interest.
3. Iteration:
   (a)
   - First Karamba static analysis to compute l_{col} if relevant option selected.
   - l_{col} already known.

   (b) Second Karamba instance used for static analysis followed by column capacity and spacing checks. Penalties are added to the selected objective function.
   (c) Galapagos modifies the column arrangement either independently or symmetrically and the column number if option selected, based on user's decisions.
4. GA converges with optimised column arrangement.

As discussed in § 5.2.1.3, the user can run the optimisation multiple times with different objective functions to fully assess strength and stiffness of the slab. Python components developed by the author and from the GH plug-in Ladybug[1] are used to automatically output the main results of the tool to an Excel spreadsheet so that the user can run each optimisation, store the optimised column arrangement and store the results to then easily compare the different arrangements obtained.

5.2.2.4 Structural model definition

Karamba is used for modelling and static analysis of the slab. The slab is meshed using triangular elements with a thickness specified by the user. The mesh resolution can be modified by the user. Vertical loading as point loads in the negative z direction and moment from the façade and balconies are added to the appropriate nodes on the perimeter of the slab. The self-weight, dead and live loads are added as mesh loads on the slab. Supports are taken as the end points of all columns, any point support specified by the user and if the user uses lines in RH for support, closest nodes of the mesh to these lines are also added as supports. All supports are assumed to be pinned, which means that the translational degrees of freedom are fixed whilst the rotational ones are not. The material properties can be set by the user and are assumed as linear elastic. Some

[1] https://www.ladybug.tools

material assumptions are discussed in § 5.2.2.1. The method used to compute columns length when it is required by the user is explained in § 5.2.2.1.

Three-noded triangular shell elements, discussed in Chapter 4, § 4.2.1 are used in Karamba to model the slab, and linear analysis is performed. Maximum deflection, peak and net moment and net strain energy are obtained from the analysis and can be used as the objective function with the relevant penalties added in Galapagos. The column utilisation penalty is computed from the analysis results. Additional results from the analysis can be displayed by Karamba, such as the slab deflections, principal and von Mises stresses, loads, reactions or utilisation.

5.3 Results

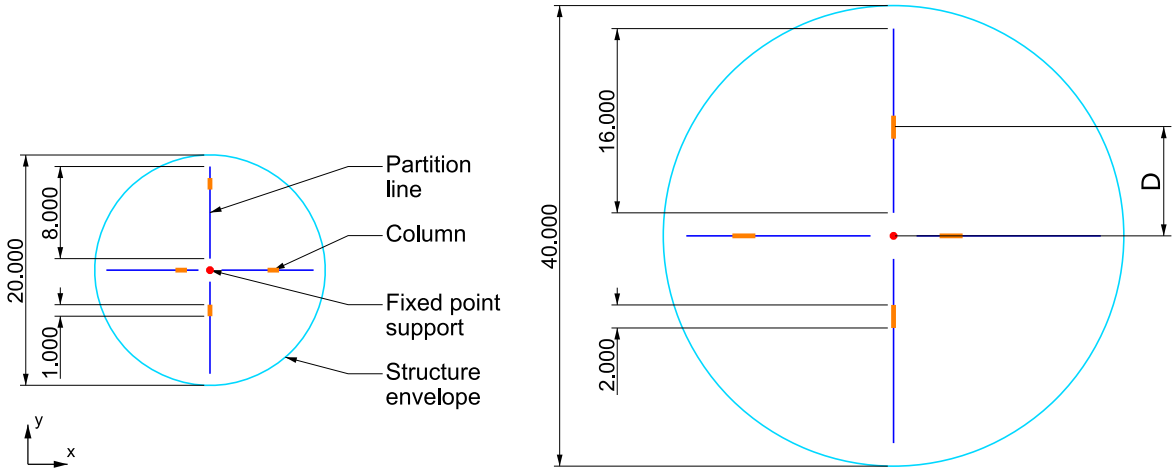
The same material definition has been used for every model presented here. It is taken as reinforced concrete with E and G reduced as discussed in § 5.2.2.1. This means that E is 8.5 GPa and G is 3.542 GPa, equivalent to a Poisson's ratio (ν) of 0.2. A specific weight of 25 kN/m^3 and a yield strength of 23.3 MPa are used for the slab. If the column length is to be computed in the analysis, a yield strength of 22.7 MPa for concrete and 435 MPa for steel is used. A slab thickness of 0.250 m is also used for every model presented. All models are subjected to the same load case: slab self-weight of 25 kN/m^3, dead load of 1.5 kN/m^2 and live load of 2 kN/m^2, reaching a mesh load of 9.75 kN/m^2 applied on the slab mesh in the negative z direction; a façade load of 4 kN/m applied on the slab outline in the negative z direction and a balcony distributed load of 6 kN/m^2 from live and dead loads and self-weight. The line load and moment for the balcony loading are automatically calculated in the tool based on the connection line length drawn in RH. Loads are factored for ultimate load capacity by 1.35 for dead loads and 1.5 for live loads. A personal workstation (2 × Intel Xeon E5-2620 v3 2.40GHz 12 CPUs and RAM 64.0 GB) was used to run all models.

5.3.1 Doubly-symmetric simplified model for GA assessment and mesh convergence study

The first model presented is a circular plate with four partition lines as shown in Figure 5.5. The aim of this model is to verify the solution reached by Galapagos using GA and to conduct a mesh convergence study.

5.3.1.1 GA assessment

The four column variables are taken as independent variables in the optimisation and for this case, the objective function is to minimise the net strain energy U_{Net}. Given the double symmetry of the slab and partition lines, the expected result of the optimisation would be for the centre of columns to be equidistant form the centroid of the slab. This distance between the centroid of the slab and the centre of the columns is D. Also, if the scale of the slab, partition lines and column length is doubled, which is shown in Figures 5.5a and 5.5b, D is expected to be doubled in the scaled up model compared with the initial one.

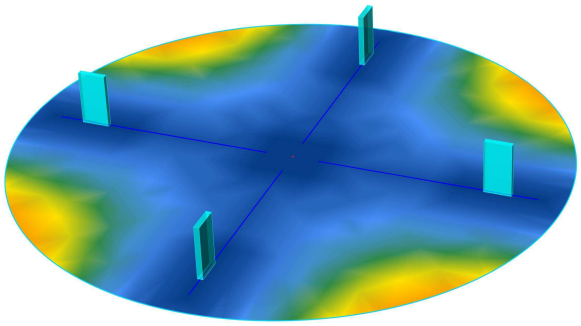


(a) Initial model. **(b)** Model scaled up by a factor of 2.

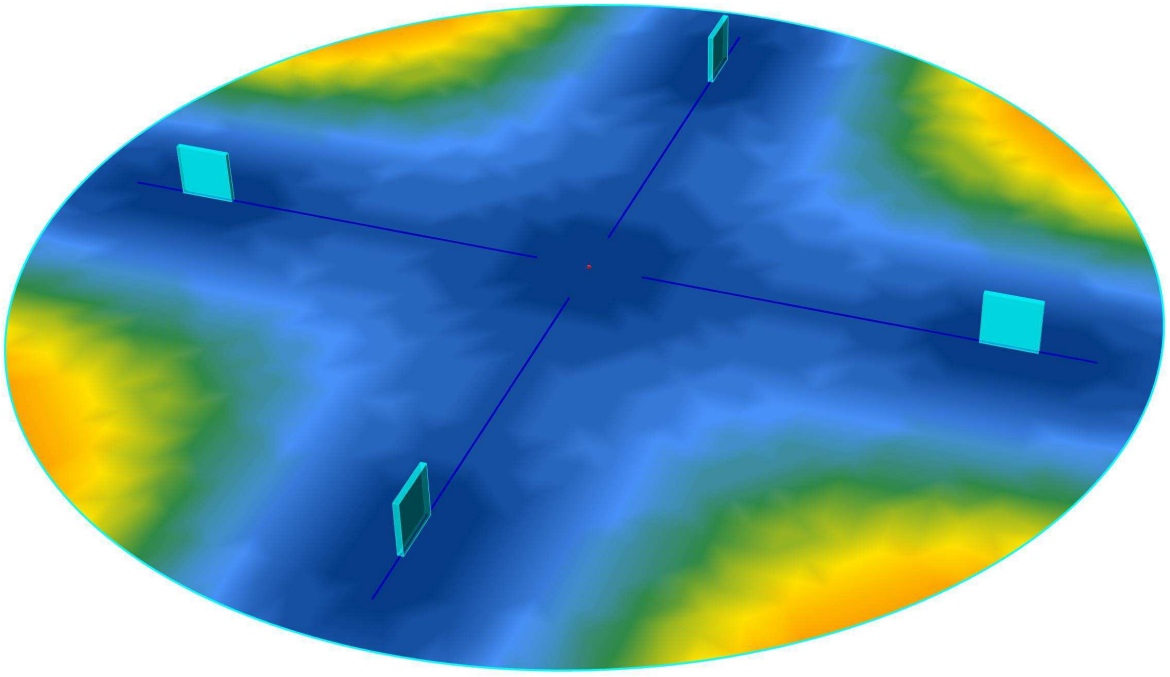
Figure 5.5: Plan view of a circular slab with a fixed point support at its centroid, four doubly-symmetric partition lines with one column in each partition, used for GA verification. All units are in meters unless otherwise specified.

The initial position of each column is set to a random point along the partition line and is different in each model as shown in Figure 5.5, to ensure that the GA solution reached is not dependent on the starting point. The column length is taken as the one drawn in RH to ensure symmetry and exact scaling. The column position along each partition line is taken as a parameter going from 0 to 1 in 0.01 increments, where 0 is away from the centroid of the slab and 1 is closest to the centroid. This means that there are 100 potential positions for each column, therefore the size of the design space is 100^4 in each model. A mesh resolution of 1.0 m is used.

The column arrangement after optimisation for each model is shown in Figure 5.6. Deflections plots are used here and in the next case studies unless otherwise specified for simple comparison and it is not possible to plot strain energy in Karamba. For the initial model, the four columns are in the exact same location away from the centroid



(a) Initial model.



(b) Model scaled up by a factor of 2.

Figure 5.6: Deflection of the slab after optimisation of the column arrangement minimising U_{Net} for the GA verification model.

of the slab. D is 7.5 m. For the scaled-up model, the optimised column arrangement is again equidistant from the centroid of the slab, with D being 13 m. The distance in the scaled-up model is exactly double the distance in the initial model. These results were obtained after around 80 generations in Galapagos for both models, equivalent to approximately 25 min for the initial model and 65 min for the scaled-up model, and from random initial column positions, different for each model. It therefore seems that for a design space of this size, GA as implemented in Galapagos leads to a global optimum. The difference in run time is expected as for the same mesh resolution in both models, there are approximately 2500 shell elements in the scaled-up model compared with approximately 700 elements in the initial model. As discussed in Chapter 4, the run time of the analysis

component in Karamba and of the GH definition as a whole is dependent on the number of shell elements in the finite element (FE) model.

As discussed in Chapter 2, the ability to find a global minimum of GA is dependent on the size of the design space. In real structural engineering projects, it is likely that there would be more variables than in the model presented here. This is why the computational tool has been developed with multiple options. The user can reduce the design space in multiple ways, which could enable increasing the speed of convergence of the optimisation, and ensure that the global optimum is identified. The user can group the partition lines by symmetry which decreases the number of variables, or modify the discretisation of the partition lines, reducing the number of possibilities for each variable. In this model, the first suggestion would mean only finding one column position which can be applied to all the columns on the slab, which means that the design space decreases from 100^4 possibilities to 100 for the discretisation described above, equivalent to a 99.9999% reduction. The second suggestion means changing the column position parameter from 0 to 1 in 0.01 increments to 0.1 increments, meaning that each column only has 10 possible positions. If each column position is optimised independently, the design space goes from 100^4 possibilities in the initial model to 10^4 possibilities, reducing the design space by 99.90%. These assumptions may be reasonable to make early in the design process to approximately position the columns. In more detailed design stages, or after running the optimisation with these assumptions, leading to an approximate optimal structural arrangement, the user can reduce the design space by reducing the range of each variable. In the initial model, running the optimisation with each partition line discretised from 0 to 1 in 0.1 increments gives optimal columns position at 0.1. For more precise positions, in a second optimisation, the column position parameter could vary from 0 to 0.3 in 0.01 increments, leading to a design space of 20^4 possibilities if each column position is an independent variable in the optimisation, meaning that the design space is reduced by 99.19%.

5.3.1.2 Mesh convergence study

The model shown in Figure 5.5a has been used to conduct a mesh convergence study. The columns are set to be equidistant from the centroid of the slab and D is varied to check the convergence on various arrangements. D is taken arbitrarily as 2.1 m, 3.7 m, 5.3 m and 6.9 m. The mesh resolution is taken as 0.3 m, 0.5 m, 1.0 m, 1.5 m, 2.0 m and 3.0 m. For each arrangement and each mesh resolution, the maximum displacement obtained from Karamba was recorded and is shown in Appendix D.3. In Figure 5.7, the absolute percentage difference of the maximum deflection in the slab between the finest

mesh resolution and the other mesh resolutions for each value of D is plotted. The run time of the Karamba analysis component is shown in Table 5.1.

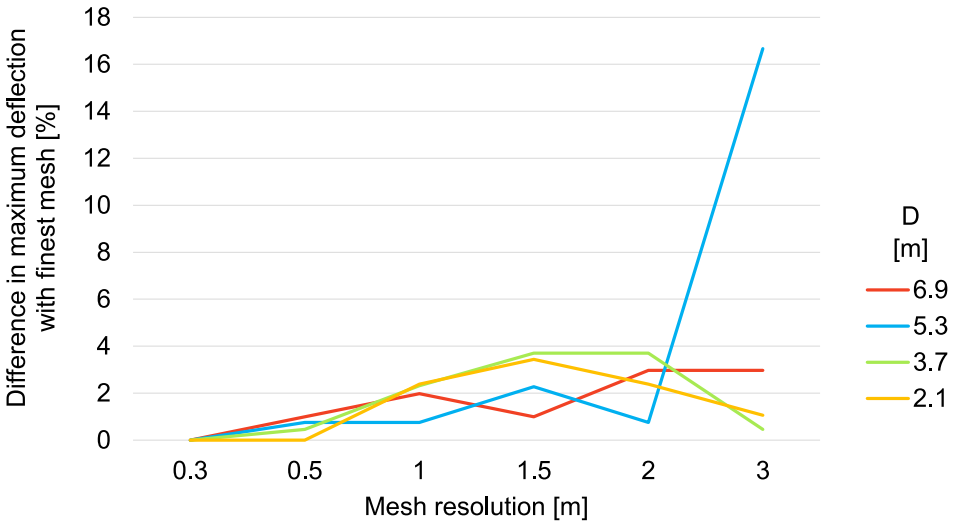


Figure 5.7: Convergence plot showing the absolute percentage difference between the maximum deflection of the slab obtained with the finest mesh with a resolution of 0.3 m and other mesh resolutions, for columns positioned at four different distances away from the centroid of the slab.

	Mesh resolution (m)					
	0.3	0.5	1.0	1.5	2.0	3.0
$D = 5.3$ m	400	160	60	50	45	40

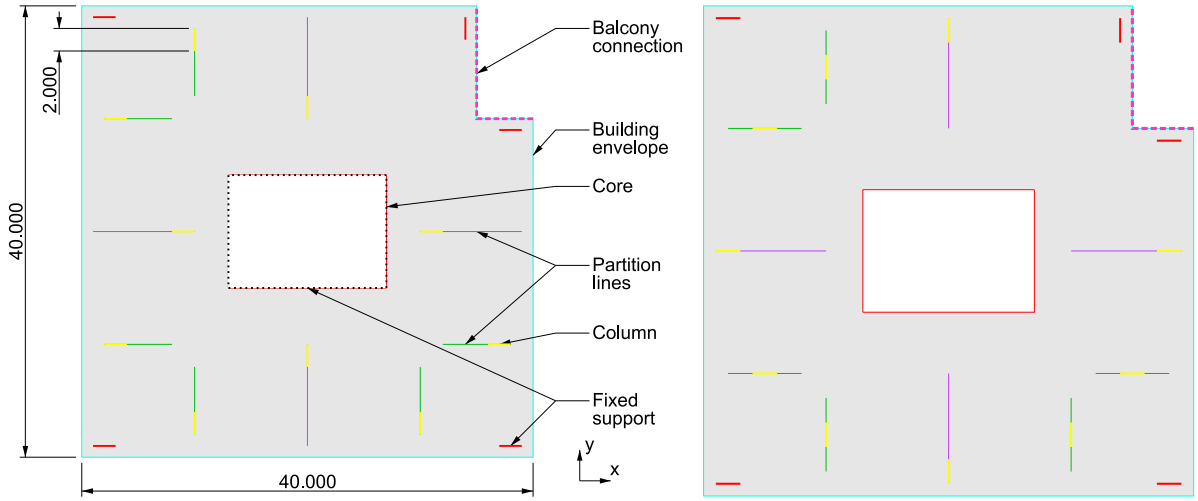
Table 5.1: Approximate Karamba analysis component run time (ms) for the model shown in Figure 5.5a with D arbitrarily taken as 5.3 m.

From Figure 5.7, the absolute percentage difference between the finest mesh and other mesh resolutions for the maximum displacement in the slab is below 4% for all mesh resolutions except 3.0 m, for which the results may be unreliable. Given that the tool is not aimed to be used for detailed design of slabs and columns but for structural arrangement optimisation of the columns, up to 5% inaccuracy should be acceptable. The aim is to compare the impact of changing column positions on several outputs rather than look at the outputs for one particular column arrangement in detail. Comparing the results in Figure 5.7 with those in Table 5.1, a mesh resolution of 1.0 m reaches an absolute difference of maximum deflection of 2% or less for all the values of D studied whilst the run time is comparable to coarser meshes. The convergence is improved for a mesh resolution of 0.5 m, however the run time of analysis is significantly greater. For these reasons, a mesh resolution of 1.0 m is advised when running the optimisation with a large design space

and in early design stages. A finer mesh can be used for more detailed analysis or for irregular slab structure.

5.3.2 Theoretical asymmetric model for numerical assessment

The second model presented is a more complex, asymmetric slab with a balcony, a core, fixed supports, asymmetric partition lines and one column per partition line. The column length l_{col} is taken as constant for all the columns on the slab as 2.0 m. It is illustrated in Figure 5.8 where variable columns are shown in yellow and fixed supports are shown in red. This model is used to numerically validate the Karamba results against a more robust FE software, Abaqus (Dassault Systèmes 2013). The slab thickness, material properties and loading described at the beginning of this section are used. In Abaqus, three-noded S3R triangular shell elements with linear shape function and one integration point are used and linear analysis is conducted.



(a) First column arrangement. **(b)** Second column arrangement.

Figure 5.8: Plan view of the model used for numerical comparison with Abaqus. All units are in meters unless otherwise specified.

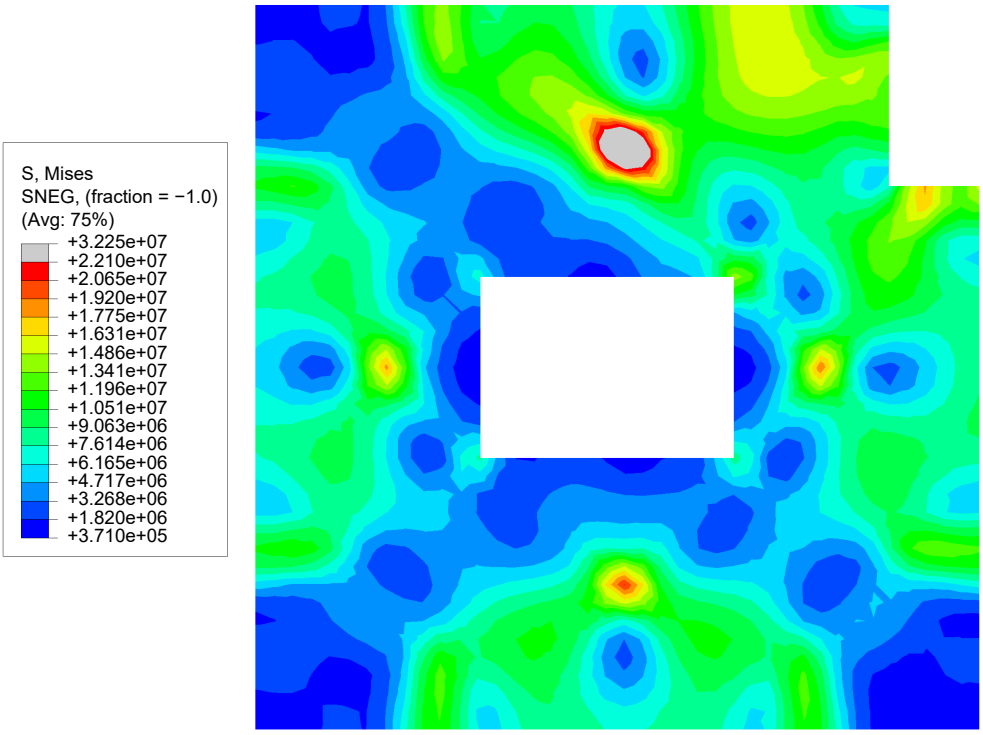
Initially, the analysis was run in Karamba and in Abaqus with a mesh resolution of 1.0 m with the column arrangement shown in Figure 5.8a. Figure 5.9 shows the von Mises stresses on the top of the slab obtained from each analysis. Von Mises stresses are used as it is one of the only measures that can be used to obtained comparable plots in both solvers whilst moments cannot be plotted in Karamba. For the figures comparing Abaqus and Karamba, the contour values match for each comparison but the legends are not ordered in the same way. It appears that whilst the contours in both plots are in good agreement, the results from Karamba underestimate the peak stresses. A second

analysis was then run in both softwares with a finer mesh resolution of 0.5 m. The von Mises stresses obtained from this second analysis are shown in Figure 5.10. In this case, the results from Karamba are noticeably closer to the results from Abaqus, particularly for the elements with high stresses. The results from Abaqus from the coarser to the finer mesh vary less than those from Karamba. To verify these results, the same analyses were run for the same slab but with a different column arrangement, shown in Figure 5.8b. The results with a 1.0 m mesh resolution from the two analysis softwares are shown in Figure 5.11 and the results with a 0.5 m mesh resolution are shown in Figure 5.12. The same observations as for the first column arrangement can be made regarding Karamba failing to capture high stresses with a coarser mesh. Similar observations were made for the peak moment in the slab.

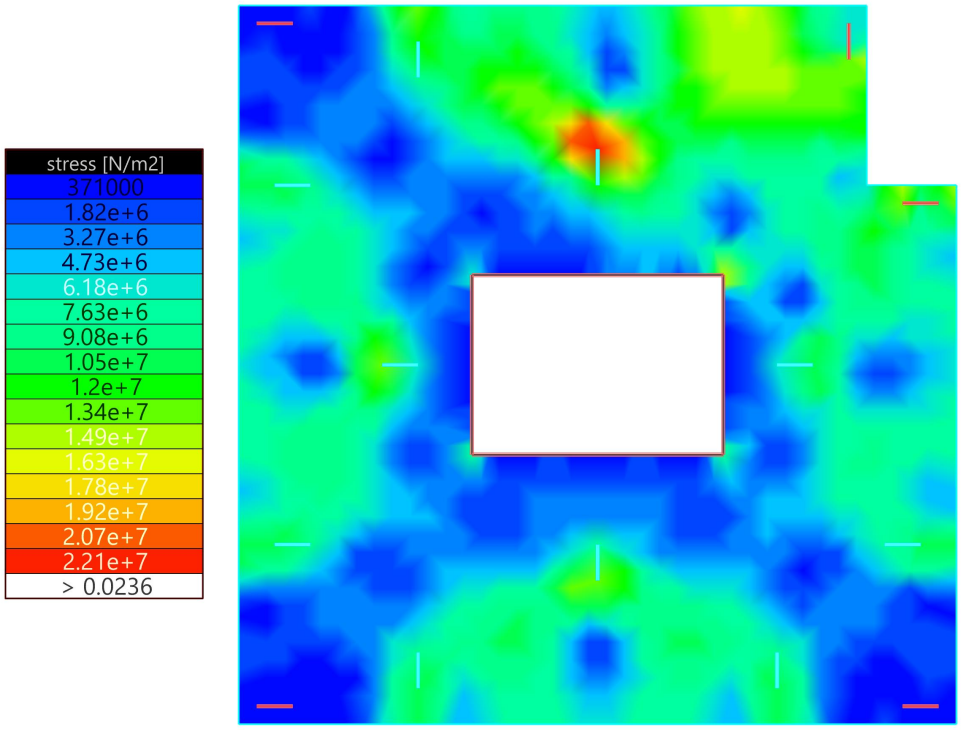
The results with the finer mesh resolution from Abaqus and from Karamba are consistent. They are not as consistent with the coarser mesh resolution for von Mises stresses for high stresses but 95 percentile values were checked and are consistent. Regarding maximum deflection, less than 3% difference is observed comparing the results from the two softwares and from the two mesh resolutions, and this is true for both column arrangements. All the analyses were run in Abaqus with 4-noded quadrilateral S4R elements with one integration point for further comparison. The results matched those obtained in Abaqus with triangular elements within 0.5% both for deflections and von Mises stresses.

This case study may imply that a 0.5 m mesh resolution should be used in the optimisation tool if an objective function other than maximum deflection is used. However, the tool is aimed to be used for structural arrangement optimisation of the columns on the slab rather than for detailed design of the slab or the columns. To run the optimisation, what is important is comparing the slab performance from different column arrangements rather than analysing the actual slab performance for each arrangement.

Galapagos was used for this model, using minimising U_{Net} as the objective function, with each mesh resolution. The partition lines were grouped based on symmetry where the two groups are shown in purple and green in Figure 5.8 and were discretised to 10 points each, reaching a small design space. The column arrangement obtained from each optimisation was exactly the same. The optimisation with the finer mesh took approximately 5 min whilst the optimisation with the coarser mesh took approximately 1 min 30 s, so less than a third of the time than with the finer mesh. Comparatively, the analysis processing time in Abaqus is similar to the Karamba one for each mesh resolution. However, adding the pre-processing time in Abaqus required after any modification of the model, such as changing the column arrangement, leads to an overall run time of approximately 40 s in Abaqus for either mesh resolution for one arrangement. To run

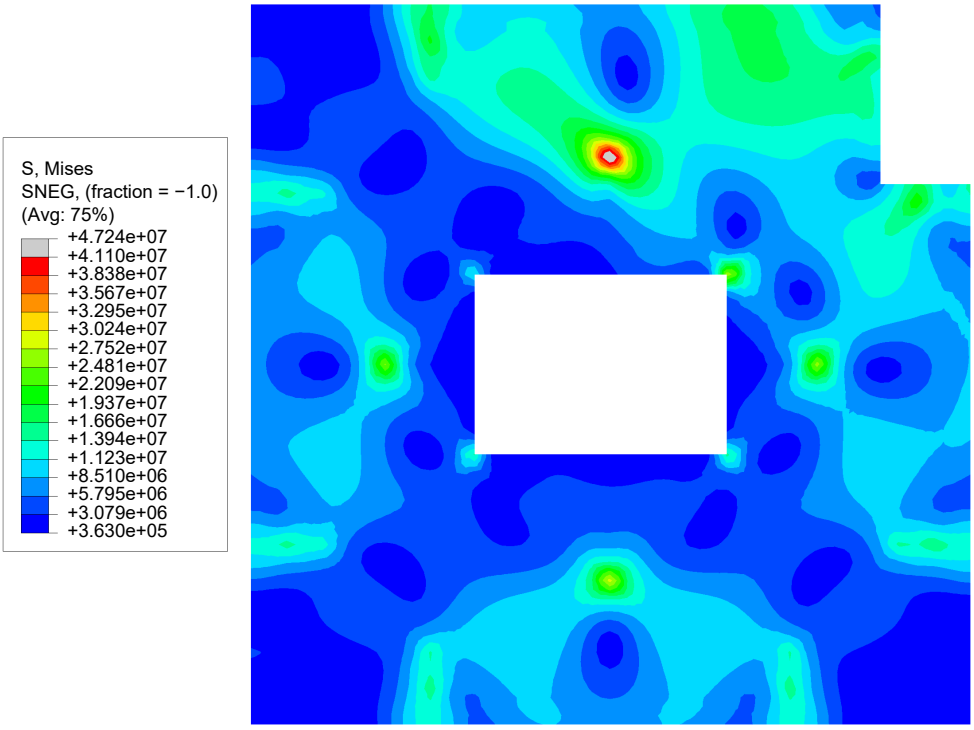


(a) Abaqus results.

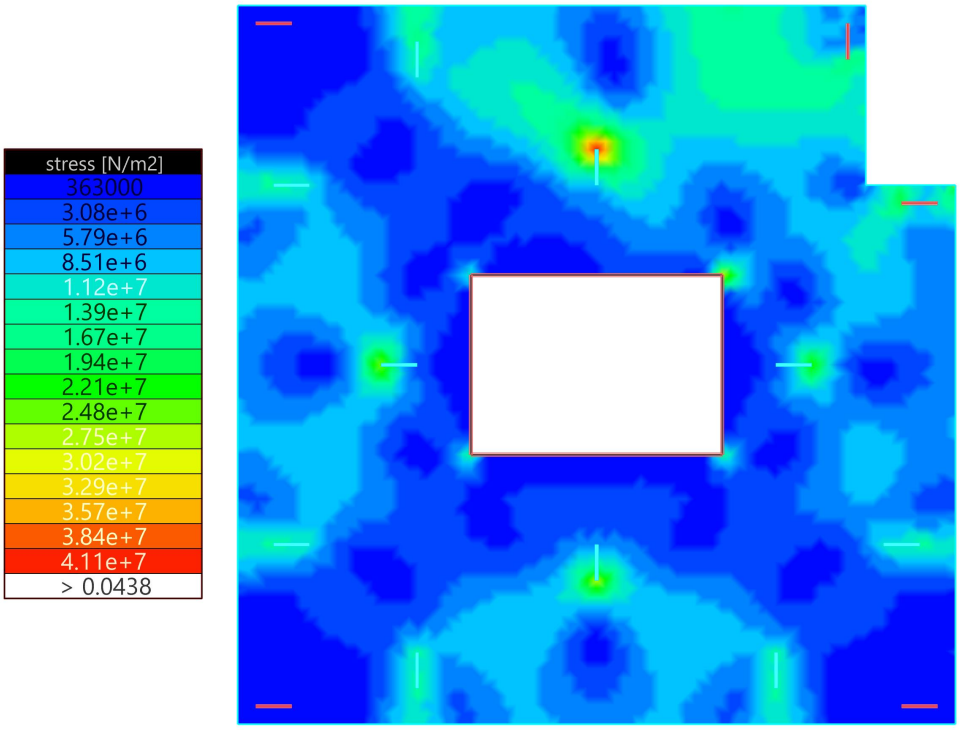


(b) Karamba results.

Figure 5.9: Von Mises stresses for the first column arrangement in the case study used for validation of the RH/GH FE model with a 1.0 m mesh resolution.

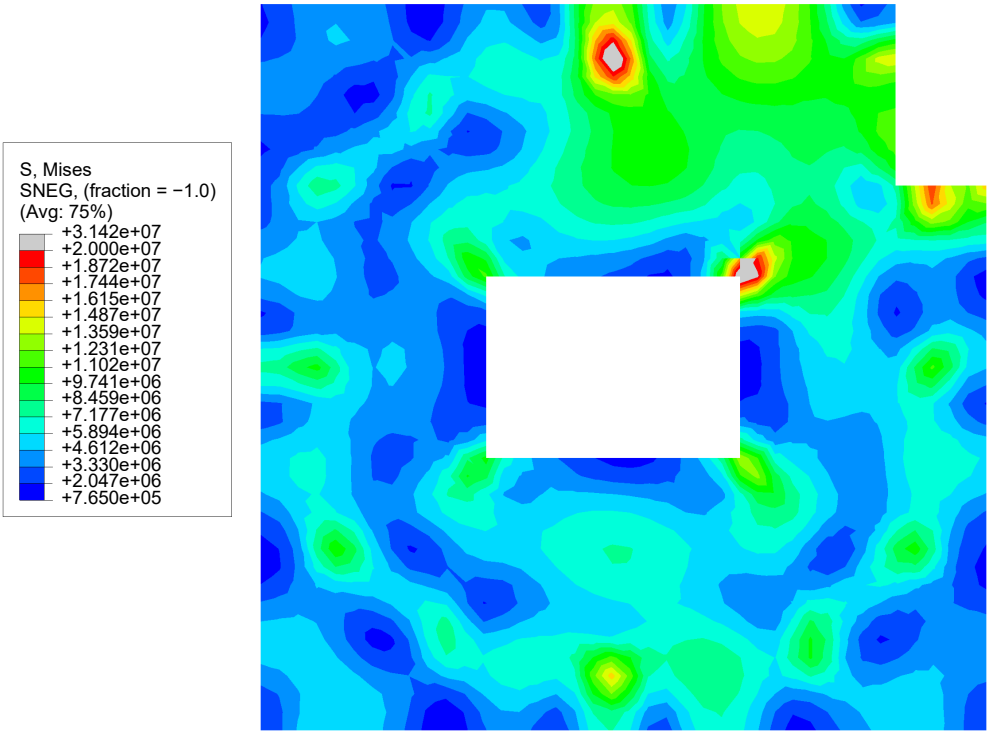


(a) Abaqus results.

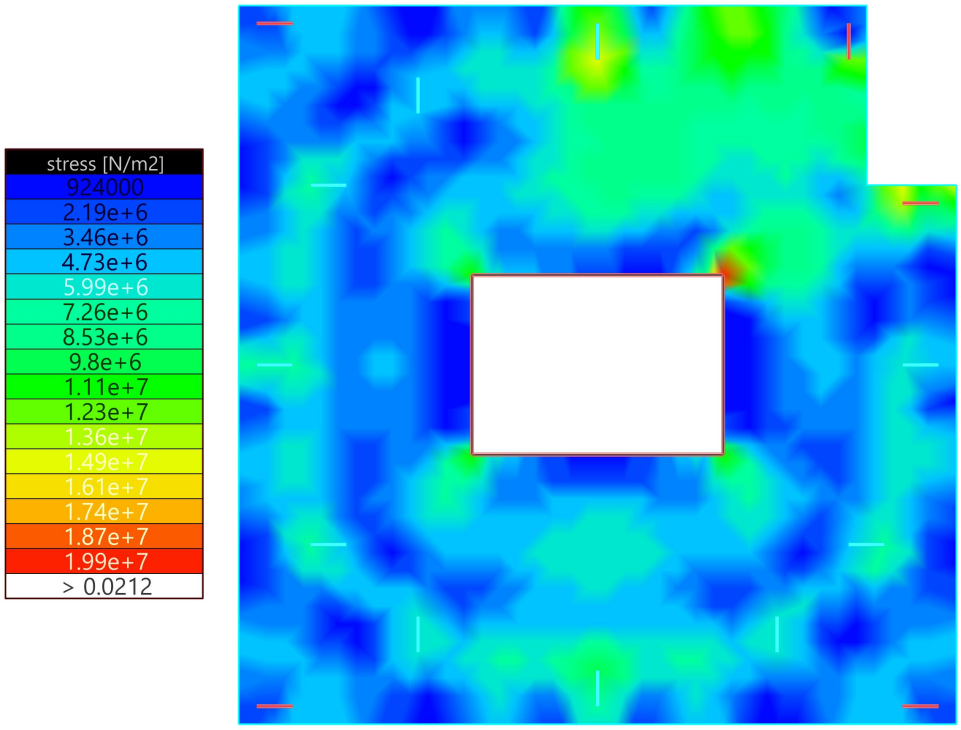


(b) Karamba results.

Figure 5.10: Von Mises stresses for the first column arrangement in the case study used for validation of the RH/GH FE model with a 0.5 m mesh resolution.

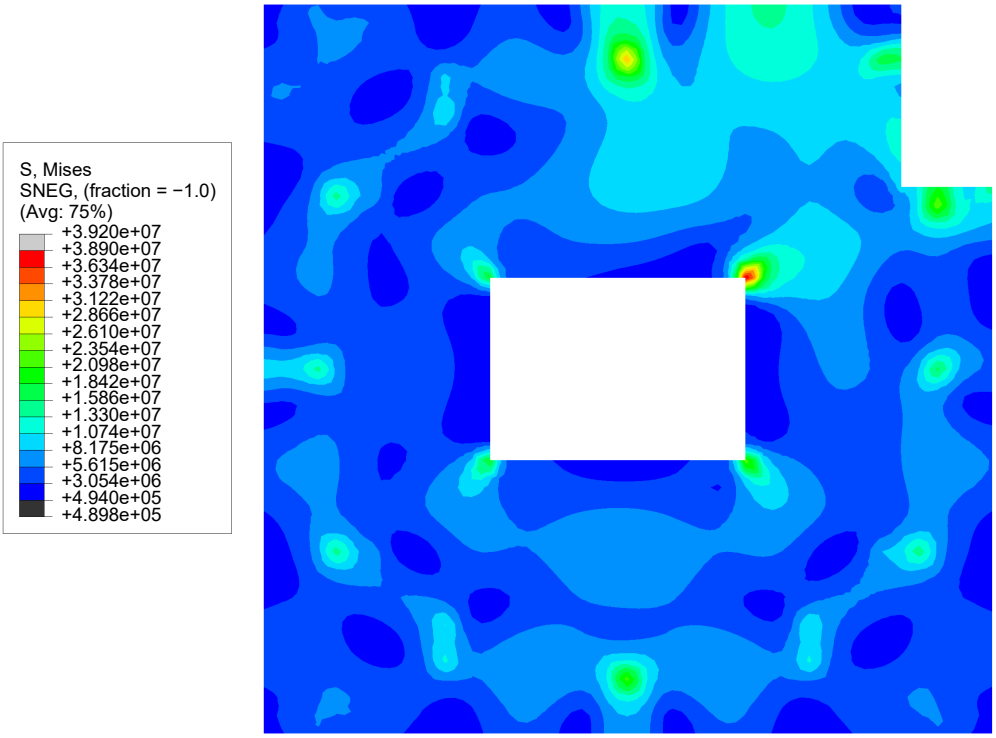


(a) Abaqus results.

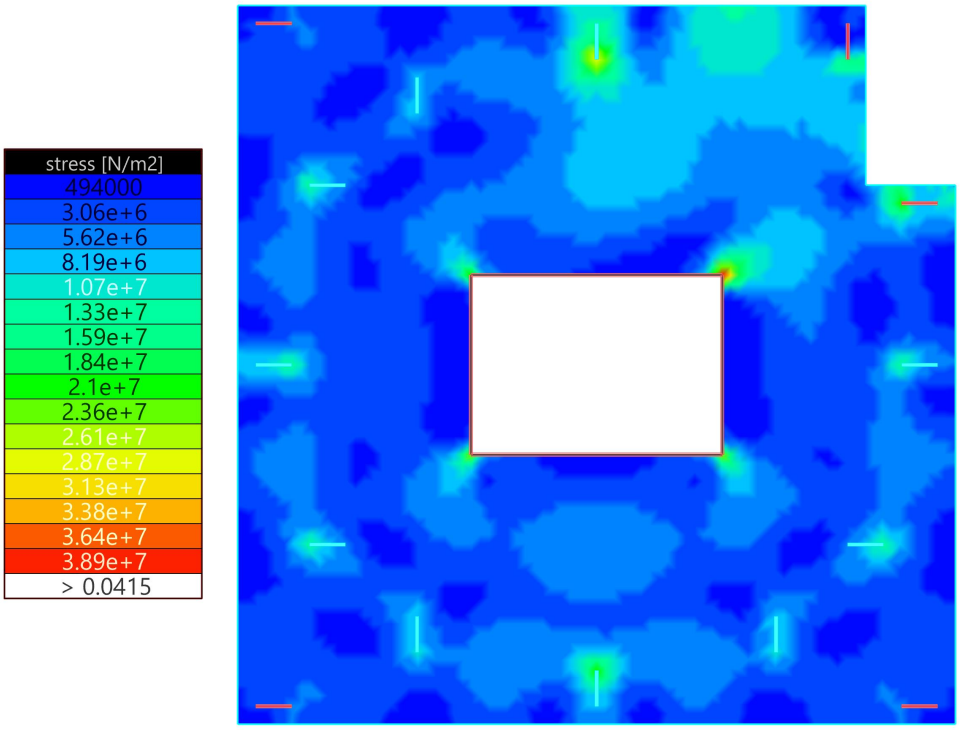


(b) Karamba results.

Figure 5.11: Von Mises stresses for the second column arrangement in the case study used for validation of the RH/GH FE model with a 1.0 m mesh resolution.



(a) Abaqus results.



(b) Karamba results.

Figure 5.12: Von Mises stresses for the second column arrangement in the case study used for validation of the RH/GH FE model with a 0.5 m mesh resolution.

the optimisation with a similar number of arrangements explored, 100 in this case given the reduced design space, automating the process would require a code, in Python for example, which would need to be created to modify the input file based on the results with an optimisation algorithm that would also require coding as there is no optimiser such as Galapagos in Abaqus. It is expected Abaqus would take approximately 60 min if the optimisation is automated, taking 12 to 40 times longer than running Galapagos with Karamba, depending on the mesh resolution. This implies that even though Karamba may not capture high values with a 1.0 mesh resolution, comparatively it still enables the optimisation to converge in a meaningful way and in a noticeably shorter time frame. The GH interface to manually modify the variables is also more intuitive with reduced response time compared with Abaqus. This model is more realistic in its size than the first model presented but the number of variables is reduced compared to real projects. Therefore based on these results, a mesh resolution of 1.0 m is recommended for cases with a large design space when running the Galapagos optimisation, particularly in early stages where architectural changes may happen often and where fast turnover is required. A mesh resolution of 0.5 m may be more suited when the design space is reduced when running the Galapagos optimisation, to size l_{col} and generally when the tool is used for more detailed applications.

5.3.3 Retrospective case study

The last model presented is a retrospective case study of a concrete high-rise building provided by RBG. The slab floor plan with the original column arrangement is shown in Figure 5.13. It is a 25-storey residential building with a central concrete core providing vertical support to the slabs as well as overall lateral stability, columns in partitions and on the perimeter and balconies. The column arrangement is constant with height and aims to minimise the slab thickness whilst adapting to the architectural constraints to minimise disruption. The original column arrangement was designed with a maximum internal span of 8 m and maximum column to building edge distance of 7 m. The slab thickness, material properties and loading described at the beginning of this section are used.

Based on plan drawings provided, the original column positions and sizes are identified. It was decided that some columns would have fixed positions when outside of the partitions, which are shown in red in Figure 5.13 whilst the variable columns are shown in yellow, and the partition lines for the columns that could be moved are drawn in RH. The partition lines have been grouped by symmetry so that symmetrical column optimisation can be conducted. These groups are shown in Figure 5.13 with main columns

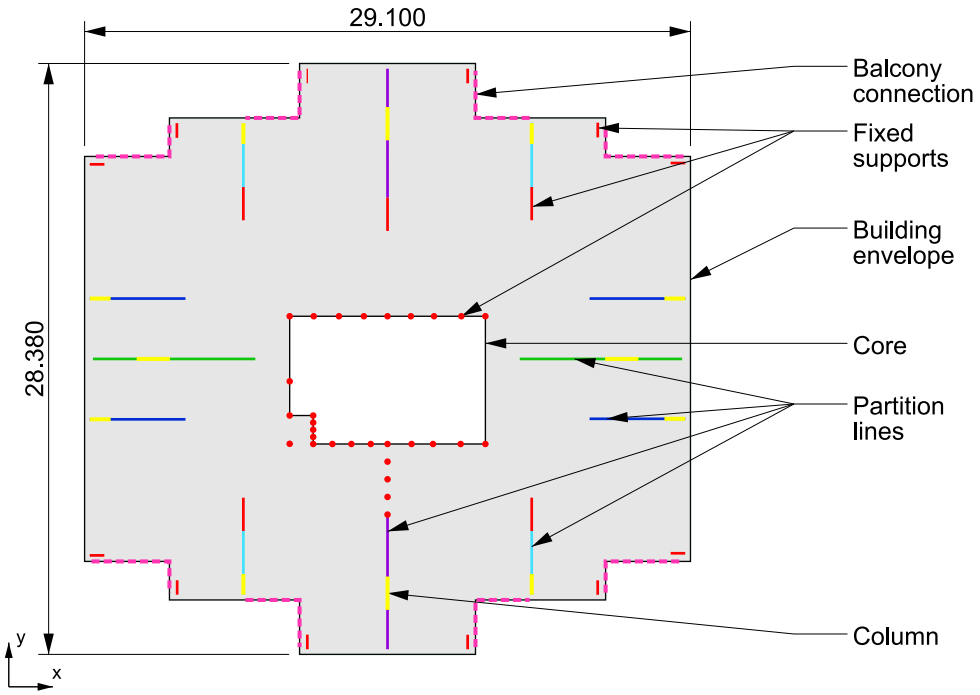


Figure 5.13: Plan view and original column arrangement of the retrospective case study. All units are in meters unless otherwise specified.

in the x direction in green, main columns in the y direction in purple, smaller columns in the x direction in dark blue and small columns in the y direction in pale blue. For all optimisations presented here, the partition lines have been discretised to 10 possible positions. The connection line between the balconies and the slab is provided. For all optimisations presented, a mesh resolution of 1.0 m as been used.

This case study is used to assess two parts of the tool. First, it is used to compare the results after optimisation using each objective function available. It is then used to compare the impact that different optimisation decisions have on the results and on the performance of the tool. In this second part, the impact of adding penalties on the column utilisation is also observed. The different results obtained are benchmarked against the original column arrangement. For the optimisation, the default settings are:

- l_{col} drawn in the original column arrangement.
- Grouped variables based on symmetry.
- Fixed number of columns in each partition line, in this case one in each partition line.
- No penalties added to the objective function.
- Minimising strain energy U_{Net} used as objective function.

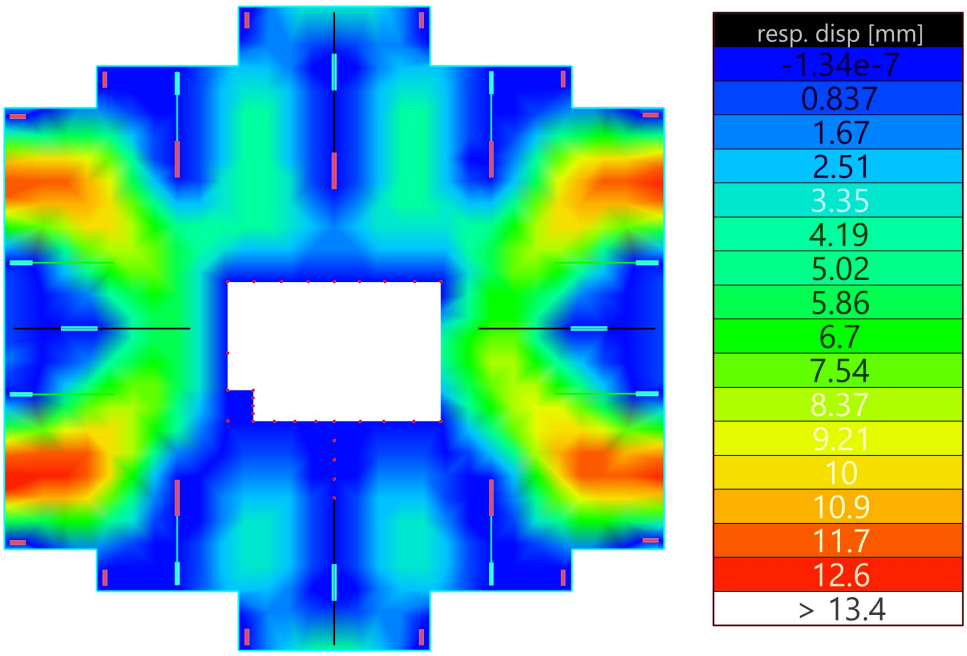
Deflection plots from the original column arrangement and the column arrangement obtained after running the optimisation with these default settings are shown in Figure 5.14. They are used as they allow comparison between the various core arrangements. In these plots, the red rectangles show fixed columns and in blue are the variable columns in their optimised location and this is illustrated in an elevated view in Figure 5.15. Plan views are used as they allow easiest comparison between the column arrangements. Using the drawn column length, a fixed number of columns and grouping the variables have been selected for defaults as they lead to a reduced design space and the fastest analysis run time compared with other decisions. When comparing the optimised results from different objective functions, no penalties on the column utilisation are added because the objective is to see the maximum benefits that could be obtained by changing the column arrangement, and the column size could be modified for utilisation compliance. It is unlikely that the column size would be set before the position. The drawn length is only used here for easy comparison between the models.

The first four default settings are initially used, changing only the objective function to compare the results they each reach. The deflections plots and new column arrangement after optimisation using the other four objective functions are shown in Figure 5.16. Table 5.2 shows the percentage difference of the results between the original column arrangement and the ones obtained after optimisation with the various objective functions. A negative number mean that the result is lower in the optimised model compared with the original. In red is highlighted when the optimised arrangement leads to worse results.

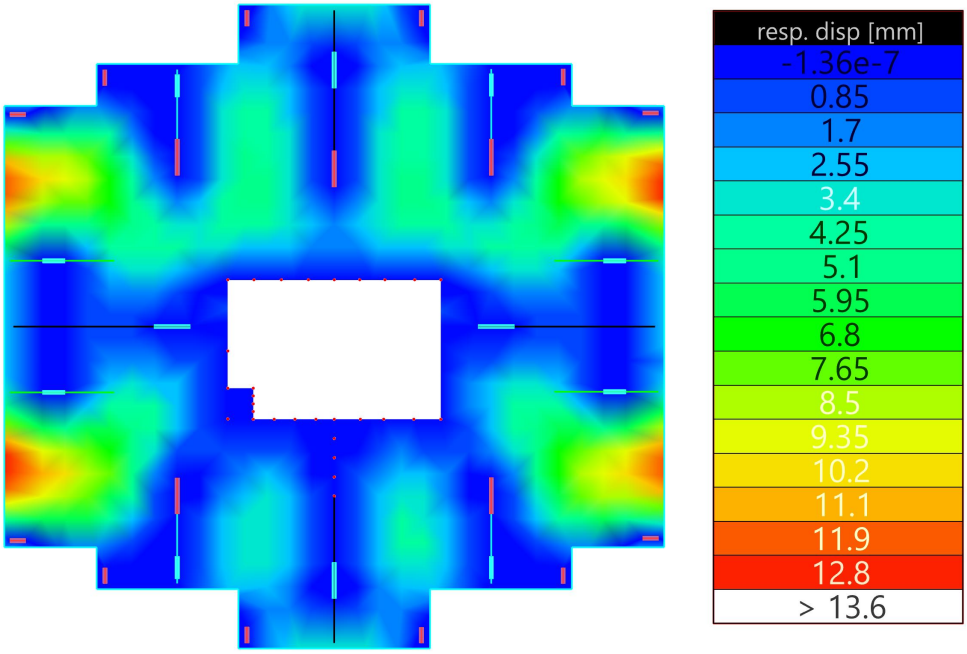
		Output data				
		U_{Net}	M_{NetMin}	M_{Net}	M_{Peak}	d_{Max}
Objective function	Minimise U_{Net}	-26	-11	-11	-18	2
	Minimise M_{NetMin}	-23	-12	-12	-15	12
	Minimise M_{Net}	-23	-12	-12	-15	12
	Minimise M_{Peak}	-21	-8	-8	-19	1
	Minimise d_{Max}	-5	-1	-1	-11	-9

Table 5.2: Percentage difference of various results between original column arrangement and column arrangement after optimisation with different objective functions.

Several observations can be made. Minimising d_{Max} is the only objective function that improves all the results for this model. However, the improvement on M_{Net}, M_{MinNet} and U_{Net} is marginal compared with the results from the other objective functions. The improvement on M_{Peak} is higher but still lower than with the other objective functions and d_{Max} is lowered by less than 10%. This happens because the maximum deflection occurs in areas where the movement of the columns has little impact. The deflection



(a) Original arrangement.



(b) Minimising U_{Net}.

Figure 5.14: Deflection plot and column arrangement of the retrospective case study from the original drawings and after optimisation minimising U_{Net}. Fixed columns are shown in red and variable columns in blue.

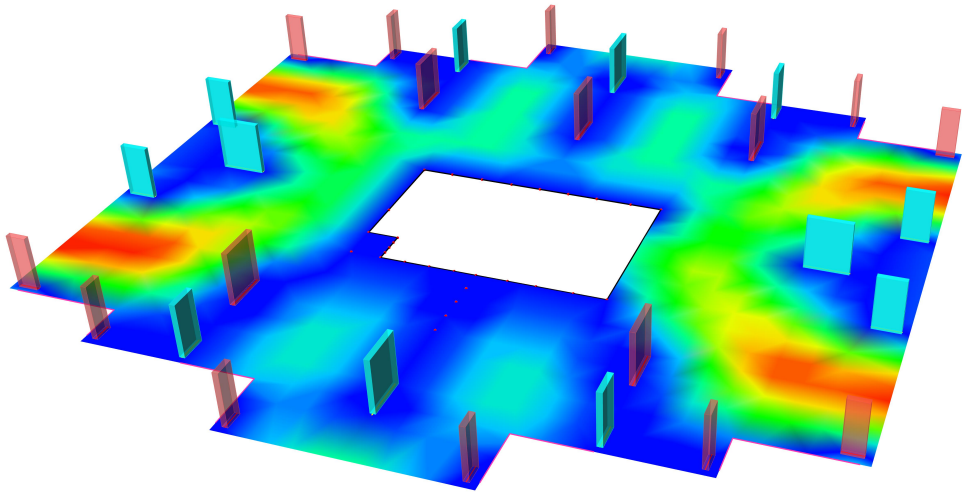
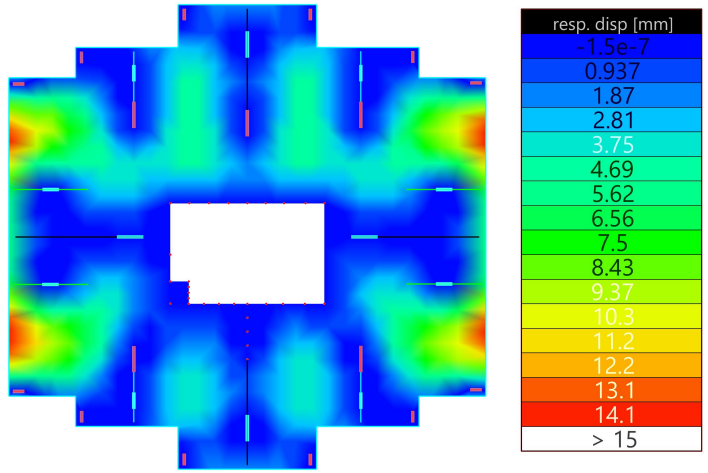
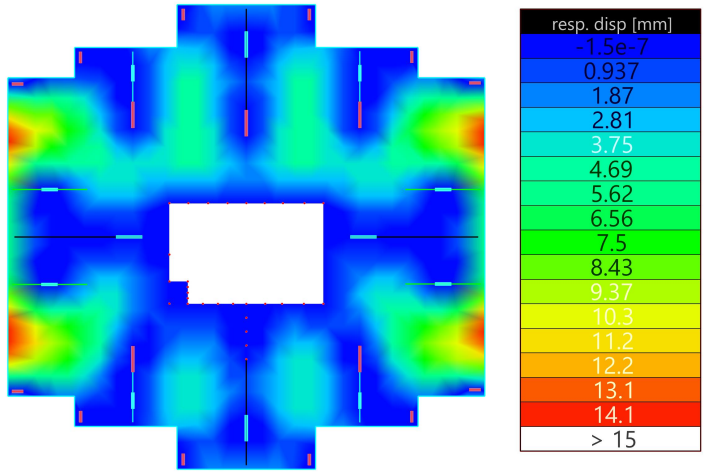


Figure 5.15: Elevated view of the slab with the original column arrangement. Fixed columns are shown in red and variable columns are shown in blue.

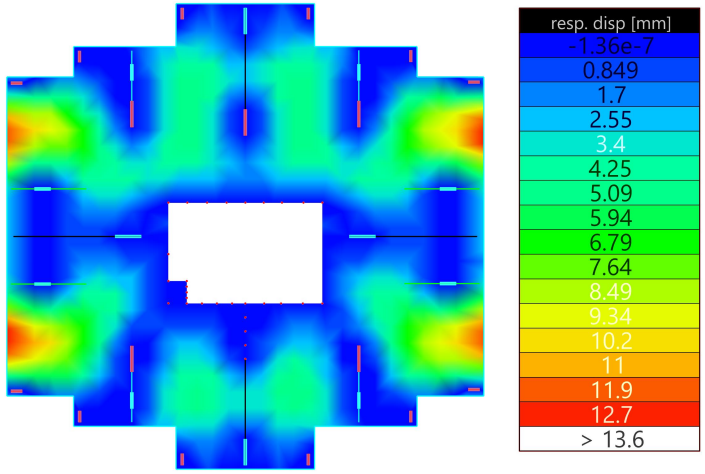
contours stay the same as with the original column arrangement, comparing Figure 5.16d with Figure 5.14a even though the deflections are lowered. The main column movement is in the columns aligned with the y direction. Minimising M_{MinNet} and M_{Net} reach the same column arrangement as seen in Figures 5.16a and 5.16b. This could be expected given that each partition line is discretised to only 10 positions. The number of elements where the moment is lower than M_{min} is expected to be relatively low compared with the net moments in the slab, thus factoring in for this M_{min} is unlikely to reach noticeable results unless all elements have low moments. For this case study, more refined discretisation of the partition lines could lead to minor differences between the two objective functions. Both objective functions lead to optimised arrangement where all the results are noticeably improved except d_{Max} which is increased by 12%. The main difference with the original column arrangement shown in Figure 5.14a is the movement of the columns aligned with the x direction towards the centre of the plate. Minimising M_{Peak} has a similar impact than the previous two objective function with a negligible negative impact on d_{Max}. However, the improvement on M_{Net}, M_{MinNet} and U_{Net} is not as high comparatively. Bending moment in the slab is likely to impact the slab depth and reinforcement requirement (Brooker 2009). Minimising M_{Peak} could reduce the highest moment locally but increase lower moments in the rest of the slab. This may require increased reinforcement provision, therefore minimising M_{Peak} may not be the most suitable objective function. Finally, minimising U_{Net} reaches improved results almost as good as when running the relevant objective function for all but d_{Max} and for this, the results are close to the original case. The column arrangement, shown in Figure 5.14b, is close to the one obtained from obtained from minimising M_{Net}, shown in



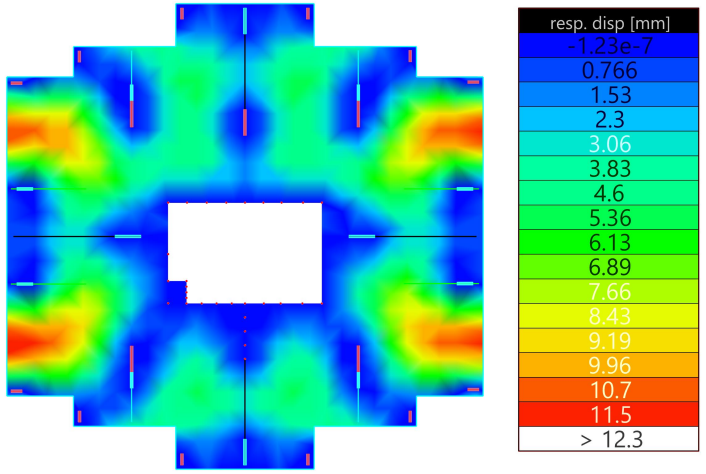
(a) Minimising M_{MinNet}.



(b) Minimising M_{Net}.



(c) Minimising M_{Peak}.



(d) Minimising d_{Max}.

Figure 5.16: Deflection plot and column arrangement of the retrospective case study after optimisation for different objective functions. Fixed columns are shown in red and variable columns are shown in blue.

Figure 5.16b, with movement of the columns aligned with the x direction compared with the original arrangement shown in Figure 5.14a.

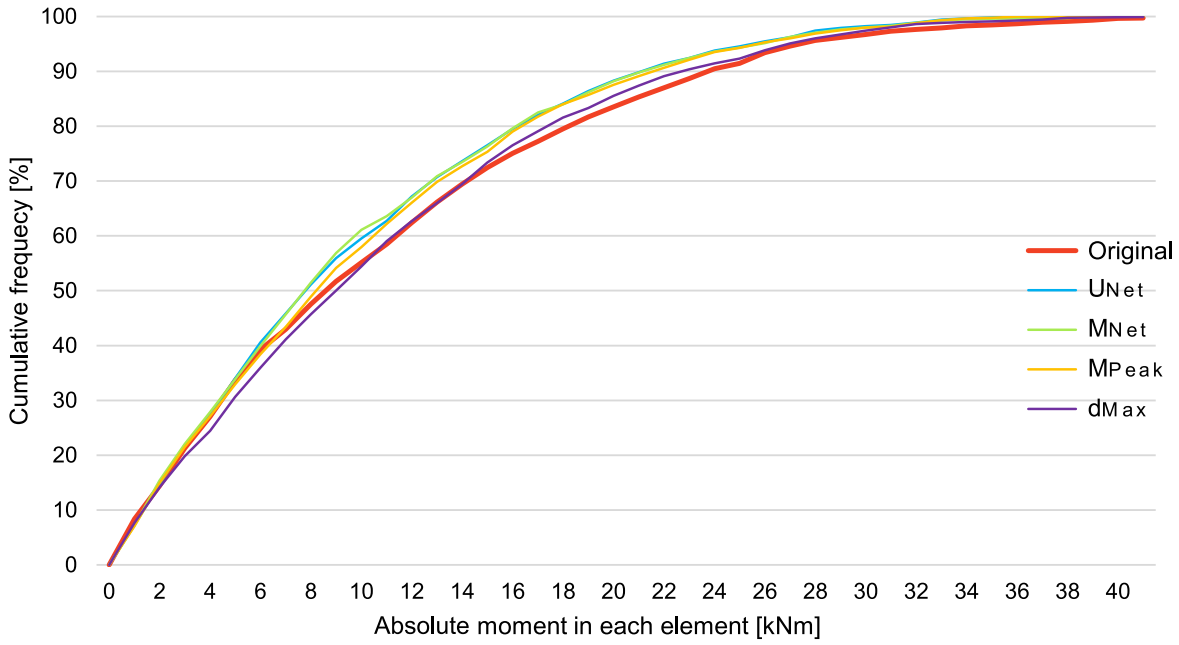
Figure 5.17 shows cumulative frequency of absolute moments and deflections in the slab in red for the original column arrangement, in blue for the column arrangement obtained after optimisation to minimise U_{Net} and in other colours for the results from using the other objective functions. Results from minimising M_{MinNet} are not shown as the same arrangement to minimising M_{Net} was obtained. Absolute moment and deflections are shown as bending strength and deflections are usually critical when designing slabs based on BS EN 1992-1-1:2004 (2004) (Brooker 2009), therefore reducing deflections and bending moments should lead to material reductions in the slab. Figure 5.17a shows that the various objective functions lead to overall reduced moments as expected from Table 5.3. Figure 5.17b shows that deflections are also reduced overall for all objective functions. Minimising U_{Net} leads to the greatest overall deflections which are 21% lower than with the original column arrangement.

Based on the results, it seems that minimising U_{Net} leads to the best performing results overall and should be used if only one optimisation is conducted. However, it is recommended that engineers run optimisations with each objective function and compare the results and column arrangements to then decide on the final column arrangement using their technical expertise and potentially rationalising the results for increased constructability considerations.

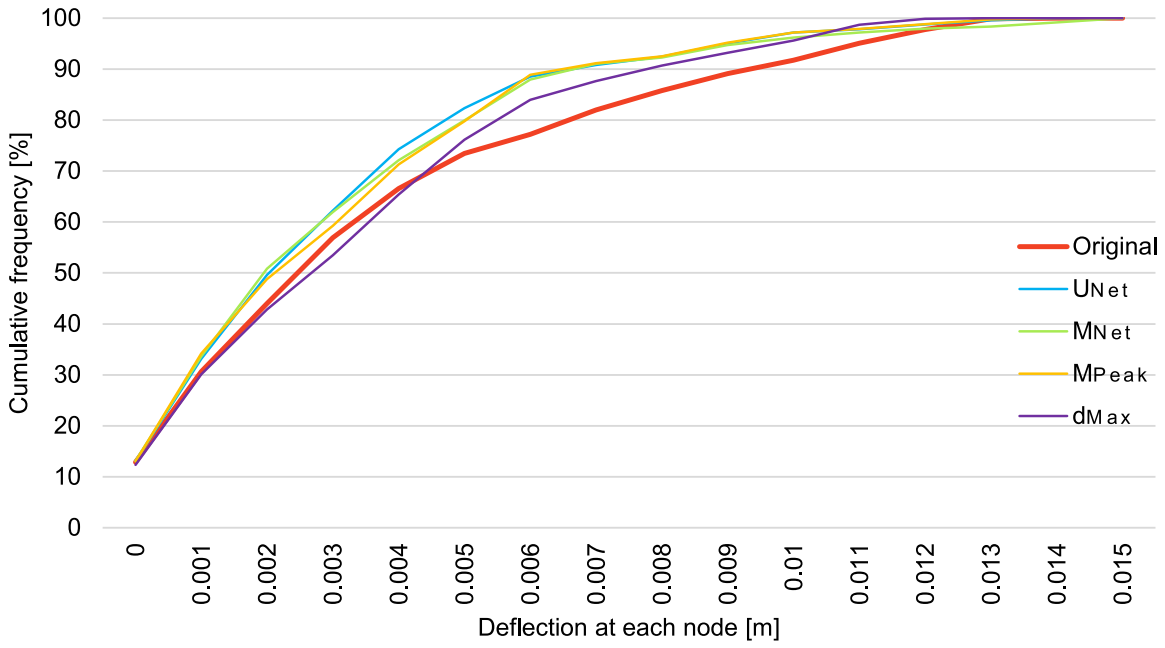
The second part of the tool of interest is the different optimisation decisions that can be taken by the user. As discussed in § 5.2.2.2, the optimisation decisions can be combined in ten different ways. For this study, three different combinations will be studied. The default settings are used with the following modifications:

- Each column position is optimised independently, case 2 in Table 5.3.
- l_{col} is computed in the analysis, case 3 in Table 5.3.
- The number of columns can be varied. In this case, l_{col} is also computed in the analysis, case 4 in Table 5.3.

For the last two cases, l_{col} is limited to a minimum of 0.250 m and a maximum of 2.0 m, and the spacing between columns is limited to a minimum of 5.0 m and a maximum of 12.0 m, for constructability considerations. Penalties can also be added on the column utilisation and on the column spacing as discussed in § 5.2.1.3. An optimisation with the default settings, only adding penalties, is run and is case 1 in Table 5.3. Penalties are also added in the two optimisations with l_{col} computed in the analysis as it makes sense that the computed size should comply with utilisation criteria and to ensure that



(a) Absolute moment.



(b) Deflection.

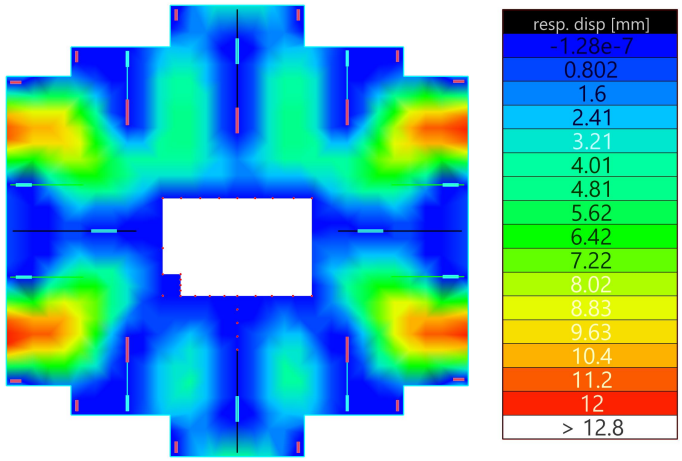
Figure 5.17: Cumulative frequency plots of moments and deflections in the slab where the red line is obtained from the original core arrangement and the other lines are obtained from the core arrangements after optimisation with the respective objective function.

the optimisation does not tend to provide too many columns when their number can be varied. A summary of the optimisation settings used are shown in Table 5.3. The table shows the values of U_{Net}, the minimum axial force utilisation of all columns of the plate $Util_{Min}$, the maximum utilisation $Util_{Max}$ and the run time of the optimisation to reach convergence, for the original column arrangement, the optimised column arrangements obtained from the default settings and the four other settings of interest. Figure 5.18 shows the deflections plots and column arrangements from the four new optimisations, which can be compared with the original one in Figure 5.14a and the default settings one in Figure 5.14b.

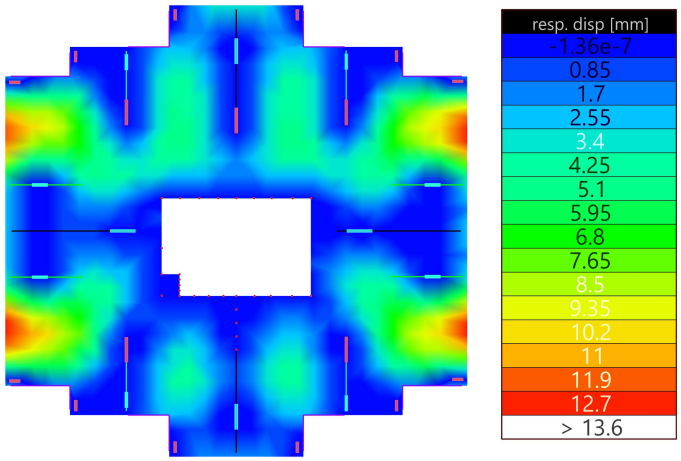
		Output data			
		U_{Net} [kNm]	$Util_{Min}$ [-]	$Util_{Max}$ [-]	Time [min]
	Original	33.8	0.41	1.10	-
Default	Drawn length Grouped Fixed number No penalty	25.2	0.43	1.43	35
1	Drawn length Grouped Fixed number Penalty	28.6	0.42	1.17	36
2	Drawn length Independent Fixed number No penalty	25.1	0.41	1.44	109
3	Calculated length Grouped Fixed number Penalty	29.0	0.81	0.90	45
4	Calculated length Grouped Varying number Penalty	29.0	0.81	0.90	71

Table 5.3: Various output data for the retrospective case study optimisation minimising U_{Net} for different optimisation decisions.

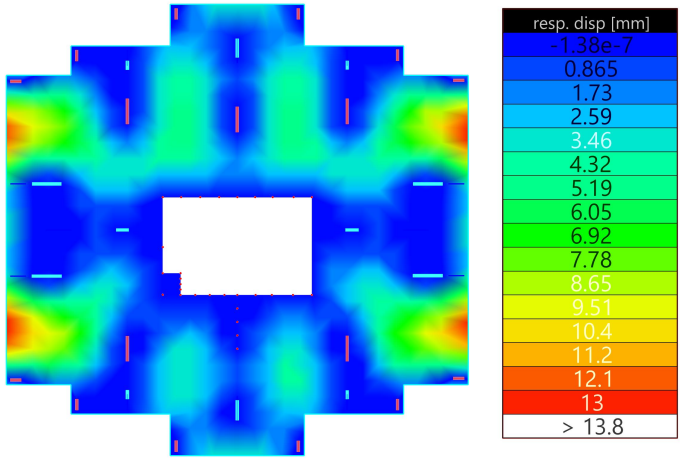
Adding penalties on the column utilisation but using the drawn length in the optimisation leads to a column arrangement, shown in Figure 5.18a, halfway between the original one, shown in Figure 5.14a, with a similar $Util_{Min}$ and $Util_{Max}$, and the



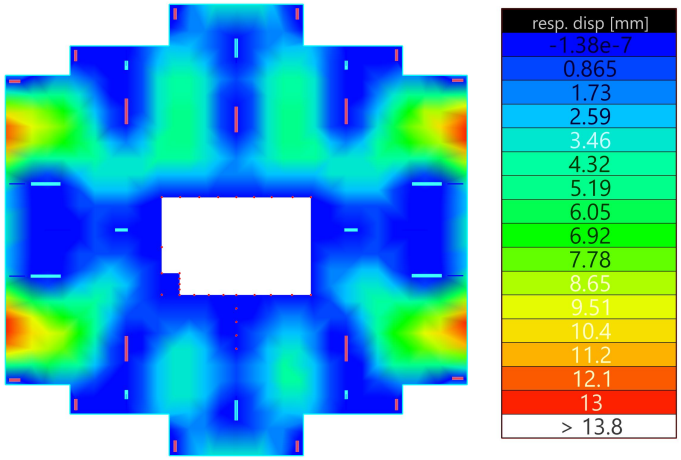
(a) Penalty on column axial force utilisation, case 1 in Table 5.3.



(b) Independent variables, case 2 in Table 5.3.



(c) Calculated l_{col} and penalty, case 3 in Table 5.3.



(d) Calculated l_{col}, varying number of columns and penalty, case 4 in Table 5.3.

Figure 5.18: Various output data for the retrospective case study optimisation minimising net strain energy for different optimisation decisions. The default settings are: using the drawn length, grouped variables, fixed number of columns and no penalties added to the objective function. Fixed columns are shown in red and variable columns are shown in blue.

default one, shown in Figure 5.14b. This could be expected as the columns should have been designed to sustain the loads in the original arrangement, therefore limiting the utilisation without changing the column size is unlikely to lead to a significantly different arrangement. However, the small changes still lead to a noticeable reduction of U_{Net}. This shows that using standard design methods, and therefore only exploring a limited number of options, is unlikely to reach optimal designs and that even small changes could be beneficial. Comparing this optimisation with the default one shows as expected that the reduction in U_{Net} is not as high given that the column movement was limited by the penalty. The run time between the two analysis is similar, which is also expected as adding or removing penalties has no impact on the size of the design space. Figure 5.18b shows the results when each column position is independent and not grouped by symmetry, with no penalties. This column arrangement is very similar to the default one shown in Figure 5.14b, and so are U_{Net}, $Util_{Min}$ and $Util_{Max}$. Given the symmetry of the slab, this results is not surprising. However, the run time of the optimisation is decreased to a third when the variables are grouped, which is expected as the number of variables goes from twelve to four. The optimisation is also more likely to reach the global optimum with fewer variables. It is therefore advised to group variables by symmetry when possible for more efficient optimisation. It is expected that this can be used on a number of projects as typically, symmetry and rationalisation of the design is used for constructability considerations. The results from the last two optimisations, where l_{col} is computed in the analysis, with and without a varying number of columns and with penalties are shown in Figures 5.18c and 5.18d. The same results were reached for both optimisations. This is because the partition lines are relatively short, between 3.0 m and 8.0 m, with a minimum column spacing of 5.0 m. This feature of varying the number of columns in each partition line is expected to give more noticeable effects with longer partition lines. The run time when using a varying number of columns is longer than when the number is fixed, which is expected as there are more variables. For both optimisations, the column arrangement obtained matches the one obtained from the default optimisation but the column lengths are different. This can be explained as the default arrangement minimises the strain energy irrespective of the columns length, but l_{col} is calculated to satisfy column axial force utilisation and axial shortening penalties. $Util_{Min}$ and $Util_{Max}$ are improved compared with all the other optimisations as expected. The run time when calculating l_{col} is longer than the default optimisation, even without a varying column number, because the need for two instances of Karamba leads to a longer run time for each iteration of the optimisation. The last observation is that U_{Net} is higher when varying l_{col} than in the default optimisation even though they have the same column arrangement. This is because the supports provided are taken at each end of the column and therefore the supports location vary between the two, changing U_{Net}. This should be taken into consideration when l_{col} is shorter than in the original design as it means that

a more efficient column may lead to a thicker slab or with more reinforcement. In most high-rise buildings, the vertical structural elements, including the columns, require less material than the horizontal elements which are the slabs (Taranath 2009). This should be considered when sizing the columns. To see the impact that the column size has on the performance of the slab, the tool provides the option of using a constant length for all columns. These features of computing l_{col} or using a constant length could be used without running any optimisation for rough column sizing based on axial load capacity or for slab performance assessment.

This retrospective case study shows that using the computational tool developed can reduce the net strain energy in the plate by more than 25%, the net bending moment by more than 10% and the net deflection by more than 20%. Detailed analysis of the slab with the column arrangement with minimised U_{Net}, or with an arrangement derived from the various optimisations, would be necessary to assess the material savings that could be made in the slab. Based on BS EN 1992-1-1:2004 (2004) guidelines for the design of slabs and given that bending strength and deflections are expected to be governing criteria for slab depth and reinforcement provision (Brooker 2009), it is estimated that an optimised column arrangement could reach approximately 8% reduction in slab reinforcement compared with the original arrangement. These savings could be done for each of the 25 storeys of the building, reaching considerable material and embodied carbon savings. Regarding column optimisation, the sum of column length in the original arrangement is 14.4 m whilst it is 13.7 m in the arrangement with computed l_{col}. Assuming a floor height of 4 m and a column thickness of 0.250 m, this means that the concrete and reinforcement volume necessary for these columns could be reduced by 4.9%. Such savings can be achieved by using the automated tool, combined with engineers' technical expertise, in less than one hour for the fastest optimisation.

5.4 Conclusions and discussion

A computational tool has been developed to assist efficient slab and column design in concrete high-rise buildings under vertical loading. It has been developed in partnership with industry to integrate the 'rules of thumb' that are used by engineers when designing such structures, for the tool to be applicable to a range of projects and at various design stages whilst ensuring pertinent results and encompassing constructability considerations. Dialogue with industry also helped increase the efficiency of the tool and reduce the design space available. Similar to the tool discussed in Chapter 4, the aim is for engineers to use their technical knowledge whilst using the tool which enables column arrangement optimisation based on various available objective functions, with an overarching aim of

reducing embodied carbon through material minimisation of concrete columns and slabs. The column arrangement is modified by moving columns that are located in partition rather than locate them anywhere on the plate, to comply with architectural constraints, achieving minimum disruption. Axial shortening considerations can be included in the optimisation. The computational tool has been developed in Rhinoceros 3D/Grasshopper 3D (RH/GH) which is an accessible and user-friendly software which enables finite element analysis (FEA) through the Grasshopper 3D (GH) plug-in Karamba. It can facilitate the dialogue between key stakeholders as architects commonly use RH/GH and the results are easily visualised. The tool can be used on standard personal workstations. The user can modify and optimise the column arrangement, and assess the performance of the slab. Different options are available for the optimisation, depending on which design stage the tool is used in. The columns can be sized as part of the analysis for axial load capacity. If multiple optimisations are conducted, the results can easily be outputted for comparison and assessment.

5.4.1 Assessment of the computational tool

The computational tool has been used on three different case studies. The first one assessed the performance of GA, varying the size of the design space for a circular, symmetrical plate. GA in Galapagos appeared to reach the global optimum, however the run time and accuracy of the optimisation is dependent on the number of variables and the size of the design space. To reduce the optimisation run time and ensure finding the global optimum, options are provided in the tool to reduce the design space. They include grouping the partition lines in which the columns can move based on symmetry, reducing the number of variables, or changing the discretisation of the partition lines. This model was also used for a mesh convergence study using Karamba. For the regular, symmetrical design, the study showed that a mesh resolution of 1.0 m reached results with less than 2% difference compared with the finest mesh analysed. Given the scope of the study, this is deemed sufficient. A second case study with a more irregular slab design was used for numerical comparison of the FEA part of the tool in Karamba with the more robust FEA software Abaqus. This model showed that with a mesh resolution of 1.0 m, the von Mises stress contours are in agreement in the two softwares, however for peak stresses the results from Karamba are lower than those from Abaqus. With a finer mesh, the stress contours are in agreement between the two software, as well as the peak stresses. However, the finer mesh in Karamba triples the run time of the optimisation. It is also expected that running the optimisation in Abaqus could increase the optimisation run time as one analysis requires around 40 s including preprocessing. It is less intuitive and smooth in Abaqus to generate and modify models compared with GH. Given the

applications the tool could be used for, what is important is comparing the results whilst changing the column arrangement rather than using the results for detailed design. The optimisation run time may also be critical in early design stages, when the slab design may change often and results need to be obtained rapidly. Therefore in early design stages, a 1.0 mesh resolution is deemed sufficient and a 0.5 m mesh resolution can be used for more detailed analysis. The tool enables conducting FEA in early design stages, for a significantly greater number of options than would be done with standard design methods, reaching potential material and embodied carbon reductions of 5 to 10%, as shown by the third case study.

5.4.2 Recommended use of the tool

The aim of the tool is to be applicable at different design stages to optimise and assess the column arrangement and slab performance in concrete high-rise buildings. The main application of the tool is in early design stages where it enables exploring many options and material savings in the slab and columns in a short time frame. Using architectural drawings, the user needs to identify which columns can be moved in partition walls. In Rhinoceros 3D, the user needs to draw the building outline that is used as the slab external edge, cores that are internal edges to the slab, balcony connection lines to the slab if loading from the balconies is to be included in the analysis, any supports with fixed positions, the partition lines along which the columns can move, in sublayers if they can be grouped by symmetry to increase the optimisation efficiency, and the column lengths if they are to be used by the analysis. A template with the relevant layers and sublayers is provided to facilitate data importation in GH. In GH, the user can make decisions on what column length to use, which can be computed in the analysis, if the number of columns can be varied in the optimisation and whether to group the variables based on symmetry or not. The user also needs to set other parameters in GH. The user can then choose from five objective functions to be used for optimisation. Minimising net strain energy appears to reach the best results across all the output data and should be used if rapid optimisation is required. The advised use of the tool is to run multiple optimisations with the different objective functions and compare the results to make informed decisions on the column arrangement. Penalties on column utilisation can be used, particularly when sizing the columns in the analysis or to consider axial shortening as part of the optimisation. The mesh resolution can be modified depending on the design stage it is used at. The tool can also be used to size the columns for axial load capacity without running any optimisation, increasing its versatility. The retrospective case study showed moving the columns by a few meters in the partition walls could reduce strain energy in the slab by over 25% and the bending moment by over 10%, which could lead to non-negligible

material and embodied carbon savings given that bending strength and deflections are often governing criteria in slab design. These results could be achieved easily thanks to the tool, in a reasonable time frame for industry, compared with standard design methods where a limited number of design options are analysed, likely to miss improvements that could be made with very small changes in the column arrangement.

5.4.3 Limitations and future work

The tool is to be used for concrete slab and column optimisation and assessment through column arrangement optimisation, mainly in early design stages. The results outputted are aimed for optimisation of the column positions and for column arrangement comparison but are not expected to be directly used for sizing or detailed design of the slabs and columns. Because detailed design is not performed in this computational tool, direct assessment of material savings is not possible. Using the tool in combination with other tools more appropriate for detailed design by sharing relevant data requires further work but could prove beneficial.

The objective functions and variables selection was done in collaboration with industry. This means that the results are applicable for real projects. However, optimisation with other objective functions or with less constrained variables, as can be found in literature, could reach different, more optimal results. Whilst these results may not be as applicable, comparison between a less constrained optimum and an optimised column arrangement fitting architectural constraints could inform the design process and enable engineers to discuss alternative options with architects or other stakeholders with structural analyses from the earliest stages. More flexibility in the variables could be implemented in the tool in the future. The variables were also constrained to reduce the size of the design space. For large slabs with a high number of partitions and where symmetry cannot be identified to reduce the design space, the optimisation run time would increase significantly and the probability of reaching the global optimum may be reduced.

In tall building design, load take-down and axial shortening are important considerations. The latter can be included in the optimisation process, and for slabs it is expected that the optimised column arrangement will achieve material reductions at each storey. It may be interesting to use the results of the tool with a load take-down analysis to assess a building performance in the z direction rather than only in the x-y plane as is done currently. This could enable optimising the column size with height including consideration of axial shortening, accounting for the resistance supplied by the core to vertical loading.

Chapter 6

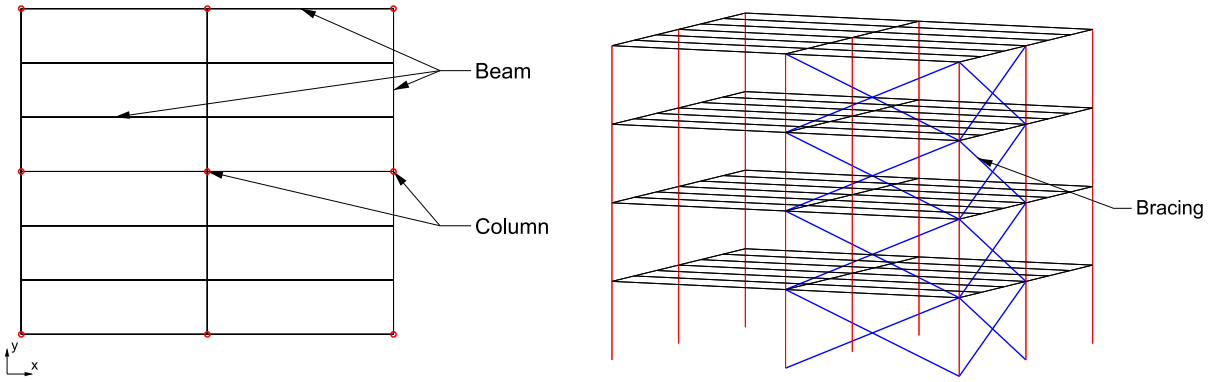
Steel high-rise building optimisation

In this Chapter, steel tall buildings are the structural form used for the development of a computational optimisation tool. The methods used are explained, the tool is tested on case studies and is discussed.

The author would like to thank Theodoros Mourtis from Robert Bird Group (RBG) for his advice during the development of the computational tool.

6.1 Introduction

Steel is a common material used in construction and can be used in tall buildings, as discussed in Chapter 2, § 2.4.3. Steel members such as beams and columns can be used to sustain and transfer vertical loads to the ground (Parsons et al. 2010). These members are typically arranged in a grid of beams with columns at some intersections of beams as shown in Figure 6.1a. This is because steel members are manufactured off-site and brought to site. Custom members can be fabricated, but this is typically more expensive and can make the construction process more difficult. Usually, standard lengths and cross-sections are therefore used when designing buildings, explaining the utilisation of a grid layout. This is particularly relevant for symmetrical buildings with a regular building envelope as the loading conditions will be similar throughout a floor system so similar members can be used. Lateral stability systems of such buildings to resist for example wind loading include concrete cores or steel bracing that can also be arranged in a core (Steel Buildings in Europe 2012). Bracing is represented in Figure 6.1b.



(a) Plan view.

(b) Elevated view on four storeys.

Figure 6.1: Illustration of steel building structural elements.

As explained in Chapter 2, there is existing literature on the optimisation of steel structures. Existing research is applied to other structural forms (Kociecki and Adeli 2013, 2014; Frans and Arfiadi 2014; Cicconi et al. 2016) than tall buildings or focussed on sizing optimisation (Chan et al. 1995; Balogh and Vigh 2013; Eleftheriadis et al. 2017b). There is also research available on seismic design for steel tall buildings (Xu et al. 2006; Papavasileiou and Charmpis 2016). It was also identified that structural elements in steel buildings tend to not be fully utilised, partly because of the amount of design changes that can happen in early design stages and the time that standard design methods used in engineering offices require (Moynihan and Allwood 2014; Dunant et al. 2018). As discussed in Chapter 3, utilising computational tools in the construction industry could help increase the efficiency of design and the optimisation of structural elements. Based on conversations with RBG engineers, structural arrangement optimisation of steel grid and sizing optimisation was identified as an area of interest. It could enable searching the design space efficiently to reduce the structural mass by using members that are more fully utilised. Therefore a computational tool has been developed in Rhinoceros 3D (Robert McNeel & Associates 2018) (RH) and Grasshopper 3D (Rutten 2016) (GH), an accessible, user-friendly and easily adapted software. The tool is aimed to be used in early design stages to optimise grid arrangement and element sizing for steel tall buildings, including analysis, constructability considerations and 'rules of thumbs' that engineers would use when designing such structures. The aim is for the tool to be versatile and applicable to a range of projects. Some companies appear to have developed tools that can be used for steel tall building optimisation, such as the high rise explorer from Ramboll (Jeffries 2018) or the design explorer and generative structure tools from Thornton Tomasetti (Thornton Tomasetti 2012; Howes 2016), however limited information on these tools is available and it is not clear whether analysis and constructability considerations are used in the tools.

The methods used in the development of the tool are examined. The tool has been used on case studies and the results are presented. Discussion on this computational tool is provided with concluding remarks.

6.2 Methods

Similar guidelines to those discussed in Chapter 4, § 4.2 have been followed to develop a computational tool aimed at lowering the embodied carbon of steel tall building as well as increasing the efficiency of the design process for such structures. The optimisation is conducted in two steps, first to optimise the grid layout subjected to vertical loading for minimal structural mass with sizing optimisation. Bracing can then be added to analyse the structure when subjected to horizontal loading and compare bracing arrangement performances. Rhinoceros 3D/Grasshopper 3D (RH/GH) has been used to develop the tool. The problem formulation is presented, followed by the proposed optimiser. An overview and explanations of the key steps of the GH definition developed are given in Appendix B.3.

6.2.1 Problem formulation

6.2.1.1 Design variables and parameters

In the first step, to optimise the grid layout for minimal mass when subjected to vertical loading, the variables that can be used in the automated optimisation are:

- The grid spacing in one direction.
- The grid spacing in the orthogonal direction.
- The grid orientation.
- The grid offset in the x direction.
- The grid offset in the y direction.
- The cross-section of the different structural elements.

These varibles are used to model the various structural elements. These are displayed in Figure 6.2. In this example, the grid orientation is aligned with the x-y axes. The spacing in the x direction is smaller than the spacing in the y direction so by default, the beams aligned with the x direction, in orange in Figure 6.2, become the primary

beams and beams aligned with the y direction, in green, are secondary beams. This leads the spanning direction of the slabs which is used to compute the loading as explained in § 6.2.1.2 and the spanning direction can be switched by the user. Columns are located at the intersection of the beams in the two orthogonal directions, shown in purple. The last two variables allow to move the grid layout in the plan without changing the spacing or the orientation, in order to cover as many grid arrangements as possible in the optimisation. The cross-section of the different structural elements can be optimised in the analysis for minimum mass which is done by the finite element solver of GH, Karamba (Preisinger 2013). The different elements can be grouped to be given the same cross-section for constructability and cost considerations, for example all primary beams to have the same cross-section.

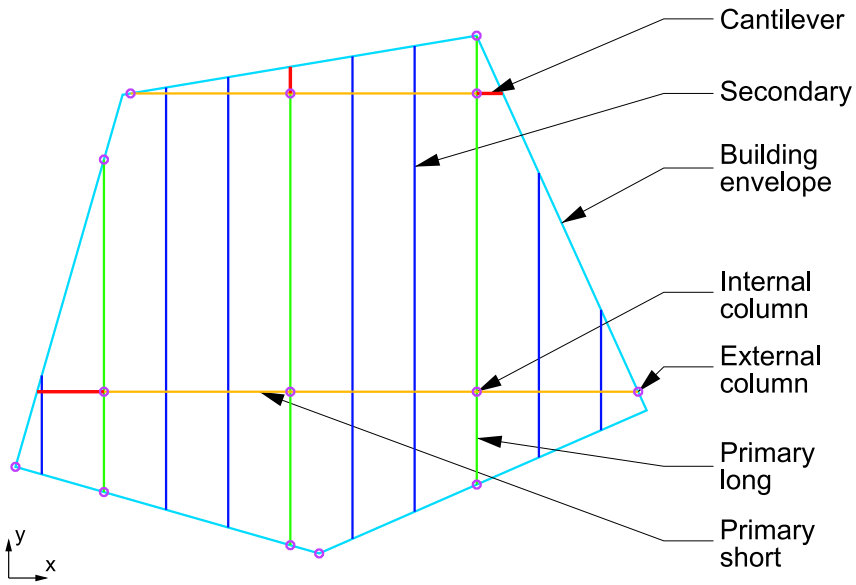


Figure 6.2: Sample plan view of the various structural elements that can be part of the optimisation process.

Additional parameters that are not variables in the automated optimisation but that can be set by the user to model the grid layout are:

- The building outline to be populated with the grid layout, which is assumed to be constant with height. The outline is modelled with beams at each storey.
- The approximate spacing between secondary beams d_{sec}. If the secondary beams connected to columns in the grid are greater than this value, additional secondary beams will be provided, perpendicular to the primary beams but not connected to columns, to have a slab span close to the one specified. They are shown in blue in Figure 6.2. To distinguish between beams that connect to columns and beams that do not, primary beams are called 'primary short', secondary beams that

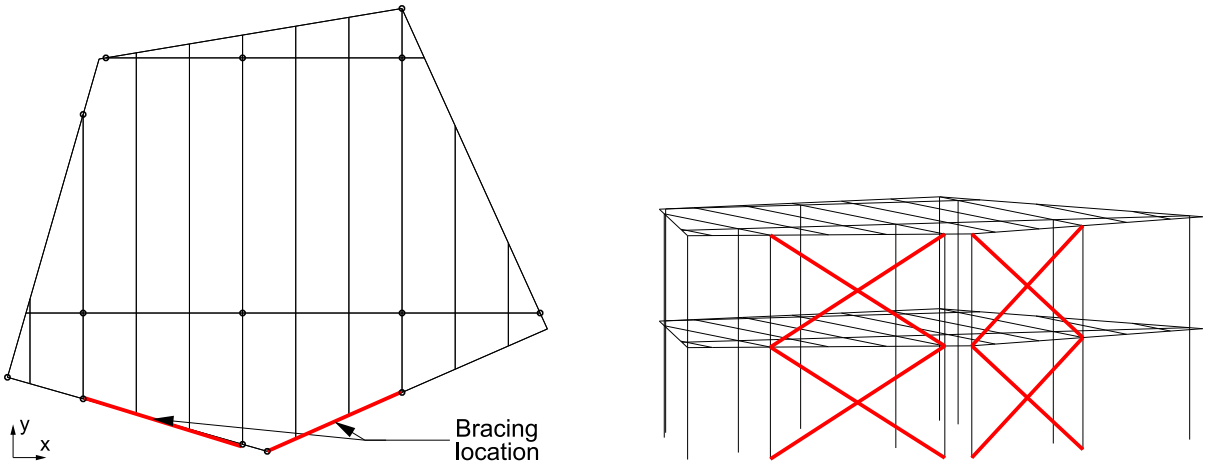
connect to columns are called 'primary long', and other secondary beams are called 'secondary' and this convention is used in Figure 6.2. This is to provide flexibility in the connection types and the grouping of cross-sections for sizing optimisation as discussed in § 6.2.2.4.

- The number of storeys.
- The floor height h, taken as constant with height. The number of storeys and floor height are used to model the building in height.
- The maximum distance from a corner on the outline to any other column before adding a column in this corner, $d_{maxCorner}$. This is to moderate clusters of columns near the outline of the building.
- The maximum distance primary long and short beams can cantilever to the outline before adding a column at the end of the beam on the outline $d_{maxCantilever}$. This is illustrated in Figure 6.2 where cantilever primary beams are shown in red whereas longer primary beams have an added column on the outline.
- The vertical loading which includes the potential slab self-weight, live and dead loads, façade load. The slab is not directly modelled to reduce the size of the model so a theoretical thickness of the slab needs to be provided to compute the self-weight load. Loading is discussed in detail in § 6.2.1.2.

The second part of the tool is to analyse the structure when subjected to horizontal loading with bracing arrangements. There is no automated optimisation here, the aim is to compare the performance of different bracing arrangements. In this case, the variables would be the bracing location which can be located between any two columns. One potential arrangement on the example is illustrated in Figure 6.3. The user can draw multiple arrangements and analyse and compare the structure performance. The bracing elements are sized in the analysis for minimal mass. The modelling of the bracing is further explained in § 6.2.2.4. This is all done in the same GH definition and requires all the parameters from the first part. One additional parameter is required. It is the wind direction for the loading. More details are provided in § 6.2.1.2.

6.2.1.2 Loading

In the first part of the tool, the aim is to optimise the grid arrangement and element sizing for minimal mass when subjected to vertical loading. The vertical loads that are applied are the theoretical self-weight load of the slabs which are not modelled, by multiplying the specific self-weight of the slab that will be used with a rough slab thickness, which gives



(a) Plan view.

(b) Elevated view on two storeys.

Figure 6.3: Illustration of the bracing modelling on a sample grid layout.

a uniformly distributed surface load. The live and dead loads are included as uniformly distributed surface loads. The loads are calculated for ultimate limit state (ULS) design as is usually done for member sizing. In order to reduce the model size, the slabs are not modelled as shell elements. It would considerably increase the run time of the model assembly and analysis because of the increased number of degrees of freedom per element compared with beam elements. This could be problematic in early design stages and for automated optimisation where it can be important to obtain results in short time frames. Therefore an approximation is made for the loading of the beams and is shown in Figure 6.4.

For a simple load take-down, the slab is assumed to be one-way spanning between the secondary and primary long beams. They have a contributing area, known as tributary area, where the load applied is transferred to the corresponding beam. This load can be modelled as a uniformly distributed line load. The load is then transferred to the primary short beams which in turn transfer the load to the columns to be taken down. Because the tool is to be used in early design stages and not for detailed design, the tributary area is assumed to be the length of the relevant beam multiplied by the spacing between secondary beams, as illustrated in Figure 6.4. It shows that the approximate tributary areas do not match exactly with the building outline so the loading of each beam may vary marginally compared to the real beam loads. However, for the example in Figure 6.4, the sum of the approximated tributary areas is 0.48% greater than the area inside the building outline which suggests that the assumption is reasonable for early design stages. This was agreed with RBG engineers. A façade load is also added as a uniformly distributed line load to the beams on the building outline, which will be transferred to the columns on the outline and primary cantilever beams.

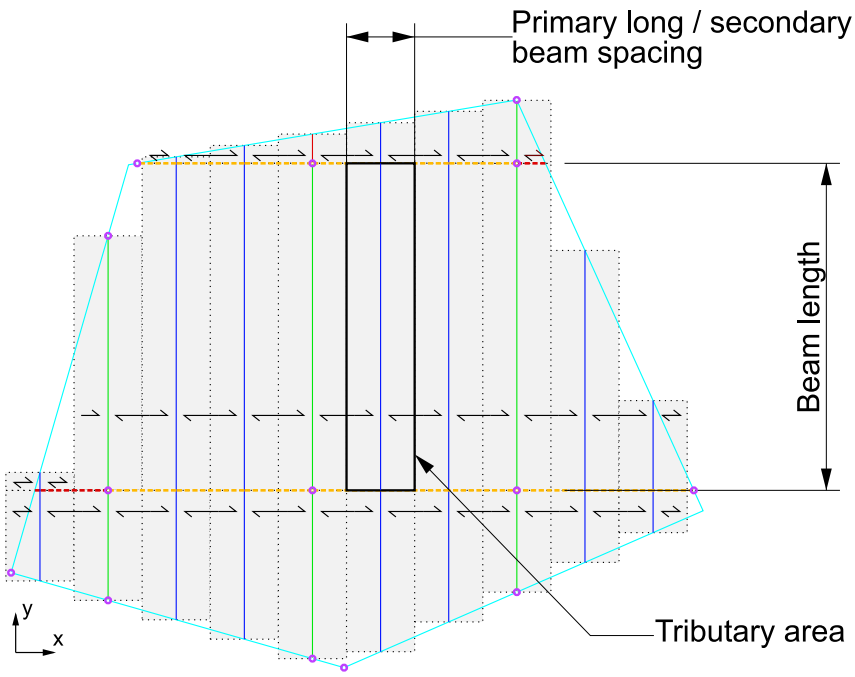
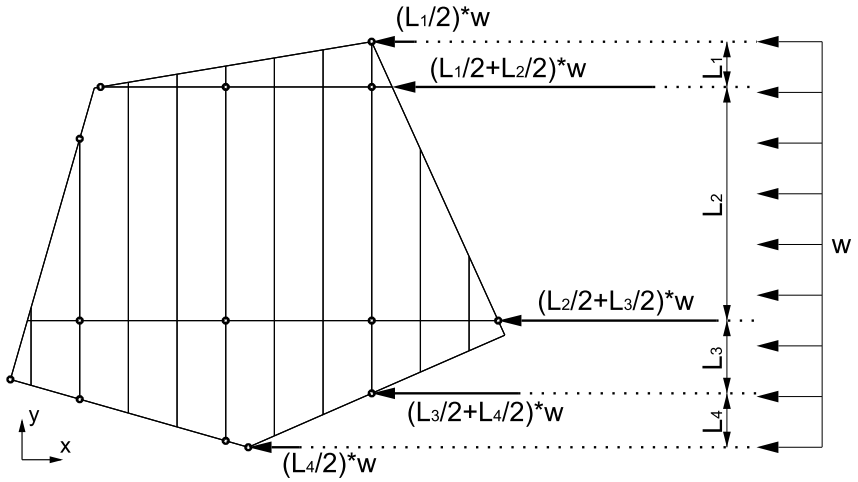


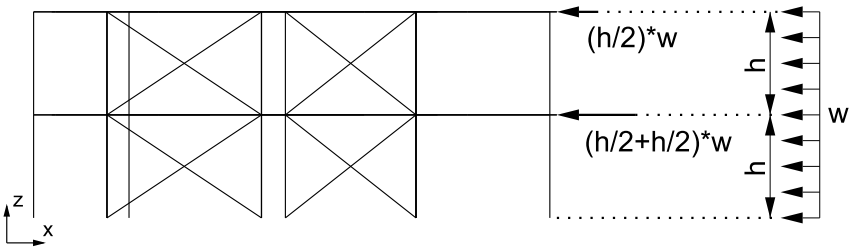
Figure 6.4: Illustration of the vertical loading distribution on a sample grid layout in plan view.

To provide lateral stability, the design is usually influenced by the building height. For buildings up to four storeys, rigid frames can be used. This can easily be modelled in the tool by modifying the connection type in the model but this is not the aimed application of the tool. For taller buildings, braced frames can be used for mid-rise buildings and concrete or steel cores can be used for mid and high-rise buildings (Steel Buildings in Europe 2012). In this case, pinned connections are typically used. A tool to optimise concrete cores has been developed and is discussed in Chapter 4 and can be used for steel buildings. For braced frames and braced steel cores, a second part has been added to the tool discussed here to model the bracing, analyse it under wind loading and compare bracing arrangements that could be available for a design. The user can model the wind coming from multiple directions to size the bracing elements for the worst case scenario. The loading condition for one wind direction is shown in Figure 6.5.

A similar method to the one explained in Chapter 4, § 4.2.2.2 is used and the loading given in Equation (4.1) is used except that the load is applied to multiple points for accurate representation. It is applied as point loads at floor levels to columns that are located on the outline of the building and primary short or long beams that are connected to the outline and that are oriented within 45° of the wind direction. This is shown in Figure 6.5a where a load is applied at a beam without column because it is aligned with the load direction. These have been selected as they are the elements expected to be used for wind loading take-down. The line of projected length L is divided to each point of



(a) Plan view.



(b) Elevated view on the top two storeys.

Figure 6.5: Illustration of the horizontal loading distribution on a sample grid layout.

application as show in Figure 6.5a based on the distance between two consecutive points where load is to be applied. As in Chapter 4, the building height h in Equation (4.1) is halved in the top floor due to the tributary area of each storey. This is illustrated in Figure 6.5b. This loading with the different load magnitude applied to the different points in plan is expected to be able to capture torsion caused by any wind direction. Because the slabs are not modelled, beams with a very high stiffness are used to link all the columns in any storey, as described in Chapter 4. This is to capture the diaphragm action of slabs, as they ensure that there is no deflection in plane at floor levels.

6.2.1.3 Objective function

In the first part of the computational tool which relates to analysis under vertical loading, the objective function is to minimise structural mass. This is done through structural arrangement optimisation and sizing optimisation. The sizing optimisation is done through Karamba to minimise mass as discussed in Chapter 4, § 4.2.1. For any grid arrangement, the total mass of all structural elements after sizing optimisation is obtained and is used as the objective function to be minimised using genetic algorithms

(GA) in the GH component Galapagos. It was observed when running various analyses that if the variables allow a grid arrangement without secondary beams, this option is usually optimal for mass minimisation as the number and therefore mass of secondary beams added with larger spans is usually greater than the number and therefore mass of columns removed with the larger spans. However, for architectural constraints, larger spans may be preferred. Various objective functions have been investigated to account for this and it was found that to obtain longer spans as optimum, the objective function had to be artificially modified and did not impact as much mass minimisation. For this reason, minimising mass of the structural elements has been kept as the objective function and penalties can be added to account for connections where a beam to column pinned connection or fully fixed connections can be heavier than secondary pinned connections. Connections are further developed in § 6.2.2.4. This is done as a percentage of the mass of the relevant beam and this percentage can be set by the user such that the objective function is:

$$\min \left(W_{material} + 2 \sum_{i=1}^{N_{pin}} Wpin_i \times P_{pin} + 2 \sum_{j=1}^{N_{fixed}} Wfixed_j \times P_{fixed} \right) \tag{6.1}$$

where $W_{material}$ is the structural mass of beams and columns, N_{pin} is the number of beams with pinned connections (two connections per beam), $Wpin_i$ is the mass of each pinned beam, P_{pin} is the percentage of the mass of the pinned beams to be added per pinned connection, N_{fixed} is the number of beams with fixed connections (two connections per beam), $Wfixed_j$ is the mass of each fixed beam and P_{fixed} is the the percentage of the mass of the pinned beams to be added per fixed connection.

This is a reasonable assumption as fixed connections are typically heavier than pinned connections. Additionally, the user can set the spacing in the two orthogonal directions to minimum or maximum values in the optimisation or give them a specific value and remove them as variables. Constraints on the variables are discussed in § 6.2.1.4. This allows the user to analyse the optimum grid orientation whilst following architectural constraints, which enables searching a greater design space than would normally be done.

In the second part of the computational tool where the structure is analysed when subjected to wind loading, there is no automated optimisation. The objective here is to analyse and compare the performance of the building against multiple wind directions for the various bracing arrangements that could be available. In this case bracing elements and columns connected to bracing are sized in the analysis for minimal mass by Karamba.

The aim of the computational tools discussed in this thesis is not only to automate design processes and to minimise structural mass but also to allow engineers to search the

design space more efficiently in order to make informed decision. The tool can be used in other ways than automated optimisation for example for approximate sizing optimisation on a set grid layout, manually changing the variables to gain understanding on the impact they may have on a structure's performance or mass, or analyse the structure with a set grid layout under wind loading to compare bracing arrangements for example.

6.2.1.4 Constraints

The variables have been constrained to encompass design guidelines that engineers would follow for constructability and cost considerations which have been derived from conversations with RBG engineers. This means that the results of the optimisation would be relevant for design offices but for some variables, it also enables reducing the design space, thus reducing the run time and increasing the probability of finding the global optimum in the automated optimisation. The constraints are the following:

- Structural elements can be grouped to be allocated the same cross-section. For example, all secondary beam elements can be given the same cross-section which will have minimal mass for the worse case scenario. That may mean that some structural elements will be over-designed with a greater mass than required for load bearing capacity. However, for cost, manufacturing and construction considerations, it is common that the same cross-section will be used for similar structural elements. The user can select which elements to group.
- The offset of grid in the x and y directions can go from 0 to the maximum grid spacing in increments of 1.0 m to reduce the design space whilst allowing to search the full space. It could be refined when optimising a grid arrangement with less flexibility.
- The grid spacing can go from 3.0 m in one direction and 6.0 m in the orthogonal direction to 22.5 m in both directions in 1.5 m increments. This means that there are 15 possibilities in each directions. This is done in part to reduce the design space but also because these are the common lengths that steel beams are produced in.
- The grid orientation can go from 0° to 90° in 5° increments. Going from 0° to 90° enables to cover all 360° orientation as either direction of the grid can become primary or secondary due to the spacing formulation. The 5° increments are used to reduce the design space but this can be changed by the user for more detailed results.

Some of the constraints, such as the grouped section sizing, have been developed to be modified by the user easily as can be seen in § 6.2.2.2. Other constraints are not as

explicitly defined but can all be modified by the user so that the tool can be applied on a variety of projects in more or less details.

6.2.2 Proposed optimiser

6.2.2.1 Modelling simplifications

The tool enables analysis and optimisation of steel frame buildings when subjected to vertical and horizontal loading. The aim is to reduce the embodied carbon of such structures and to increase the efficiency of the design process that engineers go through. Simplifications have been made to model these structures towards these objectives. In the previous section, constraints applied to the variables have been discussed. They allow to reduce the design space and for the tool to be applicable on structural engineering projects. One simplification that was not discussed on the sizing optimisation is that the same section is used for every storey in height for each group. This seems a reasonable simplification as the same load is applied at every storey so horizontal members are expected to require similar load bearing capacity. Additionally, the user has options on the sizing of the columns. All columns in one floor can have the same section or they can be separated between internal and external columns as the loading may be different between the two depending on the connection to the outline beams and to primary beams and the façade loading. Also, another option is provided for the column sections to vary with height. Columns may be continuous over multiple storeys and engineers often keep the same section with height for constructrability and design considerations which is why the option of column sections to be constant with height is provided. Because the loading of the columns changes in each storey as the columns are responsible for the load take-down, it is expected that the column sections could be meaningfully reduced with height so this option is provided. The bracing elements are sized in the second part of the tool by Karamba. By defaults they are all given the same section. The columns to which the bracing elements are connected can also be resized in this second part.

Loading simplifications have been made as discussed in § 6.2.1.2 for the vertical loading so that different building geometries can easily be considered and for horizontal loading through the application points and the modelling of the diaphragm action of the slab. Similarly to what is discussed in Chapter 4, to reduce the model size, the slabs are not modelled as shells. To model the diaphragm action that the slabs have when wind loading is applied, stiff beams with a high Young's modulus (E), high shear modulus (G) and negligible specific weight are used linking all columns to the centroid of the building outline in plane. Only static analysis is conducted in this computational tool. This is a

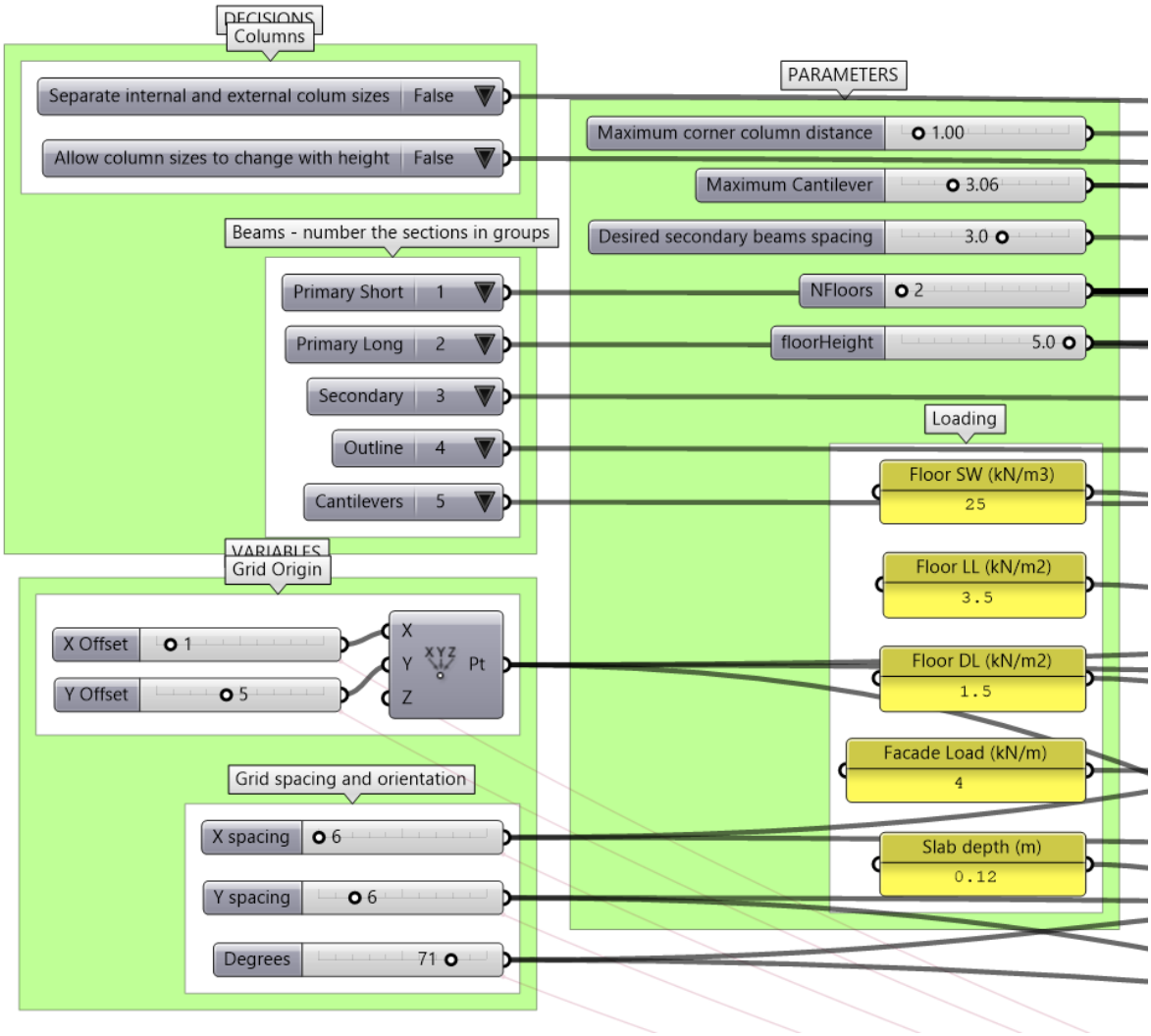
reasonable simplification for early design stages for structural arrangement optimisation and comparison but in further design stages, floor vibrations and dynamic checks would be necessary. They are outside of the scope of this study. Vertical loading is removed when horizontal loading is applied to truly assess the response of the building when subjected to wind loading. In further design stages, the loads should be combined to verify and potentially modify member sizes. The tool aims at rough sizing but more importantly compare and assess how different bracing arrangements perform for lateral stability. The optimal arrangement when considering only wind loading is expected to be the same when adding vertical loading even though members may need to be resized.

Another simplification is that linear analysis is conducted in this tool. This is a reasonable assumption for structural arrangement optimisation and preliminary sizing of members, however in further design stages, second order effects may need to be considered as well as residual stresses and geometrical imperfections. The aim of the tool is to optimise structural arrangement and member sizing for minimum mass but the outputs are not expected to be final. The aim is to enable searching a greater design space than is done using standard design methods for engineers and other key stakeholders to make informed decisions in the design process. These simplifications are therefore deemed acceptable. Another simplification is the modelling of the bracing elements. By defaults, cross bracing is provided as shown in Figure 6.3b but this could be modified by the user if needed. Bracing can only be modelled between existing columns of the grid arrangement which is a reasonable simplification with regards to what is done on engineering projects.

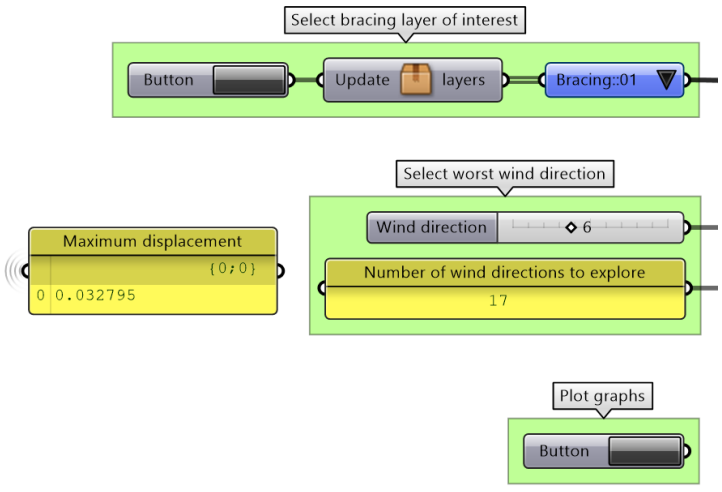
6.2.2.2 User interface

For easy utilisation of the computational tool, the necessary input from the user has been split between RH and GH. In RH, the user simply needs to draw the building envelope in a layer called Outline. For optimisation under vertical loading, this is the only input required in RH. Once a grid arrangement is obtained, the user can draw in RH in plan view the location of braced bays. The grid arrangement in GH can be displayed in RH and the user needs to approximately draw where the bracing should go in a layer called Bracing. A braced bay has to be between two columns as illustrated in Figure 6.3a. The braced bays can be arranged in a core if necessary. If multiple bracing arrangements are to be analysed and compared, they should be drawn in different sublayers of the Bracing layer. The remaining required input must be provided in GH. It is shown in Figure 6.6.

In Figure 6.6a is shown the input for the first part of the computational tool related to optimisation under wind loading. The decisions to be taken by the user on the sizing optimisation are in the first group. They include the grouping of the columns and how



(a) Analysis and optimisation under vertical loading.



(b) Additional input for horizontal loading analysis.

Figure 6.6: Input required from the user in the GH definition.

horizontal structural elements should be grouped. They are separated in five groups that are primary short, primary long, secondary, outline and cantilever beams. If the same section should be used for secondary beams and primary long beams, the user can give them the same group number for example. In the second group, the variables that are used in the automated optimisation are defined. The constraints discussed in § 6.2.1.4 are used to define the sliders that act as variables in Galapagos. The user can modify them to change the design space or can give a specific value to a slider and disconnect it from Galapagos to fix variables. In the third group, the additional parameters discussed in § 6.2.1.1 should be set. They include the maximum cantilever distance from another column before adding a column at the end of a primary beam connected to the outline, the maximum distance from another column before adding a column in a corner of the building outline, the desired span between secondary beams, the number of floors in the building and the floor-to-floor height. The loading is also set including the floor self-weight and theoretical slab depth to calculate the gravity load from the slab. Live and dead loads and façade loads should be provided.

The input necessary for the part of the computational tool that relates to analysis under wind loading is shown in Figure 6.6b. This tool is dependent on the first part of the tool and its input is also required. If multiple bracing arrangements are available, the user can select them one by one to analyse and compare them, which is shown in the first group. In the second group, the user can modify the wind direction to size the bracing elements and the columns connected to bracing elements and to analyse the structural performance from different wind directions. Deflection and inter-storey drift plots can be obtained in the RH/GH interface by pressing the button in the third group.

6.2.2.3 Optimisation process

As discussed in Chapter 4, § 4.2.1, GA from the component Galapagos in GH is used for the automated optimisation of the grid arrangement when subjected to vertical loading. The cross-section optimiser provided by Karamba is used for sizing optimisation. For a particular grid layout, the structure can also be analysed under wind loading with one or more bracing arrangement options. The optimisation process is as follows:

1. (a) User to input the relevant parameters in RH/GH, as discussed in § 6.2.1.1.
   (b) User to make sizing optimisation decisions and modify the structural arrangement variables if necessary.
   (c) Iteration:

i. Karamba used for analysis and sizing optimisation under vertical loading for ULS design based on the decisions provided by the user. The Karamba process for sizing optimisation is discussed in Chapter 4, § 4.2.1. The total structural mass is outputted and potential connection mass is added. The connection type and mass can easily be modified in the GH definition through the Joint component from Karamba.

ii. Galapagos modifies the variables that define the grid arrangement through GA.

(d) GA converges with optimised grid arrangement.

2. (a) User to draw bracing arrangements available in RH over the grid layout.

(b) Karamba used for analysis under wind loading with sizing of the bracing elements and columns connected to bracing elements for each bracing arrangement.

(c) User can compare various bracing arrangements.

As discussed in § 6.2.1.3, the tool can also be used without automated optimisation from Galapagos if a grid layout is already decided for basic analysis, for sizing optimisation, to only use the second part of the analysis with wind loading or to manually modify the variables to gain understanding of their impact on the structural mass. In the two parts of the optimisation, the user can use Karamba to display various results such as stresses, bending moment diagrams or deflections. In the second part of the tool, custom Python components are used to display deflection and inter-storey drift plots automatically.

6.2.2.4 Structural model definition

Karamba is used for modelling and analysis of steel buildings. Two-noded beam elements, discussed in Chapter 4, § 4.2.1 are used. Beam elements are not discretised when used for finite element analysis (FEA). Given the element definition, the simple loading conditions and the fact that nodes are created at any connection or point load location, for example in primary short beams where secondary beams are connected, it is not necessary to discretise the elements further. By default in Karamba, all degrees of freedom at each node of beams elements are fixed (Preisinger 2016). However when designing steel multi-storey buildings, pinned connections are often used at the end of primary and secondary beams and of outline beams which span between columns as well as at the end of bracing elements (Parsons et al. 2010). When primary beams are connected to the outline but no column is provided, connections are taken as fully fixed at both ends so that the primary beams act as cantilevers. These conditions were derived from conversations with

RBG engineers. In Karamba, degrees of freedom can be released with a Joint component which is done for all the beams described and can easily be modified. In the model, columns are assumed to be continuous with rigid connections from column to column in height. This assumption can be realistic (Parsons et al. 2010) and if pinned connections are actually provided, the results from the sizing optimisation would be conservative which from conversations with RBG engineers was deemed a reasonable assumption. For analysis under wind loading, the stiff beams are modelled with an arbitrary cross-section and the material properties are described in § 6.2.1.2.

The material properties of the steel members can easily be modified by the user. By default it is assumed that all elements apart from the stiff beams have the same properties but this could be modified as members are grouped. Fully fixed supports are provided at ground floor at the bottom of all columns but this can also be modified by the user. The loading is applied as line loads in the negative z direction over the relevant beams in the first part of the tool and as horizontal point loads at the relevant locations when wind loading is applied as discussed in § 6.2.1.2.

The model is then assembled, cross-sections are optimised for ULS design and linear static analysis is used. The mass is outputted for automated optimisation in the first part of the tool and deflection and inter-storey drift plots can be obtained in the second part of the tool. Additional results from the two analyses can be displayed by Karamba such as deflections, stresses, loads, reactions and utilisation of elements. Serviceability limit state (SLS) design load factors can be used to conduct deflection checks on the optimised grid arrangement when subjected to vertical loading.

6.3 Results

The case studies presented use the same material definition. It is steel with a grade of S355 where E is 210 GPa, G is 80.76 GPa which is equivalent to a Poisson's ratio (ν) of 0.3. A specific weight of is 78.5 kN/m^3 is used and a yield strength of 355 MPa. This is used for all structural elements except the stiff beams that act as surrogates for the slabs and their material properties are discussed in § 6.2.1.2. The floor plate self-weight is taken as 25 kN/m^3 with a theoretical thickness of 0.120 m. The dead load is taken as 1.5 kN/m^2 and the live load is taken as 3.5 kN/m^2. When conducting ULS design, the dead load and self-weight have a factor of 1.35 and live load has a factor of 1.5. These two factors are taken as 1 when SLS design is discussed (Parsons et al. 2010). This leads to a uniformly distributed load of 11.325 kN/m^2 applied to secondary and primary long beams as discussed in § 6.2.1.2 in ULS design and of 8 kN/m^2 in SLS design. The

façade load is taken as 4 kN/m with a 1.35 factor for ULS and 1 for SLS design. In the sizing optimisation, universal beam sections are used (Parsons et al. 2010). By default, $d_{maxCorner}$ is taken as 1.0 m, $d_{maxCantilever}$ is taken as 1.5 m and d_{sec} is taken as 3.0 m. The columns are taken as constant with height and all are given the same cross-section unless otherwise specified. Primary short, primary long, secondary and outline beams are grouped and respectively given the same cross-section and cantilever beams are sized individually unless otherwise specified. A personal workstation (2 × Intel Xeon E5-2620 v3 2.40GHz 12 CPUs and RAM 64.0 GB) was used to run all models.

The second part of the tool used to analyse the structure under wind loading is not discussed. The action of stiff beams to mimic the diaphragm action of slabs has already been verified and discussed in Chapter 4. It has been added to the tool for versatility and efficient early stage design process but simple FEA is conducted and no automated bracing arrangement optimisation is provided. The bracing elements are sized by Karamba but this process is discussed when applied to the other structural elements. The custom Python component used to output deflection and inter-storey drift plots is similar to the one discussed in Chapter 4 as is the analysis process. The main difference is the load application which is discussed in § 6.2.1.2.

6.3.1 Asymmetric building envelope case study

The first model presented is a theoretical example with an asymmetric building envelope shown in Figure 6.7. This model is used to analyse the impact of modifying the user's decisions in the analysis. The optimisation has been run on a building height of 5 storeys with a floor-to-floor height of 4.0 m and on a building height of 30 storeys with the same floor-to-floor height. The constraints defined in § 6.2.1.4 are used. The optimised grid arrangements for both cases are shown in Figure 6.8 where columns are provided at each beam intersection for these particular cases.

In both cases, the minimum spacing allowed is used in the optimum solution, which is 3.0 m by 6.0 m. This would be expected as discussed in § 6.2.1.3. It can also be noted that the beams have the same cross-section in the two arrangements, which again would be expected as they are subjected to similar loads independent of the number of storeys which leads load bearing capacity calculations in the beams. The main difference between the two grid arrangements is the orientation and offset. Again this could be expected as for a taller building, the loading in individual beams remains constant however the loading in columns increases substantially. Therefore the proportion of column mass to the total mass increases as the building gains height. When the building is 5 storeys, the optimised

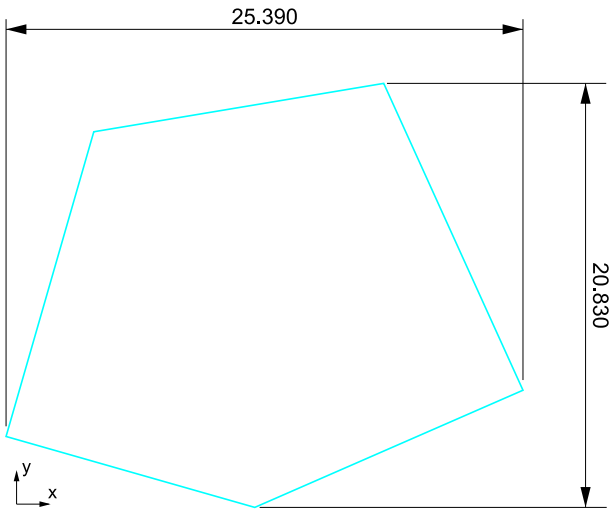
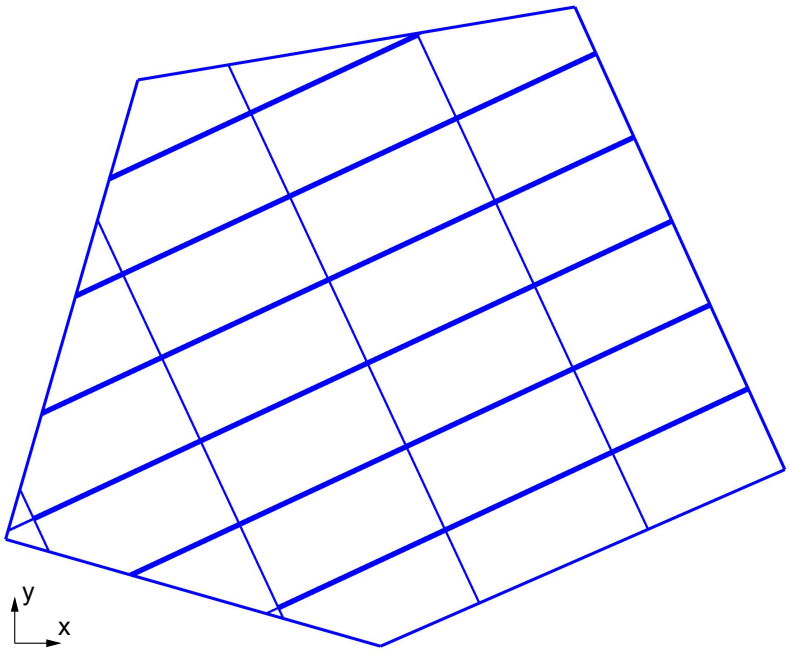


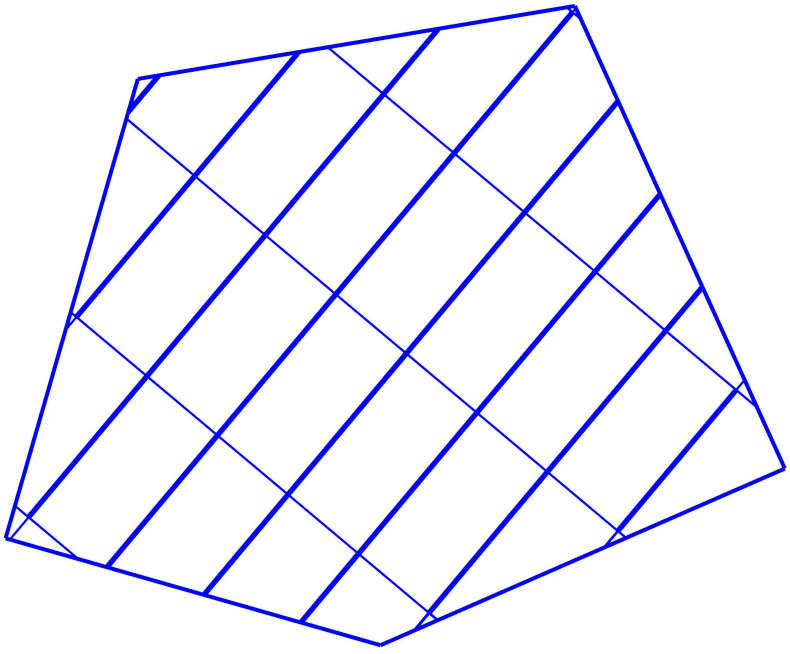
Figure 6.7: Asymmetric building envelope used for theoretical case study. All units are in meters unless otherwise specified.

results prioritises minimising the mass of beams whereas with 30 storeys, the mass of columns dominates the optimisation. In the arrangement for a 5-storey building, the grid is aligned with the two sides of the building envelope that almost make a 90° angle which may be what an engineer would use based on experience. The arrangement obtained for 30 storeys can less easily be rationalised with respect to the outline. These results show that sizing and structural arrangement optimisation with the objective of minimising mass performs as could be expected and that it reaches designs that may not be obtained following standard design methods. If the grid arrangement obtained for the 5-storey building was used for the 30-storey building, the total mass would be 1286 tonnes (t) whereas with the 30-storey grid arrangement, the total mass is 1063 t which means a 17% reduction of steel mass could be obtained which is non-negligible. The column sizing is likely to be modified when bracing is added or if the connection type changes, however it is expected that the percentage modification would be similar in each design thus leading to a percentage difference between the two total masses of similar magnitude. Both designs follow similar constructability considerations with the grouping of section sizes so it is possible that the 30-storey grid arrangement could be used. Using the tool would at least facilitate the search for alternative designs and help engineers gain understanding on the design space.

For comparison, an optimisation with 30 storeys but allowing the size of columns to vary with height and differentiating in plan between internal and external columns when attributing section sizes has been performed. The same optimised grid arrangement as shown in Figure 6.8b is obtained, however the total mass becomes 728 t. The grid arrangement from Figure 6.8a was also used for sizing optimisation with the new conditions on column sizing and the total mass becomes 729 t, thus reaching a 0.14%



(a) 5 storeys.



(b) 30 storeys.

Figure 6.8: Optimised grid arrangement and section sizes for asymmetric case-study with two different building heights. Columns are located at each intersection of beams in these cases because of the short spacing.

difference. Comparing with the total mass using the optimised grid arrangement for 30-storeys with constant column sizing, the total mass allowing for variations in column sizes is 32% lighter for both grid arrangements. The structural arrangement optimisation has also been run allowing all members to be sized independently. The optimal grid arrangement obtained is the same as shown in Figure 6.8a but with different section sizes. The total mass in this case is 574 t, which is 21.3% lighter than when section sizing is grouped. Independent sizing optimisation was also conducted for the structural arrangement obtained from the 30-storey building and the total mass in this case is 594 t, leading to a 3.5% difference between the two structural arrangements. A random grid arrangement with the primary long beams aligned with the x direction was used for independent sizing optimisation and the total mass obtained is 633 t which is 10.3% heavier than with the optimal structural arrangement. All these results imply that greater savings can be obtained from sizing optimisation than structural arrangement optimisation. However, independent sizing of members is unlikely to be applicable on structural engineering projects for constructability and cost considerations. The results also show that when sizing optimisation is rationalised by groups, noticeable material savings can still be achieved through structural arrangement optimisation. The impact of including constructability considerations when conducting the optimisation to obtain useful results is also shown.

It should be noted that the cross-section optimiser component from Karamba has a run time dependent on the size of the model which is increased substantially when optimising each member individually. Depending on the time available, engineers can also factor in the run time when making decisions on the section size grouping and the number of elements.

The spacing obtained of 3.0 m by 6.0 m could reasonably be used in a residential building where partitions are necessary and columns could be located in partitions. In other cases where larger spans are necessary and where value can be gained from large free floor areas, the arrangements shown in Figure 6.8 could not be used. As discussed in § 6.2.1.3, the constraints on grid spacing can easily be modified to obtain greater bay spacing. This is further discussed in the next case study.

6.3.2 Retrospective case study

The tool has been designed to be applicable on varied projects and can be used to design other structural forms than tall buildings. It has been used on a retrospective case study provided by RBG to optimise the steel grid in a bus station in order to fit as many busses

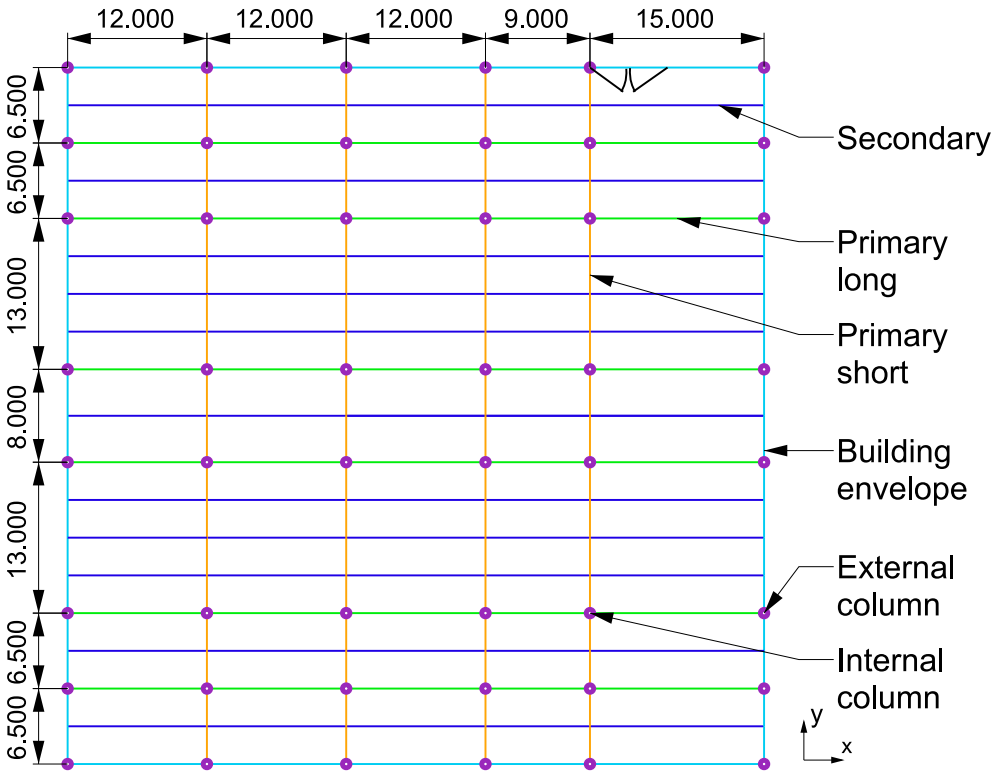
as possible. A bus size has been identified as 12.0 m in length, 2.550 m in width and 3.069 m in height. The bay size of the grid arrangement therefore has to be constrained based on these bus sizes. The building is taken as 1 storey with the busses to be parked in the ground floor. The overall building envelope is a 60.0 m by 60.0 m square and a driveway of at least 15.0 m is aligned on one side of the building with a door at one end as shown in Figure 6.9. This case study is also used to compare the results from ULS design, which is where the tool is aimed to be applied, with results including SLS design constraints. In ULS design, sections are checked for load bearing capacity. Therefore when sections are optimised for ULS, the aim is to optimise utilisation which is mostly related to stress. SLS design on the other hand requires deflections checks as well as vibration checks, which relates more to strains in sections (Parsons et al. 2010). When engineers design structural elements, ULS design is conducted first and SLS checks are then conducted, each with the loading factors discussed in § 6.3. It is often expected that structural elements designed for ULS should be sufficient in SLS deflection checks, otherwise larger sections can be used.

Because of the bus dimensions, a minimum bay size of 4.0 m was identified for the bus to fit in width. Initially, this spacing was used as minimum for both directions as minimal mass tends to be obtained with smaller grid spacing as shown in § 6.3.1 and the full envelope was used, ignoring the driveway and door. As expected, after optimisation the minimal mass was obtained with a grid aligned with the building outline and with 4.0 m spacing in both directions. The optimised mass with the grouped sections as explained in § 6.3 is 93 t. Whilst this would allow having a maximum number of buses parked, it would in reality not be possible for buses to access the parking bays with this column spacing and this optimisation was run to compare material savings that can be gained with smaller spacing. Based on information provided by RBG (Mourtis 2017a), buses would require at least 12.0 m of clear space to be able to turn and driveways should be provided so that 26 parking bays are provided and accessible. Therefore the optimisation was provided with a minimum spacing of 12.0 m in one direction and 13.0 m in the other direction which corresponds to the length necessary for a parking bay, this time using an outline of 60.0 m by 45.0 m to account for the door and driveway. A grid arrangement aligned with the outline and with 12.0 m by 13.0 m grid spacing with secondary beams was obtained. This left one bay of 9.0 m next to the existing 15.0 m wide driveway and a 8.0 m bay in the perpendicular direction at one end of the building. The total mass with grouped section sizes in this case is 457 t, so almost five times heavier than when small spacing can be used. Once this optimisation was conducted, in order to maximise the number of parking bays and provide a functional driveway based on RBG recommendations, the 8.0 m bay was manually moved to the center of the building as shown in Figure 6.9. Also, columns were added to the bays that serve as parking bays only as smaller spacing leads to material

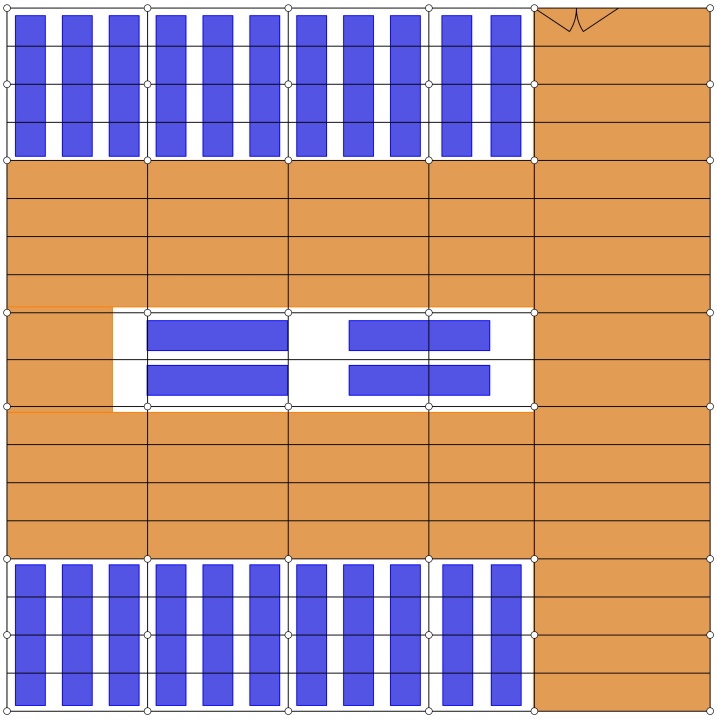
reductions. These modifications cannot be done by the automated optimisation as the spacing is constant in each direction except when meeting a building edge. However, as shown here, optimisations can be run to then inform decisions in a short time frame. The automated optimisations with the two spacing constraints each ran in under 45 min. Galapagos does not only output the optimal solution but also allows understanding of the design space, seeing if the result for a particular option is considerably different than other options or if some options offer similar results.

Figure 6.10 shows the original grid arrangement provided by RBG (Mourtis 2017b). The main difference between the two grid arrangements is that the driveway in the original grid arrangement was increased to 16.0 m, reducing the bay next to it to 8.0 m. The secondary beams are oriented in perpendicular direction in the three central bays in the two designs and these three central horizontal bays are sized slightly differently. The sizing of the elements was not provided by RBG as the case study is from a concept stage and using standard design methods, analysis and sizing of sections are often not performed as they are time consuming and changes are still likely to happen. The use of the tool can enable sizing optimisation almost instantaneously even without structural arrangement optimisation and can therefore help inform the design process from early stages. The tool was used to obtain optimised section sizes for the original arrangement and when grouping the sections is done in the original grid layout, a total mass of 557 t is obtained, so more than 20% heavier than with the optimised grid arrangement. This could be expected with the wider driveway where the load bearing capacity required would be the largest, requiring larger sections that would be applied to most beams in the plan because of the arrangement and the grouped sizing. This is assuming that in the original arrangement optimised sections would be used even though larger sections may be used using standard design methods as explained by Dunant et al. (2018) and in Chapter 2. The computational tool may therefore lead to substantial material reductions compared with standard design methods.

It may be reasonable to allow sizing of all primary long, primary short and outline beams to be done independently given that their lengths are different in each group and therefore different beams would need to be produced. Two additional sizing optimisations were therefore run for each grid arrangement, one where each member could be sized independently and one where members could be sized independently except columns and secondary beams which would respectively have the same cross-section in order to reduce the number of sections required. In the first case where each member was optimised independently, the two arrangements reached the same mass of 317 t with 28 different sections necessary for the original arrangement and 27 for the optimised arrangement, which means that following the spacing constraints, ignoring rationalisation of sizing

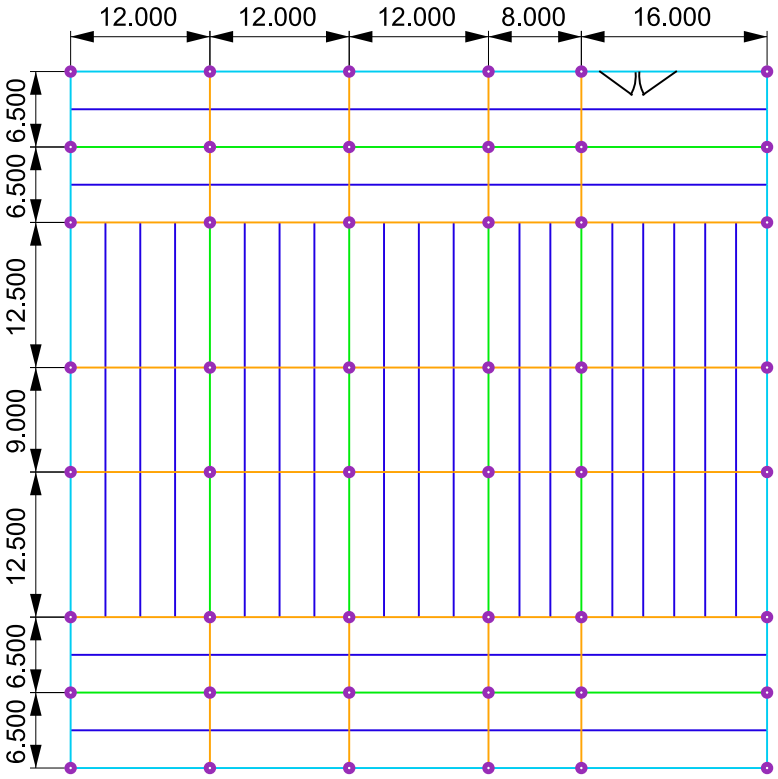


(a) Plan view with grouped members highlighted.

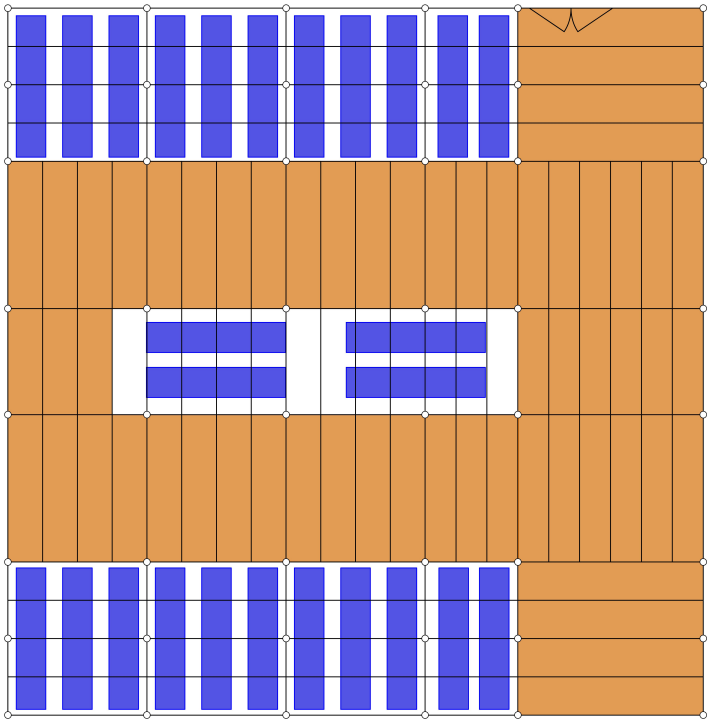


(b) Plan view showing driveway in orange and bus positions in blue.

Figure 6.9: Optimised grid arrangement following spacing constraints in retrospective case study for steel building optimisation. All units are in meters unless otherwise specified.



(a) Plan view with grouped members highlighted.

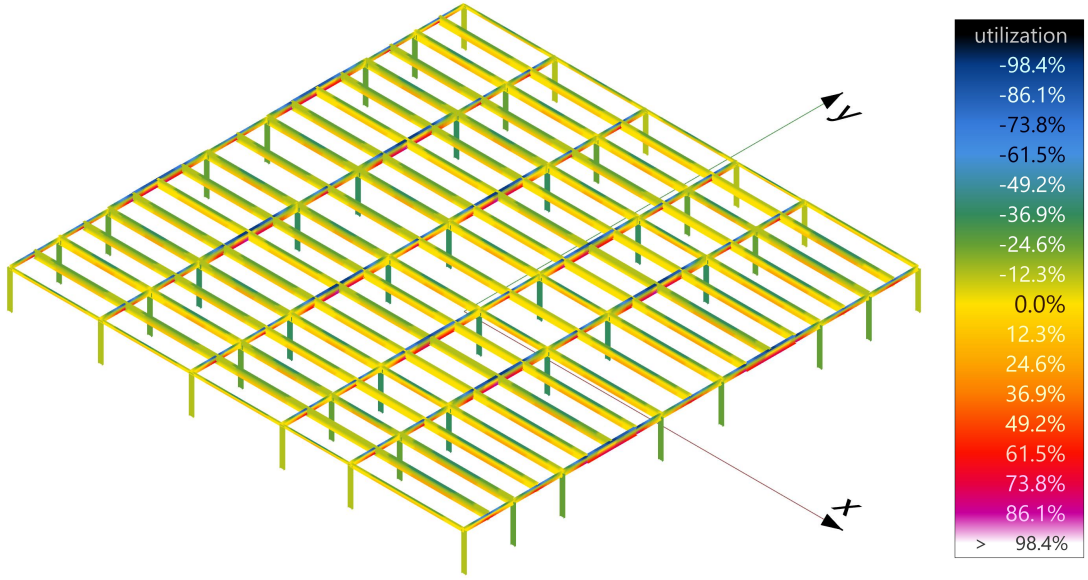


(b) Plan view showing driveway in orange and bus positions in blue.

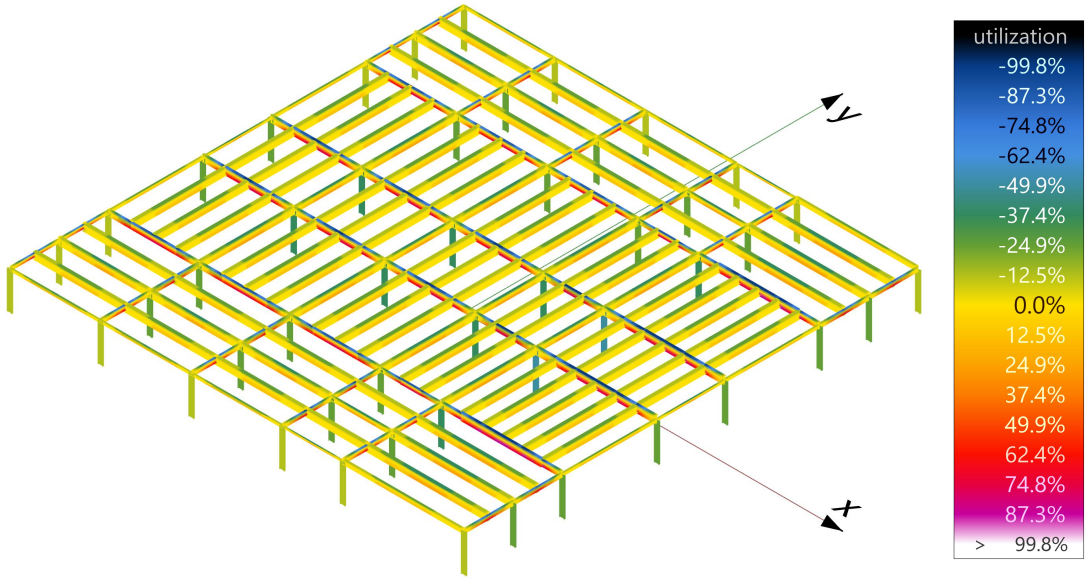
Figure 6.10: Original grid arrangement following spacing constraints in retrospective case study for steel building optimisation. All units are in meters unless otherwise specified.

and assuming again that the original arrangement would be designed with fully utilised sections, both designs perform similarly. The last sizing optimisation with some sections grouped reached a mass of 433 t in the original design with 20 different cross-sections and 379 t in the optimised design with 19 different cross-sections. An elevated view of each grid arrangement and showing the utilisation of the members is shown in Figure 6.11 with this reduced section grouping. The utilisation displayed is the ratio between normal stress and yield stress. The difference in mass could be expected as the secondary beams in the optimised design are more similar in length that in the original arrangement so sizing them in group or independently is not expected to have the same impact. It is not known how much time was required to obtain the original arrangement and how much time would be required to size the elements and compare grouping options with standard design methods. It is expected that an engineer using their experience as well as the tool may be able to reach the optimised design with sized members in under two hours with an understanding of the design space. The tool also enables exploring the design space without using the automated optimisation.

The tool enables conducting SLS design checks on deflections with the load factors describes in § 6.3. This was done on the two arrangements with independent member sizes except columns and secondary beams. The cross-sections obtained from optimisation under ULS loads are sufficient for SLS deflections checks for both cases. In other projects where the optimal grid orientation alignment is less expected with respect to the building envelope after optimisation for ULS design or when particularly slender members are obtained, conducting SLS checks or optimising for SLS design with reduced loads but with deflection checks could be beneficial. There may be cases when an optimal ULS design would require greater section for SLS deflection checks, thus increasing the mass whilst a different orientation or spacing could reach a reduced mass for SLS checks which are necessary even though the mass may be greater that the one obtained from ULS design.



(a) Optimised grid arrangement.



(b) Original grid arrangement.

Figure 6.11: Elevated view of building used in retrospective case study showing members utilisation for the original and optimised grid arrangements where utilisation displayed is the ratio of normal stress to yield stress.

6.4 Conclusions and discussion

An optimisation tool aimed at the analysis and optimisation of steel frame buildings has been developed in partnership with industry. This captures the 'rules of thumb' that engineers may use when designing such structures while using computational power to increase the efficiency of the design process and enable material reductions. The tool uses constructability considerations whilst enabling engineers to gain understanding on the design space of a project, get results in a short time frame and produce feasible designs efficiently using their technical experience. As the tools presented in Chapters 4 and 5, this one has been developed in Rhinoceros 3D/Grasshopper 3D (RH/GH) which is a user-friendly, accessible software used by architects and engineers. Finite element analysis (FEA) and sizing optimisation is enabled by the Grasshopper 3D (GH) plug-in Karamaba and automated structrual arrangement optimisation can be conducted using genetic algorithms (GA) with the GH component Galapagos. The user can analyse and conduct structural arrangement and sizing optimisation for ultimate limit state (ULS) design of steel frame buildings when subjected to vertical loads, conduct serviceability limit state (SLS) checks and analyse and compare steel bracing options of the buildings subjected to wind loading.

6.4.1 Assessment of the computational tool

The tool enables conducting sizing optimisation with FEA with almost instantaneous results combined with parametric design. This is not typically possible with standard design methods and whilst the tool is not aimed to be used for detailed design, using it can help inform the design process from the earliest design stages. This could lead to a more efficient design process, a better understanding of the design space and material reductions leading to reduced embodied carbon for steel frame buildings compared with standard design methods. Lines are used to create beam elements and given the simplicity of these elements in FEA, Karamba appears sufficient for early design stages. Engineers can use the tool even with limited RH/GH knowledge to obtain results but it was set up to easily be adapted by users if needed.

6.4.2 Recommended use of the tool

In early design stages, a simplified building envelope, assumed constant with height, can be used for steel grid optimisation to minimise structural mass. The variables of the

grid arrangement are the grid spacings in two perpendicular directions, the orientation of the grid and offsetting of the grid in plane. These variables are constrained to include constructability considerations and can be further modified to reduce the design space or steer the optimisation towards suitable designs, for example by increasing the minimal spacing. Other parameters can be set by the user. Sizing optimisation is also conducted during the analysis and can be obtained independently from the grid arrangement optimisation. The sizing optimisation is conducted for ULS checks and SLS deflection checks can also be conducted. It could be beneficial to conduct both checks to ensure that the actual minimal mass is achieved. Other than using GA to automate the grid arrangement optimisation, the user can also explore the design space to see the impact that the variables have on the structural mass. When a grid arrangement is obtained, from automated optimisation or otherwise, the response of the building when subjected to wind loading with bracing arrangements can be analysed. The process in this part is similar to the process explained in Chapter 4. The tool enables sizing of bracing elements and comparing bracing options easily whilst producing deflection and inter-storey drift plots. The tool can be used for steel frame buildings of any height and applications can include warehouses as well as residential and office buildings.

6.4.3 Limitations and future work

Similar to the two concrete tools presented in Chapters 4 and 5, this computational tool is aimed to be used in early design stages. Whilst it enables conducting FEA and sizing optimisation earlier in the design process than with standard design methods, more detailed analysis would be required in further design stages. Additionally, only static analysis is conducted. This is reasonable in early design stages for projects based in the UK but for further design stages or in seismic areas, dynamic analysis would be required and could lead the design. This could be particularly important for larger spans where floor vibrations could dominate serviceability requirements. Karamaba allows frequency and mode checks but this has not been verified as it is outside of the scope of the tool. If the tool is to be developed such that dynamic checks can be conducted, the results produced by Karamba would first require validation which has not been carried out in this study. Alternatively, the structural arrangement and sizing produced by the tool could be imported in a software dedicated to such analyses. This could also be beneficial when analysing the braced structure subjected to wind loading.

Regarding bracing arrangement, the tool currently enables the user to analyse and compare specified arrangements. Perhaps further material reductions could be obtained

with arrangements that the user is not looking at, and full automation of bracing arrangement optimisation could be valuable.

Another area where improvements could be made is with the rationalisation of the grid. In the tool, the spacing between columns is constant in two perpendicular directions applied across the entire floor plate and the secondary beams can only be specified in one direction. In order to cater for irregular plan footprints, the tool may be applied independently to individual segments identified by the user to obtain different optimal orientations in each segment. Future development of the tool can focus on automating this in one process, which could be particularly useful for complex, irregular building envelopes.

When sections are grouped, only one section can be attributed to all members of the group. Because some members in one group can have different lengths, particularly when the arrangement is manually modified, the possibility to allocate more than one section per group whilst still restricting the number of sections could reach material reductions that could reasonably be implemented on a project. This could be combined with better tools informing on-site construction to facilitate understanding of section positions in the structure.

Chapter 7

Conclusions

7.1 Summary of achievements

The aim of this PhD project was to understand the place of computational engineering in the construction industry and to develop computational tools to assist efficient and sustainable structural design. Three tools have been developed through collaboration with industry, ensuring their applicability to projects encountered in structural consultancies. Material reductions were used as a surrogate for embodied carbon reductions for sustainable design and efficient design was enabled through reduced modelling, analysis and optimisation time compared with standard design methods.

In the first part of this thesis, the rate of adoption of computational design tools in the construction industry was analysed in a qualitative study. Construction industry leaders based in structural consultancies with particular interest in digital technologies were interviewed to gain deep insights on the topic. A large amount of data was collected and analysed in depth, covering a range of themes related to digitalisation of the construction industry. Definitions of the terms and actors involved were proposed. Mainly, 'computational engineering' was identified as the most appropriate term available to describe the applications covered by this thesis, and it was identified that the increasing creation and use of computational tools leads to a change in the role and skills of structural engineers without replacing them. Construction is one of the least digitalised industries and reasons for this were established as well as incentives for change. The roles of leaders, personal interest of engineers and other stakeholders, collaboration across the construction

industry and of university education and research were discussed. Finally, a number of applications of computational technologies in practice were presented. The importance of analysis and of using appropriate software for it was highlighted. Increased computational use can lead to a more efficient design process, enabling engineers to spend more time in conceptual design stages, understanding the design space better and finding improved solutions.

The second part of this thesis focused on the computational tools developed to assist sustainable and efficient design of tall buildings. They have all been developed in Rhinoceros 3D / Grasshopper 3D (RH/GH) as it is accessible, user-friendly and increasingly used by architects and structural engineers. Finite element analysis (FEA) and sizing optimisation are enabled by the Karamba plug-in and genetic algorithms are used for automated optimisation with the Galapagos component. To ensure that the tools can be used easily by different users with varying levels of computational literacy, a limited number of Grasshopper 3D plug-ins were used and personal workstations provide sufficient computational power. The tools were developed with the end-user in mind at all times. For each tool, the methods used for its development were detailed and case studies were used to validate it and quantify the benefits that could be achieved through its utilisation.

The first tool aims at efficient optimisation of concrete core systems which resist lateral loading. The main benefits from the tool are reduced analysis and optimisation time, allowing engineers more time to explore the design space and rapidly compare core systems on a project, informing the design process from early stages. An engineer reported saving 15 h of work compared to a more traditional workflow, using the tool a limited number of core systems. If the tool was used from the beginning of a project on all core systems available, the efficiency of the design process could be noticeably increased. The second tool aims at efficient and sustainable optimisation of concrete slabs and columns when subjected to vertical loading. Structural arrangement and sizing optimisation of the columns can be performed and the design space of varying column positions can easily be explored with fast turnover of results. On a retrospective case study, it was estimated that up to 8% of materials could be reduced in the slab from reduced net moment in the slab by modifying the column arrangements whilst still following architectural constraints. Applied to all storeys of tall buildings, this could lead to sizeable embodied carbon reductions compared with standard design methods. The last computational tool was developed for structural arrangement and sizing optimisation of steel buildings. Optimised grid arrangement and element sizing can be obtained to resist vertical loading and bracing options can be analysed, sized and compared when wind loading is modelled. The tool enables considering analysis and section sizing earlier in the design process as well as

design space exploration through manual or automated grid arrangement optimisation, meaning that more efficient designs can be achieved with reduced embodied carbon.

The tools were developed in close collaboration with industry. This partnership was essential to ensure that the tools are relevant and can be used in an office with meaningful results. The main problem when this link is not present is that state-of-the-art research in construction or structural engineering may not be used by industry and benefits could be missed if research does not capture constructability, design, cost and rationalisation constraints that structural engineers face. The tools developed are now accessible to Robert Bird Group (RBG), the company who sponsored this research, and the benefits described above have been identified. Their advice in the research helped to ensure that the tools are robust, versatile and user-friendly. They have been developed for tall building optimisation, but their versatility allows for their use for buildings with a reduced number of storeys as well. They can be used at various design stages but are primarily aimed at early design stages which is where it is believed that computational engineering can lead to noticeable improvements. The tools enable users to search the design space efficiently and assist engineers to make informed decisions from the earliest stages, rather than later when conducting detailed design, facilitating the dialogue between key stakeholders.

7.2 Current limitations

Limitations were discussed in detail in the relevant Chapters. General limitations are summarised now.

The main limitation to the qualitative study is that interviews were conducted with a limited number of participants. Theoretical sufficiency was achieved with the participants as they were selected because of their interest in computational technologies. The study therefore reflected state-of-the-art opinions and methods in industry but does not reflect on computational engineering in the construction industry as a whole. Interviews with more participants from different companies and potentially from countries other than the UK could enable a more comprehensive analysis, rather than focussing on the future of the construction industry embracing computational engineering.

The main limitations are similar for the three tools developed. Interoperability and using the appropriate software for the various steps in a design process was highlighted as essential in the qualitative study. The computational tools were developed in RH/GH using Karamba for FEA. This may not be the most robust software for such analysis and the argument could be made that the tools should have been developed in a different

software environment. However, the tools are not intended to be used for detailed design and using Karamba enables introducing FEA in earlier design stages than when using standard design methods while enabling reduced modelling, analysis and optimisation time.

The tools were also designed to conduct analysis and optimisation under static loading. This is often sufficient in early design stages but in further design stages, for complex structural forms or in particular locations, dynamic, frequency and mode checks need to be conducted and can lead design decisions. It could be interesting to automate detailed design and frequency and mode checks in other software based on the results from the tools. However, in further design stages when more specific software is required, it may be more difficult to develop tools versatile enough to be used on a variety of projects.

The tools were used on a limited number of case studies. They were only recently made available to RBG engineers and the company has recently started its transformation towards greater use of computational tools. To quantify more accurately the benefits that can be achieved by using the computational tools, their use on more projects, ongoing rather that retrospective case studies, is required, and results both on material reductions and design process efficiency would need to be analysed.

7.3 Future work and applications

Collaboration with industry enabled integrating 'rules of thumb' that are used by engineers in tall building design as well as some constructability and rationalisation considerations. However, other considerations influence the design process. Construction sequencing is an important step of design and for particular structural forms should influence design decisions. Bridge design for example often accounts for construction sequencing from the early stages as construction can be particularly dependent on location and site constraints. The design process of tall buildings and other structural forms could benefit from considering construction earlier. This could facilitate construction but also reach carbon emission reductions in the structure and in the construction process as decisions from the earliest design stages could be informed by site, transport and cranage conditions for example. Structures designed and optimised in the permanent form may need to be modified when considering constructability with temporary works design or cranage capacity, which could cause material increase in the permanent elements where a large volume of temporary materials is required. For automated optimisation, the definition of a meaningful objective function would be essential as many factors influence material quantities or carbon emissions when considering the full construction process.

Other future work could be aimed at the development of computational tools for other common structural forms. Long span structures such as stadia or airports could be of interest, in which case constructability considerations may be particularly important. Other commonly used materials such as timber which can be used as structural elements, or glass, which can be used both as structural elements and most commonly for façades, could be the object of optimisation tools which could lead to efficiency and sustainability improvements.

Structural mass reduction was used as a surrogate for embodied carbon reduction in tall buildings. This is an approximation that can lead to real embodied carbon savings in the structures that are currently being built with standard design and construction methods. However, in the longer term this may not be the most efficient way to minimise embodied carbon in the construction industry. For example, alternative materials to concrete and steel such as timber require lower carbon emissions for their production and beneficial research can be conducted to increase the use of these materials as structural elements. Research in alternative, smarter materials is also relevant. Additionally, constructing more structures by definition implies more carbon emissions than not constructing them at all and in strict regard of environmental sustainability, improved use of existing infrastructure is an area of research that would lead to carbon emission reductions even though it may be outside the role of structural engineers. Alternatively, ensuring that new structures are used efficiently over time with a large design life may lead to substantial carbon emission reductions. Considering the full life cycle of buildings including deconstruction and reuse of materials can also be facilitated with computational modelling. Building information modelling (BIM) and modular construction are moving in this direction but greater improvements could be reached with further research and development. As discussed in the qualitative study, computational tools also have a carbon footprint and the net benefits should be considered before developing new tools.

Lastly, concrete and steel tall buildings are common structural forms in developed countries like the UK. Such structures are being built in those countries and more sustainable and efficient designs are beneficial. However, a large amount of construction takes place in developing countries and design and construction methods as well as materials can vary. Research on structural forms that answer the needs and constraints faced in such countries, while accounting for safety of design and of people both during construction and during the lifespan of the structure, for sustainability considerations and encompassing social repercussions, could prove extremely valuable. Any small improvement on one particular project may prove substantial when applied across multiple projects.

It is hoped that the qualitative and engineering research presented in this thesis will contribute to opening conversations on the uptake of computational technologies in the construction industry in a functional way, that it will facilitate collaboration between industry and research and will assist informed, improved decisions in structural design.

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Publications

Conference oral presentations

Bellamy L.C., Mourtis T., Phillips A.T.M. (2018). Optimisation methods for the design of tall buildings based on sustainability and efficiency factors, *13th World Congress on Computational Mechanics*

Bellamy L.C., Phillips A.T.M., Ward J. (2017). Optimisation of structural form based on multiple sustainability factors, *IABSE Conference Bath 2017 - Creativity and Collaboration*

Conference poster presentation

Bellamy L.C. (2019). Optimisation tools to assist efficient and sustainable design of tall buildings, *IStructE Young Researcher's Conference* - First Prize winner for a poster presentation

Appendix A

Ethics documents for interviews

A.1 Interview question schedule

Rate of adoption of digital design tools in the construction industry

What construction projects are you working on at the moment?

- Could you describe your career so far?
- Have any of your recent projects presented particular challenges?
- What improvements could be made to the design process that you are going through?

What do you understand by the phrase "digital design"?

- Do you think that there are differences between design skills and digital design skills? If so, what are they?
- What digital design tools are used in the construction industry currently?
- In what areas do they have the greatest impact currently?
- Is analysis part digital design? If so, what is its role?
- What is the place of BIM in the design process? Is it part of the design process or is it a distinct process?
- Is digital design replacing engineers?
- How can digital design tools be used in light of sustainability?
- Is interoperability of interest, how/why could it be implemented?

Which areas in the construction industry could benefit from further research/have been left out so far?

- Is an uptake of digital technologies in the construction industry necessary?
- What digital technologies do you think companies should invest in for construction?
- What could be their impact?
- Is there anything limiting the uptake of digital technologies in the construction industry compared with other industries?

What do you think is the role of university education in adopting digital design tools in the construction industry?

- Would you agree with the perception that analysis skills are more advanced in research whilst digital skills are more advanced in industry?
- What are universities currently doing to promote the use of digital design tools in the construction?
- How would you describe the relationship between academia (undergraduate and taught postgraduate courses and civil engineering research) and industry in construction and civil engineering in general?
- If deemed necessary, how can digital design tools be promoted through education in universities?
- What skills do you wish had been taught at university to help you become a leader in the construction industry and digital design?

Is there anything else that you would like to add?

- Are there any questions that you would like to revisit?
- Is there anything that you think has been missed?

A.2 Participant information sheet

INFORMATION SHEET FOR PARTICIPANTS

Rate of adoption of digital design tools in the construction industry

Lead researcher: Laura Bellamy

Introduction:

I am looking for construction leaders in the UK to be interviewed to investigate the rate of adoption of digital design tools in the construction industry and the role of education in university in enabling the uptake of these tools. Before you decide whether to contribute to this research it is important to understanding why the research is being conducted and what it will involve.

What is the purpose of the study?

The purpose of the study is to establish the current state of the construction industry in the UK and abroad where UK offices work on international projects regarding digital design and the impact it could have in the future. The purpose of the study is also to investigate the link between education (UG and PG programmes in civil engineering), the construction industry and civil engineering research, and whether education could have an impact on the adoption of digital design tools in the construction industry.

Why have I been invited?

You have been invited as you have been identified as a construction industry leader with knowledge and interest in digital design tools.

Do I have to take part?

It is up to you to decide whether or not to take part. If you decide to take part you will be asked to sign a participant consent form. If you decide to take part you are free to withdraw at any time prior to transcription and anonymization of the data.

What will happen next if I choose to take part?

I will contact you to arrange a date, time and location for the interview. The location should be convenient for you and can be your company's offices, the Imperial College London premises or a public place such as a coffee shop. You will be asked to sign a participant consent form prior to the interview. Interviews are expected to last around an hour and will be audio recorded with your consent. An external agency will be used for the transcription of data. Up until that point you will have the right to withdraw from the study. Following transcription of the interview I may contact you again for clarification on any issues. It is possible that I may request a further interview to explore particular areas of interest. In this case, you will have the right to withdraw yourself from more than one interview or to withdraw your data. After that point and the transcription of any potential further interview, data will be anonymised and you will not be able to withdraw your data anymore.

Participants will not be offered any reimbursement for their participation.

Will my taking part in this study be kept confidential?

All information obtained during the interview will be kept strictly confidential. Any information about you will be kept anonymous. All procedures for handling, processing, storage and destruction of the data are compliant with the General Data Protection Regulation, 2018 and with Imperial College London guidelines.

Should you wish your contribution to the research to be acknowledged this should be clearly indicated on the consent form. If you indicate that you wish your contribution to be acknowledged you will be acknowledged in reports and publications resulting from the work. All other information will be kept anonymous and you will not be attributed any text/comment or diagram/sketch.

Who is funding the research study?

The study is being funded by Engineering and Physical Sciences Research Council (EPSRC) Centre for Doctoral Training in Sustainable Civil Engineering and Robert Bird Group. They are funding the PhD of the researcher. Robert Bird Group will not have access to the data collected.

What will happen to the results of the research study?

The results from the study will be used for the PhD as qualitative research leading up to the engineering research that I am conducting and will be included in the thesis. Results may be published in relevant journals and shared with conference delegates if appropriate. Unless requested you will not be identified in any publication.

Who has reviewed the research study?

The project, the plan and arrangements for this research study were approved through the Imperial College London Educational Ethics Review Process.

Contact for further information

If you have any further queries, please contact the Lead Researcher (Laura Bellamy) using the contact details below:

Email: laura.bellamy11@imperial.ac.uk

Telephone: +44(0)7543 706101

The Research Supervisor (Dr Andrew Phillips) can also be contacted if necessary using the contact details below:

Email: andrew.phillips@imperial.ac.uk

Telephone: +44(0)20 7594 6081

Thank you for taking time to read this Contributor Information Sheet.

If you would like to take part in the research study, please express your interest by replying to the email that will be sent to you shortly.

A.3 Participant consent form

INFORMED CONSENT FORM

Rate of adoption of digital design tools in the construction industry

Name of researcher: Laura Bellamy

Please initial the relevant boxes

1. I confirm that I have read and understand the subject information sheet dated ..... for the above study. I may keep this information sheet for my records and I have had the opportunity to ask questions which have been answered fully. ☐

2. I understand that my participation is voluntary and I am free to withdraw at any time prior to data anonymisation, without giving any reason and without being penalised or disadvantaged in any way. In addition, should I not wish to answer any particular question or questions, I am free to decline. ☐

3. Please select one of the options:

   a) I do not wish my contribution to the research study to be acknowledged. I understand that my individual responses will be kept strictly confidential and I give permission for members of the research team (the researcher and her supervisor) to have access to my anonymised responses. I understand that my name will not be linked with research materials. I will not be acknowledged in the reports, publications and presentations that result from the research study. ☐

   Or:

   b) I do wish my contribution to the research study to be acknowledged. I understand that my individual responses will be kept strictly confidential and I give permission for members of the research team (the researcher and her supervisor) to have access to my anonymised responses. I understand that my name will be linked with research materials. I will be acknowledged in the reports, publications and presentations that result from the research study but I will not be attributed any particular text/comment or diagram/sketch. ☐

4. I understand that sections of my recorded comments and transcript text may be looked at by responsible individuals from Imperial College London. I give permission for these individuals to access this data as relevant to this and future research. ☐

5. I am willing to have this interview audio recorded. ☐

6. I agree to provide originals or copies of any notes or illustrative sketches made by me as part of the research study. ☐

7. I agree to take part in the above study. ☐

_____	_____	_____
Name of Participant (Printed)	**Date**	**Signature**
_____	_____	_____
Name of Researcher (Printed)	**Date**	**Signature**

1 copy for subject; 1 copy for researcher

A.4 Education Ethics Review Process (EERP) approved ethics application

1.1 First name:	Laura
1.2 Last name:	Bellamy
1.3 Address:	Flat 2, 384 Wandsworth Road, SW8 4TN London
1.4 Telephone:	07543706101
1.5 Email:	laura.bellamy11@imperial.ac.uk
1.6 Title of study:	Rate of adoption of digital design tools in the construction industry
1.7 Proposed start date:	01/03/2019
1.8 Proposed end date:	31/06/2019
1.9 Are there co-investigators?	No
1.14 Is this a student project?	Yes
1.15 First name (Supervisor):	Andrew
1.16 Family name (Supervisor):	Phillips
1.17 Email (Supervisor):	andrew.phillips@imperial.ac.uk
1.18 Course of study:	PhD
1.19 Project deadline:	05/10/2019
1.20 Has your supervisor read and agreed to this application?	Yes
2.5 Has any part of this proposal received prior ethical approval?	No
2.6 Has any part of this proposal been rejected by an ethics committee?	No
2.7 What is your main research question?	Construction is known to be one of the least digitalised industries. The study focusses on what the current and future place of digital processes is in this industry. The primary aim of the research is to assess the current and future place of digital processes in the construction industry. Construction is known to be one of the least digitalised industries and the aim is to investigate why that is and whether this should change. If so, the objective is to assess what should be done to facilitate the uptake of digital design tools. The role of university education through UG and taught PG courses in this uptake is to be investigated as part of the research. The researcher is developing digital design tools for industry and this study is aiming to inform on the gap between her research and industry usage.

2.8 Please list any sub question(s):	(1) What is the relationship between UG and taught PG degree programmes, civil engineering research and industry in construction? (2) How does this relationship impact the way digital design tools are used in industry? Is the digital design uptake low in industry because it is low in teaching in universities and in research? (3) What areas in the construction industry could benefit from further use of digital design tools?
2.9 What is the rationale for the study?	Whilst information on advancements made in civil engineering research in universities are regularly published, advancements in industry are less easily accessible. The rationale for this study is to access information that is not otherwise available. Construction is known to be one of the least digitalised industry and the aim is to investigate why that is and whether this should change. If so, the objective is to assess what should be done to facilitate the uptake of digital design tools. The aim of this study is to understand what is currently being done and what could be done better, and what benefits could be obtained by making a better use of digital processes. In some universities, students are starting to learn how to use digital design tools. The study will inform on the role that education has in the uptake of these digital design tools. The aim is to understand what industry leaders' expectations are of new graduates in a more digitalised industry if such a change is deemed necessary and whether these skills can be taught in university. Indeed, a change in the way future leaders are taught could be seen as a good way to shift the way the construction industry works. There also appears to be a gap between research and industry in civil engineering and construction, and the study is aiming to inform what is and should be done to bridge that gap.
2.10 Methods:	Interviews
2.11 Location: Please provide brief details of other private or public places:	Imperial College premises; Other private place; Other public place Interviews with industry leaders are likely to be undertaken either at their offices or in a public place such as a coffee shop. It is possible that interviews may be conducted on College premises. In cases where interviews are conducted in public places, the participant will choose the place to minimise issues regarding privacy and the participants will be selected for their professional experience, enabling them to give appropriate responses or non-responses to questions personally or commercially sensitive. Public places are given as an option to the participants as they may prefer not to meet in their office or for ease if their offices are not in London but they have to come to London for other reasons.
2.12 Participants - sort of people you are looking to recruit into the project (incl. inclusion/exclusion criteria)?	Industry leaders. Approximately 10 engineers working in construction consultancy companies will be approached. People approached will be senior engineers who have been working with or recruiting graduate engineers and use or coordinate teams who use digital design tools. First people already known by the researcher will be approached (approximately 5) and then approximately 5 other leaders will be contacted, potentially through existing shared contacts. Regarding participants that the researcher already knows, the use of a neutral email for recruitment rather than in person communication should minimise the risk of coercion or bias. 6 participants or slightly more is believed to be sufficient for a qualitative study given the scope of the project (qualitative research leading to the engineering research that the PhD candidate is conducting), especially given the fact that the number of potential participants is limited due to the deliberate target sampling of a rarefied group of individuals.

2.13 Recruitment - how will participants be approached & recruited?	All participants will be contacted by email. A maximum of three emails will be sent by the researcher at a week to 10 days interval to recruit any one participant. This method has been chosen to avoid participants feeling pressured into taking part in the study which could arise if recruitment with the participants known by the researcher was done in person. They will have more time to answer than if done in person and are free to refuse. The researcher sending the email directly is more likely to get an answer than undirect recruiting such as anonymous or third party emails. The researcher is not the manager of or senior to any participant so they should not feel coerced into participating and any decision (participating or not) will not give them any advantage or disadvantage of any form. If the researcher's supervisor was sending the email, coercion could become a consideration as he is more senior so it seems preferable for the researcher to send the emails. The researcher knows about half of the potential participants from conferences, talks or from teaching and has their email address from previous exchanges. The researcher has the email address of the other potential participants from conferences, mutual contacts or online information.
2.14 Consent - will participants get an information sheet with adequate reading time?	Yes
Will participants sign a consent form?	Yes
Will participants be informed that returning a questionnaire implies consent to participate?	N/A
Will participants have the right to withdraw and remove 'their data'?	Yes
2.15 Confidentiality - will questionnaires be anonymous or anonymised as soon as possible?	N/A
Will any transcripts be anonymised/pseudomised as soon as possible?	Yes
Will identifiers &/or pseudonyms be stored securely & separately from research data?	Yes
Will data & records be held securely & in accordance with Imperial guidelines?	Yes
2.16 Incentives - will you offer incentives to participants (financial or otherwise)?	No incentives will be offered to take part in the study. Refreshment will be provided during interviews where these take place at Imperial College London or a public location. Where interviews are held at the interviewee's place of work it is assumed that they will provide refreshment if required.

2.17 Value - provide a brief description of benefits this work may provide to you, participants & others:	The work should provide valuable insight on the current and future place of digital processes in the construction industry in parallel to a literature review of academic work. It is part of qualitative research leading to the engineering research that the PhD candidate is conducting. This will help identify areas where further research could be beneficial as well as changes that could be implemented on undergraduate and taught postgraduate courses. The researcher's supervisor is involved in both digital and analogue design courses at the undergraduate level in the department of Civil and Environmental Engineering in Imperial College London and the findings of this study could therefore help him better tailor these courses to prepare students for the future of industry.
2.18 Dissemination - provide a brief description of how this study will be communicated both within Imperial & beyond:	Journal article / report. PhD thesis. Follow-up meetings and presentations with industry and interested parties such as the Institution of Structural Engineers. These dissemination routes have been chosen as companies and are considered to be the key players and stakeholders for the study.
2.19 Summary and justification of method(s):	The method of data collection for this study is interviews with construction industry leaders. The use of semi-structured interviews will allow key areas to be investigated while allowing for participants to spend time on areas they may feel are particularly important. Interviews are expected to last around one hour. They will be audio recorded with the participants' consent and as engineers frequently use diagrams to convey concepts participants will be asked to provide originals or copies of any sketches or diagrams made during the interviews. The participant consent form and information sheet have been altered to reflect this. Collection of an audio recording of the interview, as well as collection of sketches and diagrams, will allow for transcription, anonymisation and analysis following the interview. An external agency will be used for the transcription of data due to time limitations. The participants have a right to withdraw from the study until the interviews are transcribed and anonymised which will be at least two weeks after the interview has taken place. Time permitting, there may be particular cases where after transcription of the interviews, the participant is asked to take part in a second interview to explore particular areas of interest. Each participant will have the right to refuse this second interview and separately have the right to withdraw for the study until anonymisation of data. Data will be stored securely according to Imperial College regulations. Analysis will initially use broad starting points based on the researcher's experience of the context, using a constructivist grounded theory approach (Charmaz) (albeit unlikely to achieve saturation) to extend to other concepts if necessary. It has been chosen as the area of study is under researched. Within the scope of this study and given that the number of potential participants is limited due to the deliberate target sampling of a rarefied group of individuals, 6 participants or slightly more is expected to be sufficient to achieve theoretical sufficiency through in-depth interviews and rigorous and careful simultaneous analysis. Theoretical sampling with new participants will however not be used in the study for the reasons mentioned (small target group for participants and time constraints). The researcher considers the possibility to conduct follow-up interviews to help to reach theoretical sufficiency, therefore using a modified form of theoretical sampling with existing participants only. Each participant can choose for their contribution to be acknowledged or be kept confidential. If the participant wishes to be acknowledged, they will be so in reports and publications but all data will be anonymised regardless of whether a participant is acknowledged.
3.1 Confirm that you have considered each of the following ethical issues:	Power issues; Assessment; Coercion; Potential bias; Sensitive issues; Educational advantage/disadvantage; General advantage/disadvantage; Timing; BERA Guidelines

3.2 Ethical Summary - explain how all relevant ethical issues have been appropriately considered:	There are potential power issues with interviewing industry leaders in that they may feel they are able to exert influence over the Civil and Environmental Engineering degree curriculum in Imperial College London or the investigator's research. It will be made clear to them that it is general views that are being sought. The researcher is not the manager of or senior to any potential participants so there should not be power issues with the participants feeling pressured into giving particular responses. There is an issue related to recognition of time spent by interviewees contributing to the project. It may be the case that they would like to be named as contributing to the project. In addition, knowledge of the project contributors may provide validation and legitimacy when defending the thesis or presenting the work to a wider audience. The consent form will ask each interviewee if they would like their contribution to the study to be acknowledged. The process is explained in the participant information sheet and the participant consent form. If they wish so, participants will be acknowledged in all outputs including the PhD thesis but all text/comments and diagrams/sketches will be anonymised regardless of whether a participant is acknowledged. Interviews timing will be selected to suit the participants. Participants having agreed to one interview may be asked for a follow up interview. If they refuse for any reason, including timing, it will not void their participation unless they ask so. There may be an issue since the PhD research is in part funded by Robert Bird Group (RBG). RBG has agreed for the study to happen but has not requested the study which is done from the researcher's initiative as it will provide valuable insight for the PhD thesis. RBG will not have access to the data collected. One participant of the study may be from RBG as they are a leading consultancy in the construction industry. The analysis will be done independently from RBG and under the researcher's supervisor close supervision to ensure integrity of the research and that bias and coercion does not take place in the data interpretation. The researcher has no commercial involvement in RBG, minimising the risk of bias. All participants as well as Robert Bird Group will have access to the final report derived from the data. The research does not involve students or assessment. There is very limited general disadvantage or advantage in taking part. The issue of coercion in the recruitment process will be minimised as it will be done via emails rather than in person and using a neutral recruitment email. In addition, given the experience, professional roles and personalities of potential participants the research does not involve participants who may be coerced into giving particular responses. It is expected that participants will be able to provide appropriate responses (or nonresponses) to questions considered personally or commercially sensitive. There is potential bias through the researcher's area of interest for her PhD as her thoughts and knowledge may influence her behaviour as an interviewer. It is believed that the benefits of having this knowledge during the interviews outweighs the risk as it may enable more depth in the conversation. The research will aim to use her knowledge to gain depth both in the conversations and in the data interpretation but will not voice her personal opinions. Other potential bias is in the selection of the participants. The participants will be deliberately selected for already being involved in the use of digital design processes in industry and for being involved in the continuous professional development of graduates. They will be selected as they have knowledge in the areas of interest, are likely to drive changes in the construction industry and have an opinion on the education of graduates. With reference to the BERA Ethical Guidelines for Educational Research (2011) the applicant recognises that she has an obligation to Imperial College London and the educational research community not to harm their reputation and to conduct research with integrity, authenticity and professionalism; just as the opportunity to conduct this research relies on her predecessors having carried out research with the same qualities. Participants can

	withdraw until data is anonymised and have the right to refuse a second interview if it is asked. Data will be stored securely according to Imperial College regulations. The participants' names and email addresses will be kept separately to the transcription of the interviews and full recordings will be deleted after transcription has been completed and checked.
4.1 Supporting Documentation - check any/all that you attach:	Letter/email inviting participation; Participant information sheet; Participant consent form; Interview / Focus group questions; Other documentation

Appendix B

Grasshopper definitions

B.1 Concrete core optimisation tool

Figure B.1 shows an overview of the GH definition developed for the concrete core optimisation tool discussed in Chapter 4. Custom Python components are used throughout the definition. The clusters drawn represent the following steps:

1. This is where the user inputs the necessary data, such as the variable selection for the automated optimisation and other parameters. This is also where data from RH is imported. This is where all sliders are located for the user to manually explore the design space.

2. The geometry is created. Walls are extruded with height as surfaces, points of contact between various elements are defined to be included when meshing surfaces, the rigid beams are created as lines, the load application points are identified.

3. The information necessary for the Karamba FEA is compiled and the analysis is run. The pink group is for the elements, the yellow group is for the supports, the turquoise group is for the loading, the purple group is for the elements section and the blue group is for the material properties.

4. Stresses, inter-storey drifts and deflections are checked to be included as penalties in the objective function.

5. Various Karamba components are used to display different available results and custom Python components are used to display deflections plots.

6. Galapagos is used for automated optimisation using the selected variables for mass minimisation. The custom Gene Pool component in pink enables optimising only the selected variables.

7. User information is displayed to help the user in the tool usage.

8. This is an alternative part of the definition where the full slabs are models which is aimed to be used to check deflections and inter-storey drifts of the full plate for a core system and could be used for frequency and mode checks.

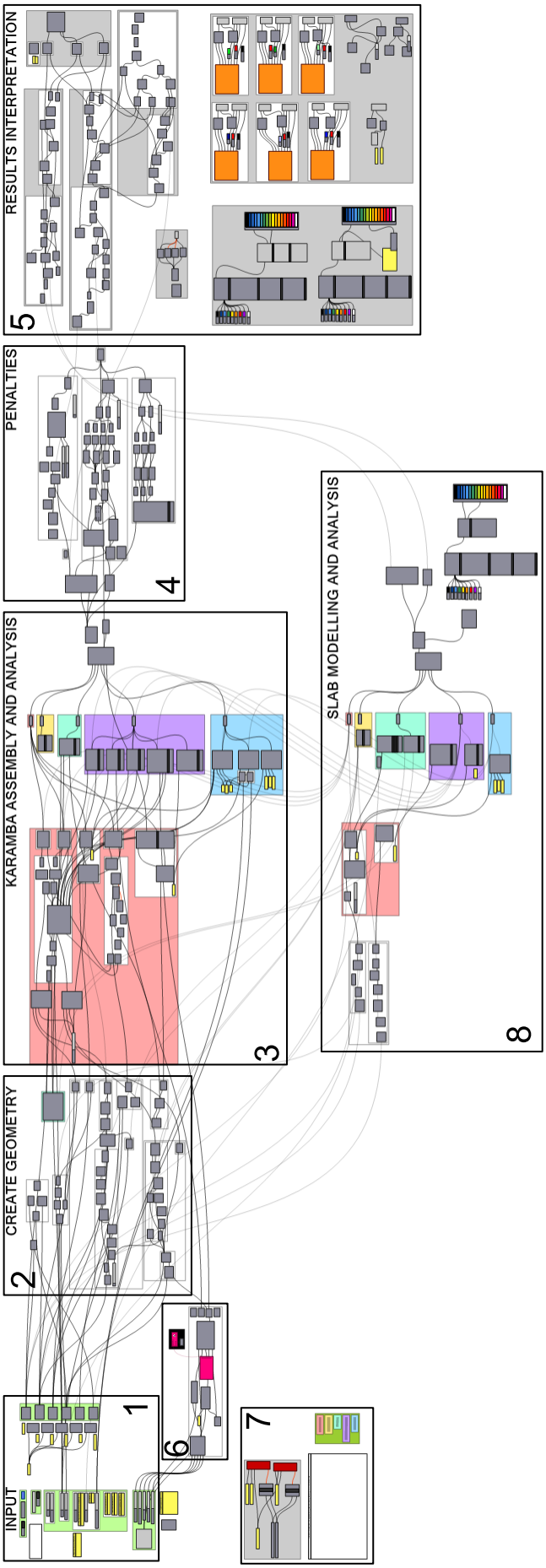


Figure B.1: Overview of the GH definition developed for the concrete core optimisation tool.

B.2 Concrete slab and column optimisation tool

Figure B.2 shows an overview of the GH definition developed for the slab and column optimisation tool discussed in Chapter 5. Custom Python components are used throughout the definition. The clusters drawn represent the following steps:

1. This is where the user inputs the necessary data, such as the decisions to be made for the optimisation and other parameters.

2. The Gene Pool components, the pink ones, are modified through custom Python and C# components based on the user's decisions, to act as genome for Galapagos. The number of sliders in the relevant Gene Pool component matches the number of variables to be used in the optimisation. The yellow group containing one Gene Pool component is used if the number of columns in each partition line is fixed, the yellow group containing two Gene Pool components is used if the number of columns in each partition line can change. In this case, one Gene Pool component controls the position of one column and the other component controls the distance between this column and the additional ones that may be added in each partition line.

3. The column length l_{col} is computed based on the user's decisions. The first orange group is used if l_{col} is to be computed in the analysis and contains a first Karamba analysis. A custom Python component is used to compute l_{col}. The second orange group is used if l_{col} is drawn in RH. The third orange group is used if l_{col} is set by the user as a constant value for all columns.

4. The information necessary for the Karamba FEA is compiled and the analysis is run. The pink group is for the elements, the yellow group is for the supports, the turquoise group is for the loading, the purple group is for the elements section and the blue group is for the material properties.

5. The different objective functions available are displayed and the user can select the one used for the optimisation. Penalties added to the objective function are calculated through custom Python components.

6. Galapagos is used for automated optimisation. Custom Python components are used to track the optimisation running time and the number of generations needed by Galapagos to reach convergence.

7. User information is displayed to help the user in the tool usage.

8. Custom Python components are used to export the results from the optimisation to a dedicated Excel spreadsheet to compare results if multiple optimisations are conducted.

9. Various Karamba components are used to display different available results.

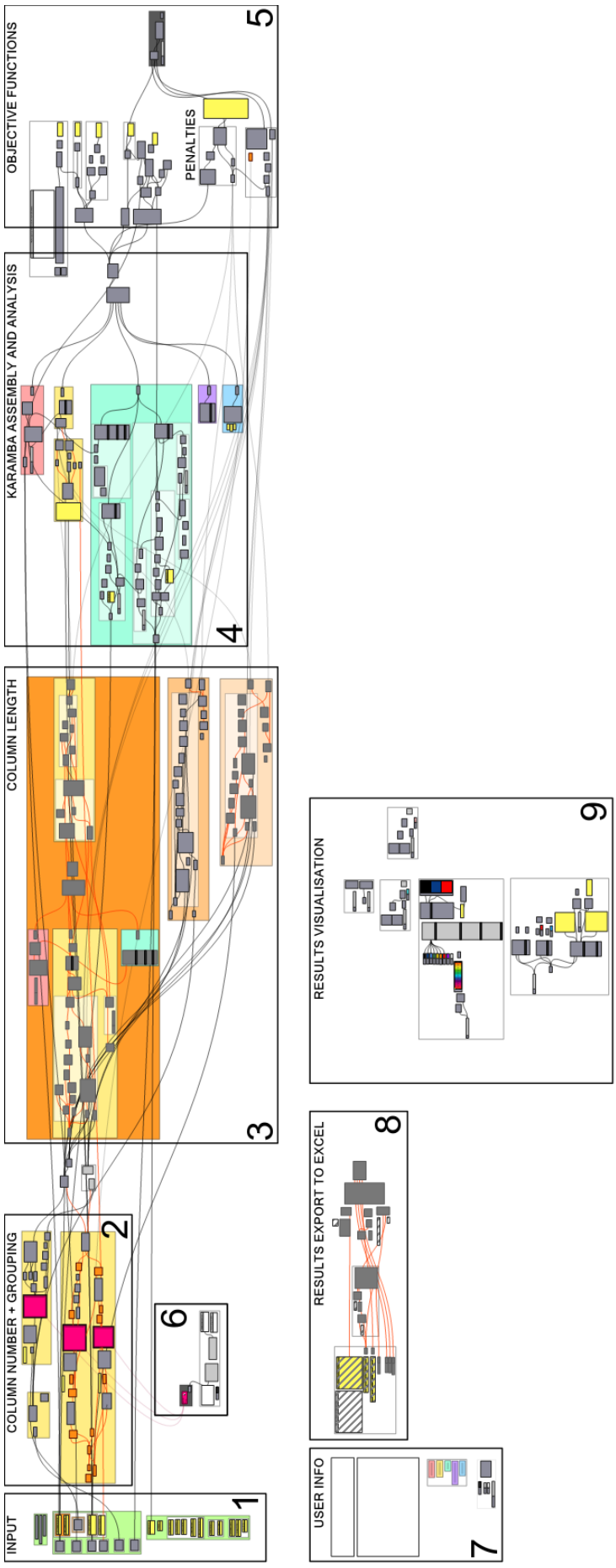


Figure B.2: Overview of the GH definition developed for the slab and column optimisation tool.

B.3 Steel building optimisation tool

Figure B.3 shows an overview of the GH definition developed for the steel building optimisation tool discussed in Chapter 6. Custom Python components are used throughout the definition. Each cluster in Figure B.3 represents a step in the definition. Steps 1 to 4 are for optimising the grid layout under vertical loading. Steps 6 to 8 are for bracing optimisation under wind loading. The steps can be explained as follows:

1. This is where the user inputs the necessary data, such as the decisions to be made for the optimisation and other parameters.
2. The beam and column arrangement is computed in this step. Based on the set variables, the primary grid is established with column locations based on the distance constraints, secondary beams are added, cantilever beams are identified, and this is added to the correct number of storeys.
3. The information necessary for the Karamba FEA is compiled, the analysis is run and the sizing optimisation is conducted. The pink group is for the elements, the yellow group is for the supports, the turquoise group is for the loading which in this step is only vertical, the purple group is for the elements section and the blue group is for the material properties.
4. Galapagos is used for automated optimisation of the grid layout under vertical loading.
5. User information is displayed to help the user in the tool usage.
6. This is where bracing location on the optimised grid layout is imported from RH and where wind direction is selected for analysis of the structure under wind loading.
7. The bracing arrangement is added with height to the optimised grid layout.
8. A second Karamba instance is created to compile and analyse the structure under wind loading with the bracing arrangement. The colour code of the groups is the same as in Step 3.
9. Various Karamba components are used to display different available results and custom Python components are used to display deflections plots under wind loading.

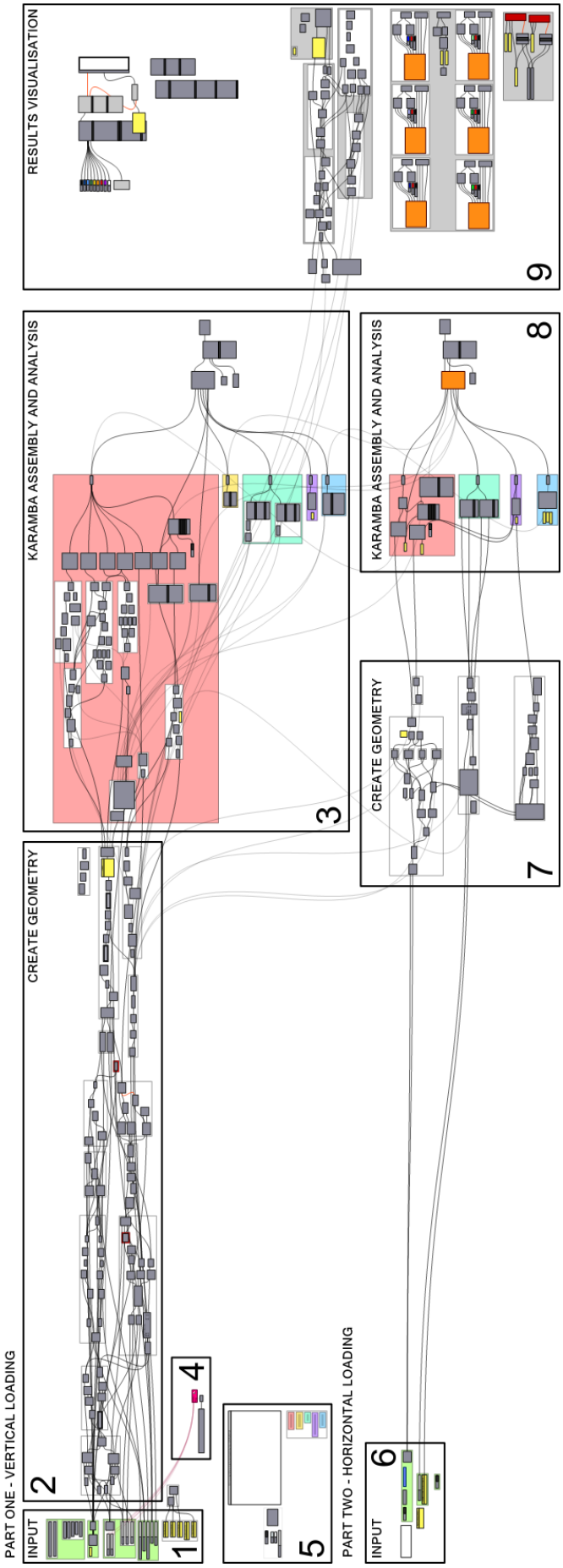


Figure B.3: Overview of the GH definition developed for the steel building optimisation tool.

Appendix C

Karamba beam element definition

The Karamba team has been contacted to obtain the exact definition of beam elements which is not provided in the user manual. No definite response was obtained. Clemens Preisinger, the author of Karamba, has answered a question on the Grasshopper 3D forum confirming that Timoshenko beam theory is used to model beam elements in Karamba[1]. This has been verified analytically using a 10.0 m simply-supported beam with a large circular hollow cross-section compared with the beam length. The cross-section and loading are shown in Figure C.1.

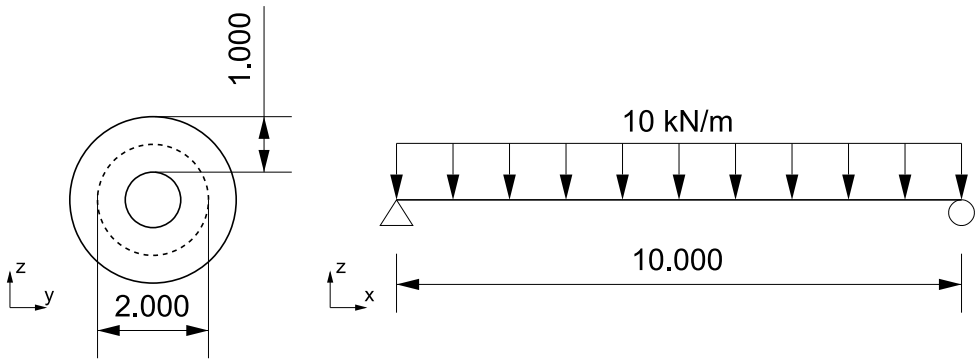


Figure C.1: Cross-section, loading and boundary conditions of the deep beam used for analytical check of the beam element definition used in Karamba. All units are in meters unless otherwise specified.

[1]https://www.grasshopper3d.com/group/karamba3d/forum/topics/question-about-the-component-linetoelement [Accessed 01/2020]

The maximum deflection, occurring at mid-span, accounting for shear deformation following Timoshenko beam theory for a simply-supported beam under a UDL is (Phillips 2016):

$$\delta_{max} = -\frac{5wL^4}{384EI} - \frac{wL^2}{8\kappa GA} \tag{C.1}$$

where w is the UDL, L is the beam length, E is the Young's modulus, I is the second moment of area, κ is a cross-section shape factor, G is the shear modulus and A is the cross-section area. Assuming E of 210 GPa, G of 80.76 GPa and using the section properties shown in Figure C.1 to derive A, I and κ according to Hutchinson (2001), the maximum deflection is:

$$\delta_{max} = -\frac{5 \times 10 \times 10^4}{384 \times 210e^6 \times 7.854e^{-1}} - \frac{10 \times 10^2}{8 \times 0.62 \times 80.76e^6 \times 3.141} \tag{C.2}$$

which is 8.689e^{-6} m. If the second term in Equation (C.1) is removed, thus ignoring shear deformation, the maximum deflection is 7.895e^{-6} m. The maximum deflection obtained from Karamba is 8.668e^{-6} m which is close to the result obtained analytically using Timoshenko beam theory. Based on this result and on the comment made by Clemens Preisinger discussed above, it appears reasonable to assume that beam elements in Karamba account for shear deformations.

A second study has been conducted on a fixed-ended beam as shown in Figure C.2 to check the shape function used by Karamba. A single beam element is used in Karamba. A relative length L varying from -1 to 1 is used to compare the displacements with a Hermite cubic shape function (Phillips 2014). Two cases were modelled: in the first case, a vertical unit displacement was imposed at one end. The results from Karamba and from the Hermite cubic shape function are shown in Figure C.3. In the second case, a one radian rotation was imposed at one end and the two results are shown in Figure C.4. The displacement is large due to the large rotation applied. The rotation was chosen in order to obtain a slope of 1 at the end where the rotation is applied. The slope of the curve obtained from the Karamba displacements and from the relevant Hermite cubic shape function are shown in Figure C.5.

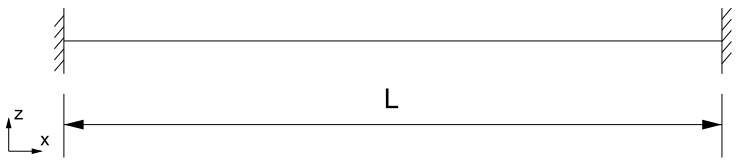


Figure C.2: Fixed-ended beam for shape function check.

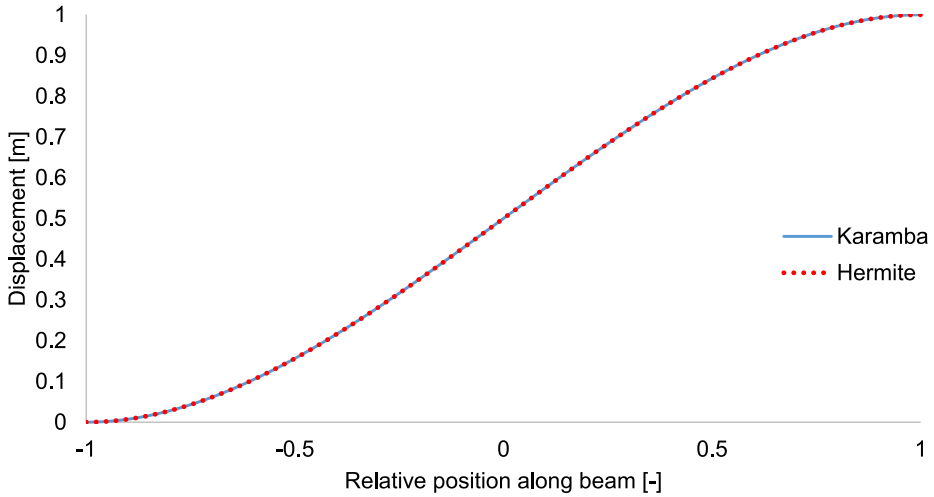


Figure C.3: Shape function after imposing a vertical unit displacement from Karamba on one beam element and using a Hermite cubic shape function.

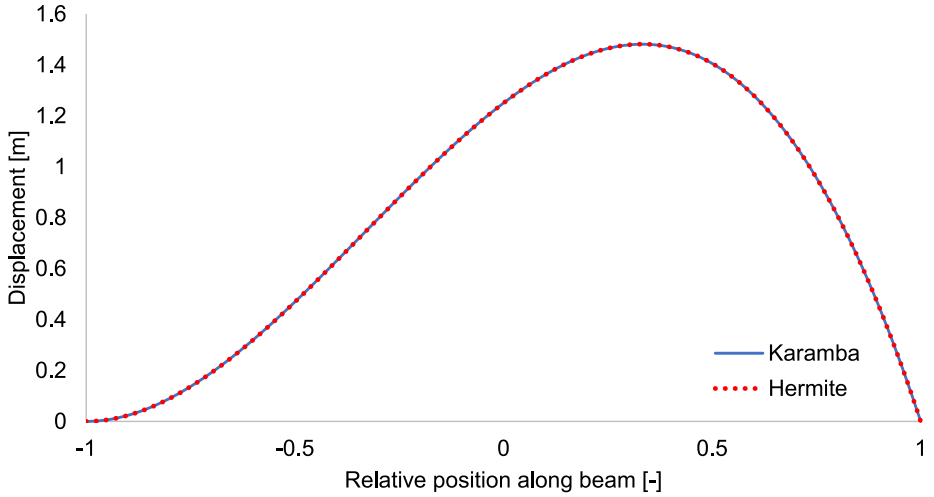


Figure C.4: Shape function after imposing a one radian rotation from Karamba on one beam element and using a Hermite cubic shape function.

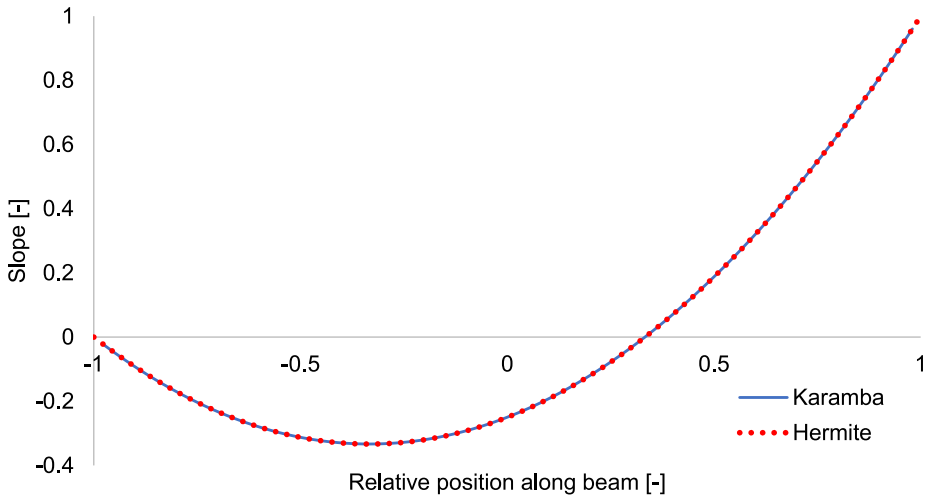


Figure C.5: Slope of the shape function after imposing a one radian rotation from Karamba on one beam element and using a Hermite cubic shape function.

Based on the results obtained, the custom shape function used in Karamba fits with a Hermite cubic shape function.

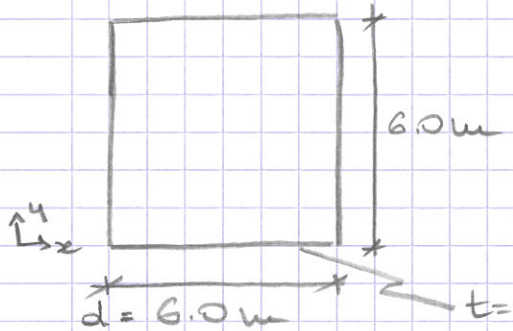
Appendix D

Additional data on the concrete optimisation tools

D.1 Concrete core analytical calculations

The hand calculations conducted for the first case study of the core optimisation tool presented in Chapter 4 are shown here. They include second moment of area of a thin-walled closed rectangular hollow section and maximum deflections for a number of loading conditions.

L.B. | SQUARE HOLLOW SECTION - ANALYTICAL CALCULATIONS



$E = 34 \times 10^6 \text{ kN/m}^2$

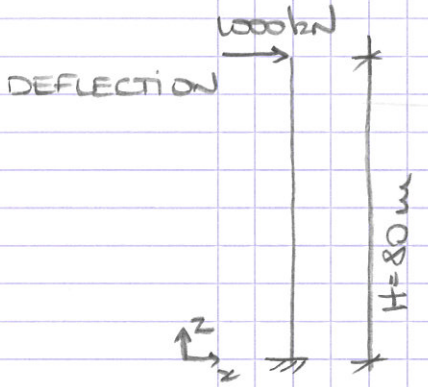
$G = 14.167 \times 10^6 \text{ kN/m}^2$

SECOND MOMENT OF AREA

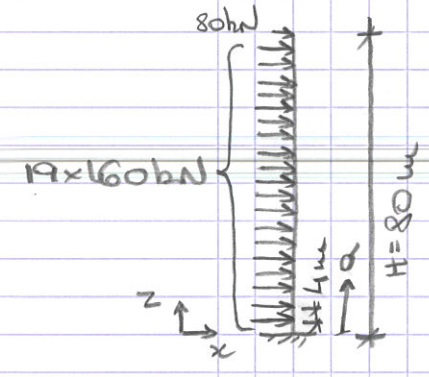
$$I_{xx} = I_{44} = \Sigma I_A + A_A d^2 = 2 \times \frac{0.250 \times 6^3}{12} + 2 \times \frac{0.250^3 \times 6}{12} + 2 \times 0.250 \times 6 \times 3^2$$

$$= 36.02 \text{ m}^4$$

DEFLECTION



$$\delta = \frac{PH^3}{3EI} = \frac{1000 \times 80^3}{34 \times 10^6 \times 36.02} = 0.139 \text{ m}$$



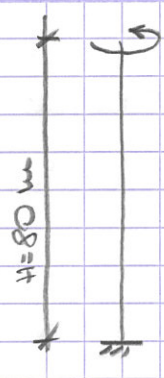
Maximum deflection for one point load:

$$\delta = \frac{Px a^2}{6EI} \times 3(H-a)$$

Total deflection with 20 point loads:

$$\delta_{tot} = 4 \sum_{a=4}^{80} \frac{Pa^2}{6EI} 3(H-a)$$

$= 0.167$ m from hand calculations & Excel check



Assume thin-walled closed section

$(10 \times t < d)$

TORSION CONSTANT

$$J = \frac{4A_c^2}{\oint \frac{1}{t(s)}\,ds} = \frac{4 \times (6^2)^2}{4 \times \frac{8}{0.25}} = 6^3 \times 0.25 = 54\ m^4$$

RATE OF TWIST

$$T_z = GJ\theta_z \quad \therefore \quad \theta_z = \frac{T_z}{GJ} = \frac{1 \times 10^5}{14.167 \times 10^6 \times 54} = 1.307 \times 10^{-4}\ rad/m$$

ANGLE OF TWIST AT END

$$\phi_z = \theta_z \times H = 1.307 \times 10^{-4} \times 80 = 1.05 \times 10^{-2}\ rad$$

$$= 0.599^\circ$$

DEFLECTION

$$\delta = l \sin\left(\frac{\phi_z}{2}\right) \times 3\sqrt{2} = 2 \sin\frac{0.599}{2} \times 3\sqrt{2}$$

$$= 0.044\ m$$

D.2 Concrete core optimisation tool convergence study

Beam distance (m) \ Mesh resolution (m)	0.3	0.5	1.0	1.5	2.0	3.0
0.3	0.141	0.141	0.139	0.136	0.133	0.125
0.5	0.142	0.141	0.139	0.136	0.133	0.125
1.0	0.145	0.143	0.139	0.136	0.133	0.125
2.0	0.153	0.149	0.143	0.139	0.132	0.125

Table D.1: Maximum deflection at the top of the core $\delta_{\max}$ (m) with a point load applied at the top of the beam, obtained with varying mesh resolutions and with varying stiff beam spacing.

Beam distance (m) \ Mesh resolution (m)	0.3	0.5	1.0	1.5	2.0	3.0
0.3	0.169	0.167	0.164	0.158	0.159	0.137
0.5	0.169	0.167	0.165	0.159	0.159	0.142
1.0	0.174	0.170	0.163	0.160	0.160	0.145
2.0	0.186	0.179	0.171	0.163	0.155	0.145

Table D.2: Maximum deflection at the top of the core $\delta_{\max}$ (m) with multiple point loads applied along the core, obtained with varying mesh resolutions and with varying stiff beam spacing.

Beam distance (m) \ Mesh resolution (m)	0.3	0.5	1.0	1.5	2.0	3.0
0.3	0.044	0.044	0.044	0.044	0.044	0.044
0.5	0.044	0.044	0.044	0.044	0.044	0.044
1.0	0.044	0.044	0.044	0.044	0.044	0.044
2.0	0.045	0.045	0.043	0.044	0.043	0.044

Table D.3: Maximum deflection at the top of the core $\delta_{\max}$ (m) with twisting moment applied at the top of the core, obtained with varying mesh resolutions and with varying stiff beam spacing.

D.3 Concrete slab and column optimisation tool convergence study

		Mesh resolution (m)					
		0.3	0.5	1	1.5	2	3
D (m)	6.9	0.101	0.102	0.103	0.100	0.098	0.104
	5.3	0.132	0.133	0.133	0.135	0.133	0.11
	3.7	0.216	0.217	0.221	0.224	0.224	0.215
	2.1	0.378	0.378	0.387	0.391	0.387	0.374

Table D.4: Maximum deflection of the slab obtained with varying mesh resolutions, for columns positioned at four different distances D away from the centroid of the slab.