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Module construction of multi-story buildings in Norway

A comparative study on limitations, structural performance, cost and serviceability

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Cover image:

The picture shows the building from Harestad Bygg AS which is used as a model for this thesis. Photo taken on November 6, 2023, at Randaberg.

I. Abstract

Modular construction focuses on making prefabricated modules and elements with preinstalled services in order to reduce the construction time, whilst also maintaining the structural performance and safety of the building. Though this have not been used much in Norway, it can be observed from other countries that this method has many advantages and disadvantages. To name a few, the construction time is faster, the cost can be reduced, inventory spacing can be managed more easily, labour cost can be reduced, labour safety can be improved, while still satisfying the structural requirements for the job. Furthermore, modular construction may be a more affordable solution to the housing crises in underdeveloped countries and a solution for cheaper student housing. This paper focuses on comparing the structural performance, cost, advantages, disadvantages, limitations and serviceability between traditional cast-in-place concrete elements, precast elements and prefabricate modules.

II. Acknowledgement

This thesis is a part of the partial fulfilment of the bachelor's degree in Structural Engineering at the University of Stavanger, Norway, at the Department of Mechanical and Structural Engineering and Material Science. Research have been conducted during the spring semester of 2024.

I would like to thank my supervisor, Professor Mudiyan Nirosha Damayanthi Adasooriya for her guidance and support during the writing of this thesis. Furthermore, I want to thank Harestad Bygg AS for supplying me with sketches and models of their new construction at Randaberg. Lastly, I want to thank ØsterHus AS, Veidekke Prefab and Total Betong for their cooperation and insights into this paper. Interviews with these firms has taught me a lot about the construction business and real-world experience.

Randaberg, 15.05.2024

Marius Ree

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1. Introduction

1.1. Aim of study

The aim of this thesis is to simplify some of the understandings regarding modular construction, as well as studying the structural performance of in-situ cast concrete, precast elements and prefabricated modules. The thesis focuses on use of modular construction in Norway, where traditional casting is the most common practice. Comparisons of advantages, disadvantages and limitations between all three construction methods will also be a major part of the thesis.

1.2. Objective of study

The objective of the study is to analyse and compare the three construction methods with respect to their potential in Norway. The study includes a design calculation of the critical beam and column element of the model building in accordance with appropriate Eurocodes. The thesis specifically includes a comparison of casting and creating approaches, installation, transportation, inventory management, fabrication of elements, installed services, customizability, cost and time efficiency, inspection and safety control, application, design codes and the connections for assuring structural performance of the building. Some parts will be simplified or limited due to the time constraints of the thesis hand-in and limitations of software. Further research recommendations will be noted in the last section. References to all citations, communication or lectures will be noted in APA 7th format.

1.3. Methodology

The thesis is purely a literature study which combines research from books, online journals, articles and other research paper. Published literature on the internet and physical books from the university library are the main sources for information. The main search engines used include Oria and Google. A few collaborations with local construction business have also provided a great deal of practical insight to the paper. Interviews, tours and talks with Harestad Bygg AS, ØsterHus AS, Veidekke Prefab and Total Betong have been a of significant help to get real-world experience into this study.

1.4. Background

The use of prefabricated construction methods has been less common in Norway than in other countries such as China and North America. This is partially due to the lack of knowledge and confidence in the construction method, and due to the the country's extensive length and mountainous terrain make transportation less optimal. In order to boost the confidence for build owners to use prefabricated manufacturing, it is important to study and analyse the many advantages, disadvantages and limitations of traditional construction and prefabricated construction methods. Factors such as installation, transportation and efficiency will affect the overall cost of the project. Therefore, it is important to compare these factors in each of the construction methods. It is of utmost importance that the structural performance of constructions is of high quality and safe for workers.

Prefabricated element construction is used to some degree in Norway, but the use of full-size modules with preinstalled services is almost completely excluded in the construction market. However, it may become more included in future projects if contractors become more familiar with the method. A mix of precast elements with cast-in-place elements are sometimes used in projects in Norway.

1.5. Assumptions and limitations

A model of a building by Harestad Bygg AS will be used as the focus point of comparison. The cover page includes a photo of the building in an early construction phase. The building is a three-story building consisting of a fitness centre on the first floor and office areas on the second floor and third floor. It is located in Randaberg, Norway and has been constructed by traditional cast-in-place concrete together with steel elements. In order to analyse the building, some simplifications and assumptions will be made to the building to make calculations easier. For instance, walls will be considered as without openings and will not carry vertical loading. All beams, columns and slabs will also be considered to have the same concrete class and reinforcement steel class. Further assumptions related to the calculations will be noted in Appendix A.

1.5.1. Building data

The three-storey building has dimensions of 27x17.4x12.675 m (Length x Width x Height). It is located in Randaberg with an altitude of 29.4 m above sea (Kartverket, 2024) in terrain category II 1.15 km from coastal area of terrain category 0. The building is realistically connected to an existing building, but for the sake of symmetric simplicity, it will be considered as free-standing. There is no specific wind direction, and it is located in a flat area with no hill.

The columns are modelled with a cross section of 610x610 mm with a height of 4 m. Beams are considered as 400x600 mm with a span of 8.2 m. The continuous beams have one intermediate pin support located at the middle of the entire 17.4m length. The beam to column connection is considered as pin supported for simpler calculations. Slabs have a thickness of 225 mm. The building is modelled in Revit 2023 and all dimensions are in mm. Different views of the Revit model can be seen in figure 1 to 4 below.

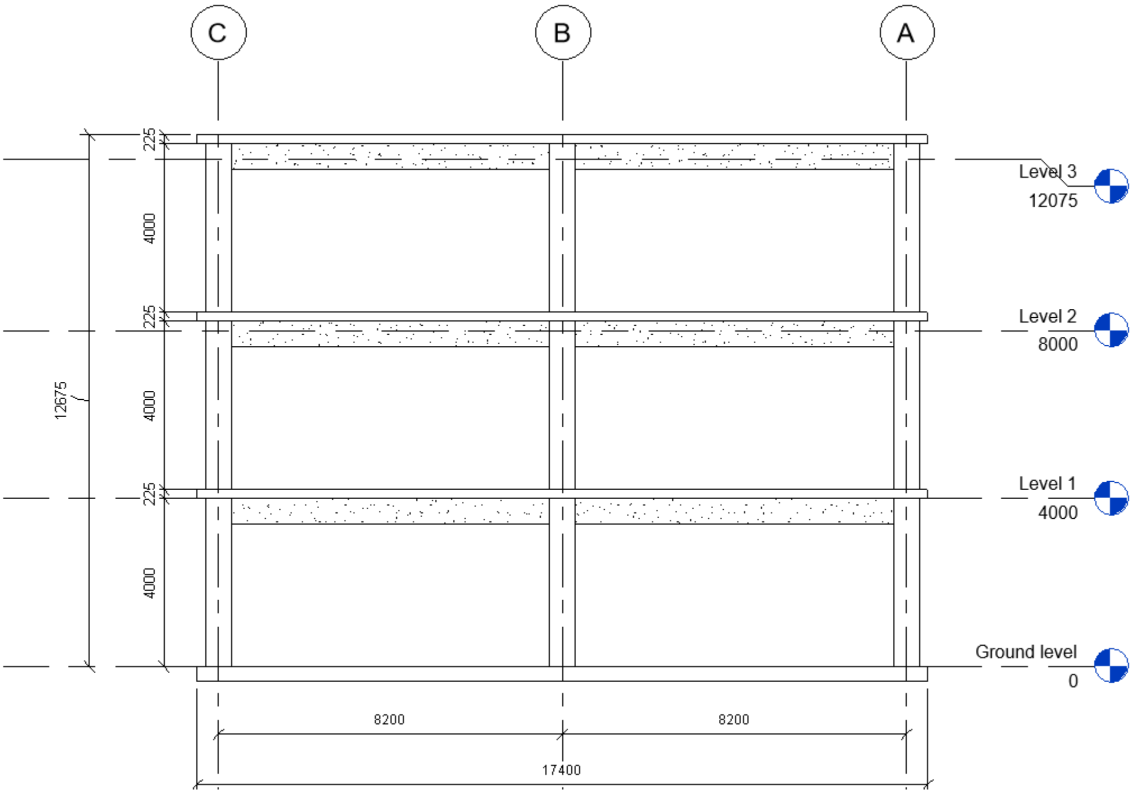


Figure 1: Side view of building modelled in Revit 2024. View direction from East

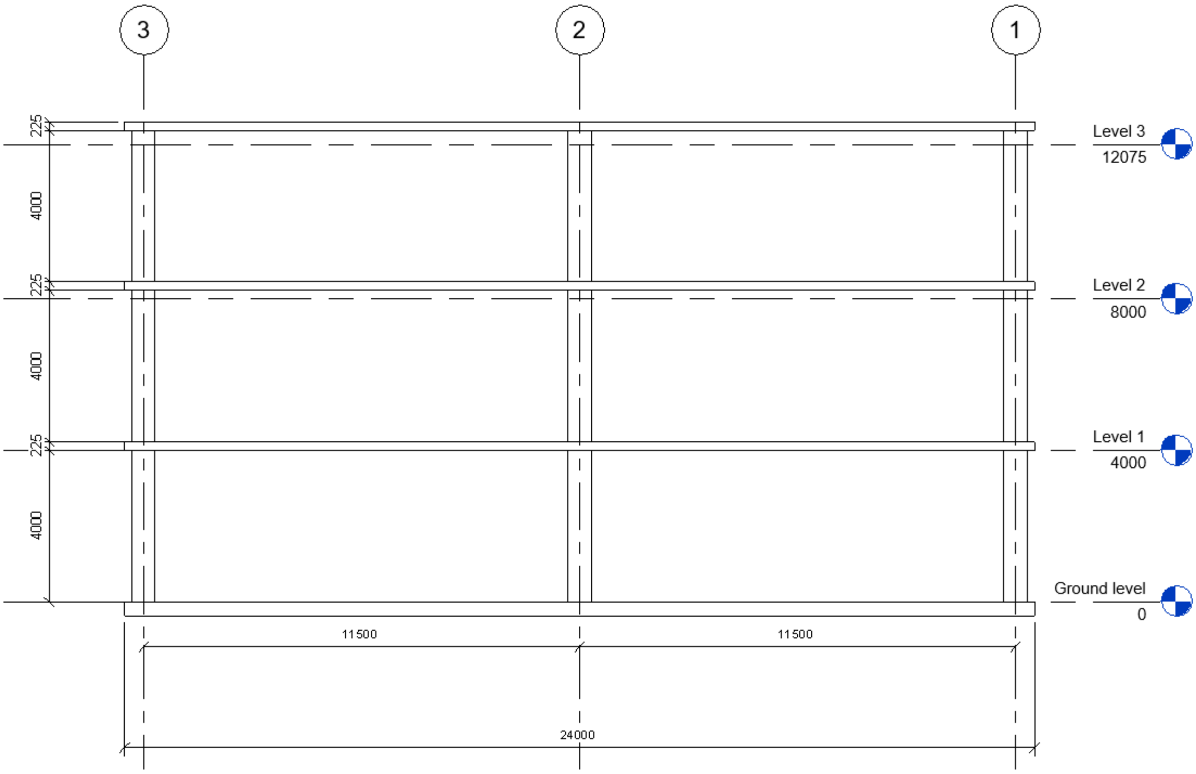


Figure 2: Side view of building modelled in Revit 2024. View direction from North

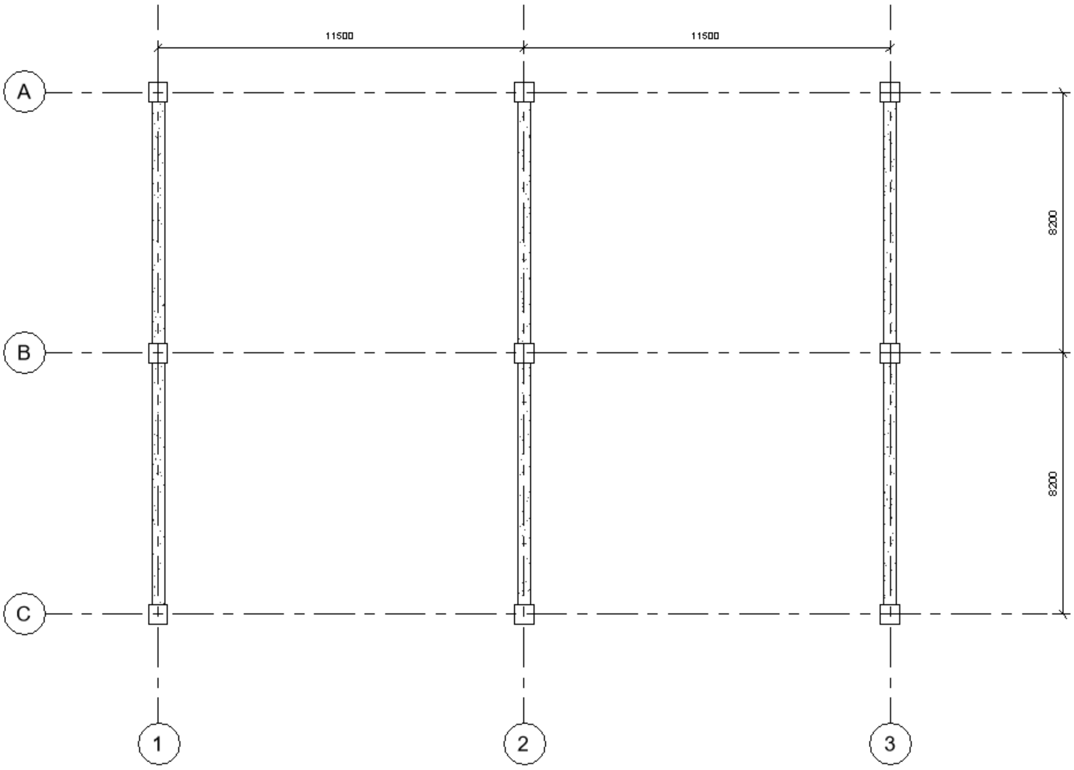


Figure 3: Plan view of building without walls modelled in Revit 2024

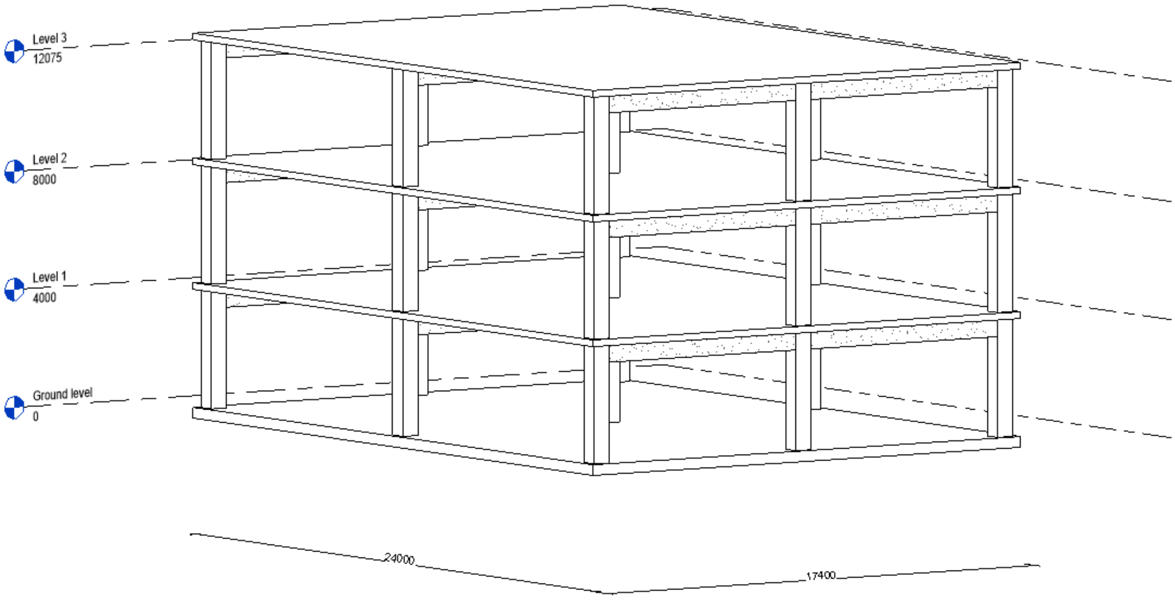


Figure 4: 3D view of building without walls modelled in Revit. View direction from South-East toward North-West.

1.5.2. Assumptions related to element design

For the design of elements, it is important to find the critical elements and ensure they are safe for the loading purpose of building. Since the main focus of this thesis is not to design the entire building to withstand forces, only the critical members will be designed according to Eurocodes. Calculations can be found in Appendix A. The calculations are computed with Smath software. Smath is a free software which lets you assign variables and calculate equations with said variables. It will automatically update calculations when changes are made. Therefore, it is easier to follow and more adaptable to change. Usually, an analysis would be made to identify the critical members of the building, but the symmetry of the construction allows for easier identification of the middle beam and column on the first floor as the critical members. These will therefore be designed to withstand forces. Without this symmetric building, the Finite Element Method could be used to compute the deformations and stress at the notches to determine the critical members of this construction.

1.5.3. Assumption related to modular design

For the design of modular units, we can consider a similar design procedure as for traditional reinforced concrete. One notable difference can be observed in the installation of a module at the construction site. As opposed to precast elements, where only one element is connected at a time, one must now connect an entire module in place. Designing precast elements and modules must follow the same Eurocode guidelines.

2. Elements and modules

For the purpose of distinguishing the different construction methods, it is important to define what is meant by traditional concrete casting, precast concrete elements and prefabricated modules. Traditional concrete casting, or cast-in-place concrete, refers to elements cast in-situ by using formwork and placing the concrete directly into their place of installation (Arellano, 2023). It is the most common method of construction in Norway (Total Betong, personal communication, 10.04.2024).

A precast concrete element is "a concrete element that is manufactured somewhere other than its final place of installation" (Safe Work Australia, 2019). The elements include walls, beams, columns, slabs and culverts. These elements can be casted at the construction site and lifted into place after hardening. Alternatively, they can be cast in an off-site controlled environment or factory and transported to their respective installation place.

As opposed to precast elements, precast concrete modules are "fully functional structures with specific purposes" (FORTRESS Protective Buildings, 2022). These can consist of multiple elements to form a structure which includes reinforcement, electrical wiring, piping, ventilation and other utilities (Real Projectives, 2019). The service voids and electrical units can be installed before casting the concrete in a mould (Lawson et al., 2014, p. 41). After factory fabrication, the modules are shipped directly to the construction site ready for installation. Some final touches must still be made to these modules, for instance connecting or joining of the modules together with infill (Real Projectives, 2019). Lawson et al. (2014) define modules to be "Three-dimensional or volumetric units that are generally fitted out in a factory and are delivered to the site as the main structural elements of the building" (Lawson et al., 2014, p. 1). On page 41, it is further included in the definition that the modules consist of "planar elements, such as slabs and walls, and linear elements, such as beams and column" (Lawson et al., 2014, p. 41).

2.1. Casting and creating approaches

The different construction methods use slightly variant approaches for designing the desired elements. The casting methods will have an impact on the overall structural performance of the building, due to the different joining methods needed in each situation. To understand this better, one needs to distinguish the design approaches and fabrication methods separately. The common procedure for concrete casting, is often as the following subchapters 2.1.1 to 2.1.4 describe. (Nirsoha, personal communication, 27.09.2023):

2.1.1. Initial sizing

This refers to sizing of elements to consider the appropriate design life, durability, exposure class, concrete strength class, concrete cover, steel reinforcement class, reinforcement bar size and thickness. These attributes are calculated to withstand the design loading by following the design requirements of the Eurocodes. For this thesis, numerous standards will be used. The standards are gathered from Standard Norge by a student license.

2.1.2. Material properties

Refers to the design strengths of concrete and steel reinforcement in the construction element. This is also calculated using the same aforementioned Eurocodes. For the case study, B35 concrete with B500NC steel reinforcement has been used in all elements.

2.1.3. Design for failure modes

After designing the elements, we need to check the elements for all relevant failure modes. This includes failure due to flexural behaviour, shear, torsion, buckling, or combinations of these. The failure would be due to the loadings on the elements, which in this case will consist of dead load, live load and snow load. Seismic action is not considered in this study. Due to the complex implications of wind action on the building, it has not been considered when determining the failure of the elements in Appendix A. Calculation of wind action is present, but it has been considered to be resisted by facades. It is important to design the elements so that the failures are not present in the final product of the building. In the case study, failure due to moment, shear and deflection has been checked in accordance with appropriate Eurocodes.

2.1.4. Deflection calculation

After the Ultimate Limit State requirements are approved, deflection control is the next necessary step in designing reinforced concrete elements. The deflection limit has been calculated and compared to the calculated deflection of the element according to the Serviceability Limit State conditions. The deflection has been calculated by a simplified span to effective depth ratio for the beam element.

2.1.5. The approach

For all three construction methods, this approach ensures adequate safety in the design of elements. However, there are notable differences evident in casting the elements and installing them with each method.

To begin, cast-in-place concrete is installed by preparing a framework with the required reinforcement ready. Later, this framework is filled with the design concrete mix and vibrated thoroughly to remove any air bubbles trapped in the mix. After 28 days, the mix has reached the required design compressive strength (Mishra, 2018) and the framework can be removed from the hardened concrete element.

Prefabricated elements are created using a near identical approach. Instead of using a framework at the installation place, the concrete mix is poured into a reusable mould in an off-site factory or on-site mini factory. Using this method, it is possible to use a vibrating floor or formwork vibrator as an external vibrator, instead of the traditional on-site vibrator. Another alternative is to use a self-compacting cement mix to reduce vibration work. When the element is ready, it can be transported to the installation place and connected by appropriate joining methods. If the element is not fabricated at the construction site, one must also consider adequate safety of transporting the element. Logistic costs would also be present.

The final construction method shares a lot of similarity to the process for prefabricated elements. When using prefabricated modules, an entire module is cast as a combination of linear and planar elements (Lawson et al., 2014, p. 41). The module is fitted with electrical work and piping services either during casting, or after casting, depending on whether internal or external services are desired in the finished build (Lawson et al., 2014, p. 204)). Later, the full module is transported to the installation place. The difficulty of transporting such modules will depend on the size and complexity of the module. Bigger modules may not be stacked as efficiently as smaller modules. Heavier modules are also more difficult to transport due to difficulty of fulfilling weight limitations on trucks in Norway. Typically, the module width can be up to 4.2 m according to Lawson et al. (2014), but lengthwise it can be up to 16 m (p. 63).

2.1.6. Added steps for precast elements

The steps listed from section 2.1.1 to 2.1.4 are common for all construction procedures using reinforced concrete. When using precast concrete elements, there are a few additional steps. After the element has been designed against loading in accordance with the Eurocodes, the formwork needs to be crafted and prepared for casting. This includes sawing or adjusting the mould to the desired shape, moisturize the mould so the concrete does not stick, constructing reinforcement layout and placing into the mould, casting the concrete mix into the mould, vibrating and compacting the concrete mix and finally storing the concrete for the hardening process. A few select pictures of this procedure at Veidekke Prefab's factory is shown below in figures 5-9.

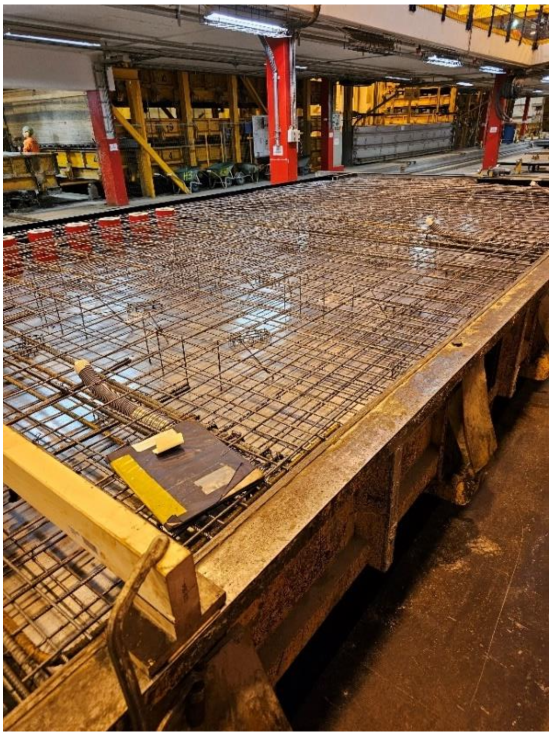


Figure 5: Mould prepared with reinforcement. Taken on 05.02.2024, at Klepp

Figure 6: Wooden panels with magnetic fasteners are placed to customize the shape of the element. Taken on 05.02.2024, at Klepp

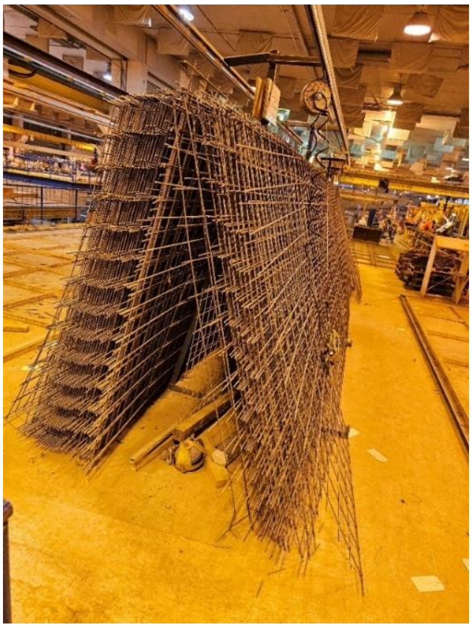


Figure 7: Reinforcement layout is being prepared and stored. Taken on 05.02.2024, at Klepp

Figure 8: Concrete mix is added onto reinforcement in the mould. Taken on 05.02.2024, at Klepp

Figure 9: The mix is smoothened out for better finishing. Taken on 05.02.2024, at Klepp

When challenged about the lack of vibration of the mix, experts at Veidekke Prefab assured that a self-compacting concrete mix was used. Thus, vibration work was unnecessary. For cases without water-reducing agents, vibration work is necessary and can be done by vibration stick or vibrating mould.

For manufacturing of special elements like columns, hollow-cores or mass-produced smaller elements, figures 10-12 below illustrate some examples of this process in Veidekke Prefab's factory.

Figure 10: A long circular column mould. Taken on 05.02.2024, at Klepp

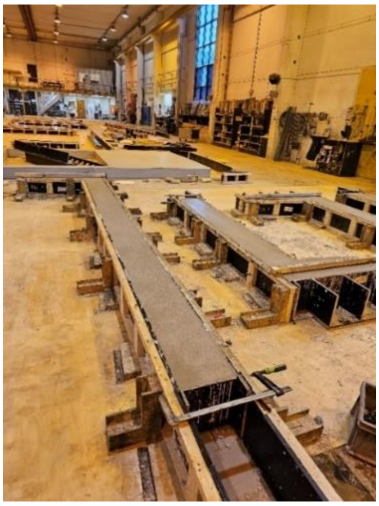


Figure 11: Mass production of smaller and simpler elements. Taken on 05.02.2024, at Klepp

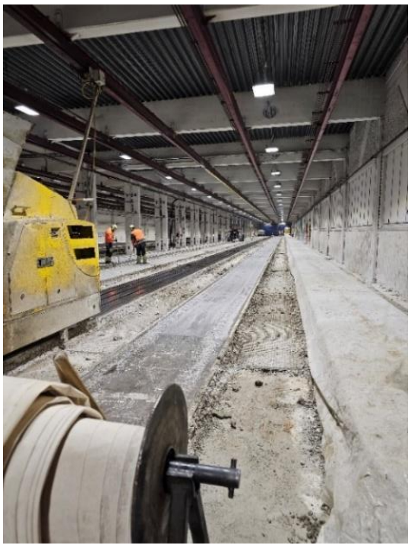


Figure 12: Long hollow-cores are casted as strips. A machine automatically drives over these strips and cut out the hollow-cores on the way. Taken on 05.02.2024, at Klepp

Even though the moulds can be customized for almost any desired shape, standard sizes and mass production is preferred in prefabricated manufacturing due to the time savings of not redoing the mould for each operation. Furthermore, additional admin hours would be needed to make calculations for safety of customized elements. This would further increase the cost, resulting in standardisation of elements being the recommended practice for manufacturers. When Veidekke Prefab had created an element which they needed more of, they could simply loosen the mould, lift out the element, fasten the mould, moisturize the mould and cast a new element (Veidekke Prefab, personal communication, 05.02.2024).

This is also experienced for the hollow-core construction process. The hollow-cores are cast at full length to maximize production. These lengths are then cut into pieces of desired lengths for projects. This vastly reduces the manufacturing time as opposed to making each hollow-core separately.

2.2. Precast element differences

Elliot (2017) states that the real difference between precast concrete and cast in-situ concrete is "its stress and strain response to external … and internal … effects" (p. 1). The elements have to be joined and be able to restrict the volumetric changes induced by thermal shrinkage and load-induced strains (Elliott, 2017, p. 1). The change in volume also apply a frictional force to the element that needs to be considered when designing reinforcement in the element. The frictional force F is computed as $F = \mu * R$ (Elliott, 2017, p. 1) where μ is the frictional constant, and R is the normal force reaction to the elements weight. F then acts in the opposite direction of the movement direction of the element. This is also coherent with a study by Chang et al. which also note that the "mechanical performances are different from those of cast-in-place buildings under extreme loading conditions, e.g., earthquakes and hurricanes" (Chang et al., 2023). Precast elements connections are also commonly semi-rigid, meaning that the column must resist horizontal actions together with vertical actions (Elliott, 2017, p. 8).

2.3. Prefabricated modules

Modular construction uses volumetric units composed of planar and linear concrete elements to form a full-sized module (Lawson et al., 2014, p. 41). Manufacturers would require specialized workers who are familiar with the process and disciplined in the new construction method. Further optimalization of this construction method requires some degree of flexibility in planning of modules, while retaining some standardisation of components for efficient manufacturing (Lawson et al., 2014, p. 63). For production, some degree of standardisation is encouraged for flexibility in module design, economic manufacturing and material procurement (Lawson et al., 2014, p. 225). The contractors must decide for themselves whether modular construction or precast element construction is the most economical and practical solution for their project. The modules should be "standardised wherever possible" to make the casting, striking, lifting and installation process as simple as possible (Lawson et al., 2014, p. 179).

3. Casting, installation, and transportation

3.1. Traditional casting

Project manager Helge Alvestad and production manager Håvard Aase at Veidekke Prefab revealed that traditional casting is beneficial for areas of the construction where it is difficult to reach with precast elements and modules (Veidekke Prefab, personal communication, 05.02.2024). Hinderances and tight spaces are difficult to reach unless you use cast-in-place concrete. However, this issue for precast elements can be taken out of consideration if the project leaders plan carefully how to place the precast element before reaching a difficult situation.

Another advantage of traditional cast in place concrete is the availability of on-demand casting. Rather than waiting for deliveries of elements to construct the building, traditional casting allows workers to manufacture their own concrete mix and place it straight away. Though the formwork and steel reinforcement should already be present before casting the concrete directly to the building.

3.1.1. On-site inventory

The use of cast-in-place concrete requires sufficient inventory space to store the materials and equipment used for casting elements. This includes materials for framework, steel reinforcement bars of varied sizes, concrete powder mix, water tank for mixing, mortar mixer or wheelbarrow, and tools. With this much storage, manoeuvring the construction site can be difficult, depending on the construction area given for the project. Therefore, traditional casting would not be well suited for tight spaces or city areas.

However, the ability to fix element mistakes on their own, would be favourable for use of traditional concrete casting. As opposed to the two other construction methods, the workers are not dependent on deliveries in order to continue the building process in case anything problematic occurs. If there is a mistake in an element, or if the build owner require any revisions, the contractors can fix the mistake with their on-demand concrete mix.

3.1.2. Freezing and thawing cycles

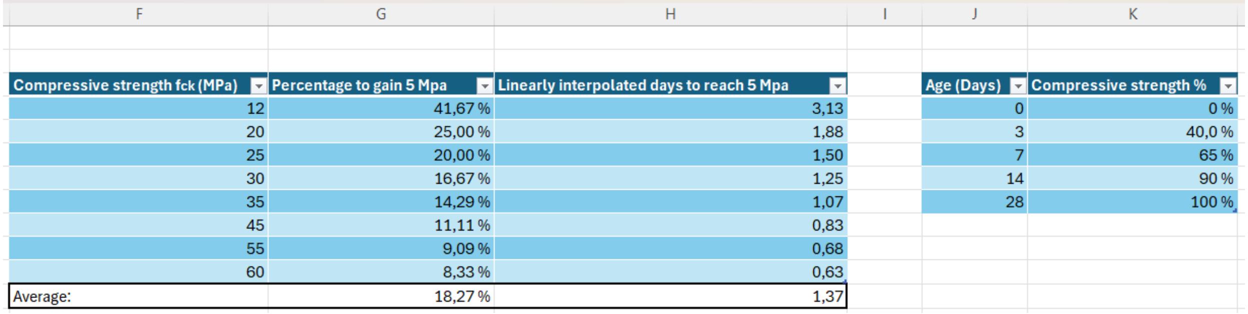
When water freezes, it expands roughly 10% of its volume. Since approximately 20% of the volume of concrete consists of water, freezing concrete can expand about 2% of its volume (Reiersen, 2020, p. 42). This in itself can result in damages, but it is especially important to consider the effect on the hydration process of cement. When the water freezes, it no longer reacts properly with the cement. Thus, the hydration process is paused until it thaws. Still, section 4.1.4 of Betongelementboken Bind G state that the concrete will usually be "porous and has poor resistance and reduced firmness" [Translated from Norwegian] (Reiersen, 2020, p. 42).

Furthermore, cycles of "freezing and thawing of fresh concrete can reduce the compressive strength by 20–40%" (Polat, 2016). To tackle the problem of freezing and thawing cycles, it is said that "air entrainment is necessary to ensure good freeze thaw resistance of CSF concrete" (Sabir, 1997). In the article by Sabir, CSF concrete refers to condensed silica fume concrete.

Due to the geological position, Norway generally has a very cold climate. This is a bad condition for concrete to harden in. The possible damages of freezing concrete result in increasing the importance of considering adding freeze-reducing admixtures to the concrete mix, in order to reduce the damages.

The use of antifreeze admixtures help reduce the freezing point of water, as well as improving the strength development of the concrete (Polat, 2016). "Antifreeze admixtures affect the pore structure of the cement paste, increase the surface area of the cement paste and increase the strength" (Polat, 2016). Here, Polat refer to "urea, calcium nitrate, calcium chloride, sodium nitrite, sodium chloride, potash and calcium chloride–nitrite–nitrate" as admixtures with this effect (Polat, 2016).

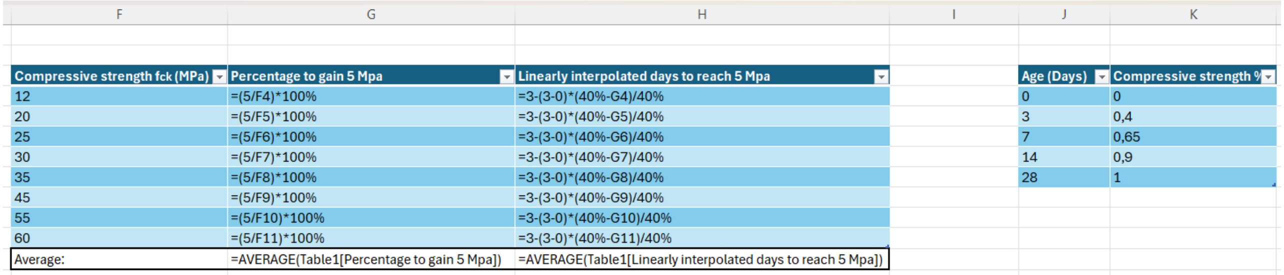
Betongelementboken Bind G state that concrete can be considered as frost resistant by ensuring that the temperature will not drop below 0 degrees in any part of the element before it has reached a strength of 5 MPa (Reiersen, 2020, p. 43). For a few concrete strength classes ranging from the weakest to some more strong ended classes, a linear interpolation has been computed to predict how many days it takes to reach this strength. The result in figure 13 below shows that for common concrete classes, it only takes between a few hours, to 3 days to reach the frost resistant 5 MPa strength. If this strength is not acquired before the first freezing cycle, the concrete will be permanently damaged. Consequences include reduced strength and durability (Reiersen, 2020, p. 43). The strength curve considered for the calculation can be found in Figure 1 of Civil Engineering. (n.d). The strength percentages are found from Mudavath. (2018). In the comments, Mudavath. (2018) confirm that interpolation between the strength percentages give an approximate value for the strength of concrete. Formulas for the interpolation can be found in figure 14.



Compressive strength fck (MPa)	Percentage to gain 5 Mpa	Linearly interpolated days to reach 5 Mpa
12	41,67 %	3,13
20	25,00 %	1,88
25	20,00 %	1,50
30	16,67 %	1,25
35	14,29 %	1,07
45	11,11 %	0,83
55	9,09 %	0,68
60	8,33 %	0,63
Average:	18,27 %	1,37

Age (Days)	Compressive strength %
0	0 %
3	40,0 %
7	65 %
14	90 %
28	100 %

Figure 13: Days to reach frost resistance of common concrete strength classes



Compressive strength fck (MPa)	Percentage to gain 5 Mpa	Linearly interpolated days to reach 5 Mpa
12	=(5/F4)*100%	=3-(3-0)*(40%-G4)/40%
20	=(5/F5)*100%	=3-(3-0)*(40%-G5)/40%
25	=(5/F6)*100%	=3-(3-0)*(40%-G6)/40%
30	=(5/F7)*100%	=3-(3-0)*(40%-G7)/40%
35	=(5/F8)*100%	=3-(3-0)*(40%-G8)/40%
45	=(5/F9)*100%	=3-(3-0)*(40%-G9)/40%
55	=(5/F10)*100%	=3-(3-0)*(40%-G10)/40%
60	=(5/F11)*100%	=3-(3-0)*(40%-G11)/40%
Average:	=AVERAGE(Table1[Percentage to gain 5 Mpa])	=AVERAGE(Table1[Linearly interpolated days to reach 5 Mpa])

Age (Days)	Compressive strength %
0	0
3	0,4
7	0,65
14	0,9
28	1

Figure 14: Formulas used in figure 13

Furthermore, the reaction process between cement and water is strongly dependant on the temperature. The speed of the reaction is halved when the temperature drops from 20 to 10 degrees, and doubles when the temperature increases from 20 to 35 degrees (Reiersen, 2020, p. 43). Heated concrete will react faster and have a reduced risk of freezing and thawing cycles. Unfortunately, it can be difficult to control the temperature of traditional in-situ cast concrete. Solutions include heated formwork or blankets, but even these are not optimal for the outside cold of the Norwegian climate. Therefore, it would be more desireful to cast the elements in controllable environments like factories. Which is why precast elements and modules may serve as a better construction method for buildings in Norway.

A conversation with Total Betong revealed that the damages on concrete when freezing is easily avoidable on-site. They have previously taken small measures to reduce the damage done by freezing effects. If they expect the concrete to become too cold, they have used an oven underneath to heat up the element. In the summer, they have experienced too hot concrete. In this case, they placed a vast amount of ice-cubes around the element to cool it down (Total Betong, personal communication, 10.04.2024). These are some practical examples of solutions which are possible for traditional casting.

3.2. Precast elements

3.2.1. Inventory

The use of precast elements allows for the construction site area to be reduced, because there is no need for a huge storage space to fit as much equipment as for in-situ cast. For efficiency, some space for storing the prefabricated elements before installation is necessary. The cost of transporting the elements depend on how many trips are needed. It is clear that fewer trips lead to less cost. In order to make fewer trips, it is favourable to organize and stack elements in order to transport multiple elements at a time. If the installers at the construction site are not able to install all the elements immediately, some site area should be allocated to storage of elements. This way, the workers can install the elements in their own pacing, while the transport of new elements are on their way. By this, some transportation efficiency is secured by sufficient inventory.

Another option is to use on-site mini-factories or mobile production units. This “drastically reduces the transportation costs and delivery times” (Ji et al., 2018). This allows for contractors to predetermine the most suitable prefabricated alternative. Either space is sacrificed or added to fit the mini factory on-site, or the cost of transporting the materials and elements must be included in the cost calculation. Contractors can choose to fabricate on-site or off-site depending on what is favourable for the project.

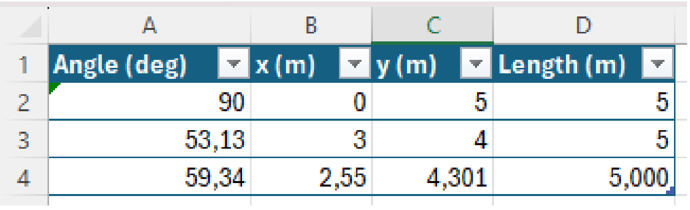
In order to place the elements in their place of installation, cranes must be used to lift the elements safely. However, the cost of cranes can be high, and it becomes a running cost if there are delays in the construction (Total Betong, personal communication, 10.04.2024). Delays can occur either from transportation issues, or from a wrongly produced element. This running cost should be considered when deciding which construction method to use in a project. Lastly, the cranes can take up a lot of space on the construction site (Total Betong, personal communication, 10.04.2024), which is to be avoided in metropolises.

3.2.2. Transportation

Veidekke Prefab had some pointers regarding transportation of precast elements. For smaller elements, stacking elements will make the transportation much smoother and efficient. However, bigger elements need to be able to rotate and be oriented so that there will not be any problems with the dimensional restriction laws in Norway. The laws state that no element can exceed a maximum width of 2.55 m (Bruksforskriften, 1990, §5-4) and a maximum height of 4.5 m (Bruksforskriften, 1990, § 4-3) for transportation vehicles.

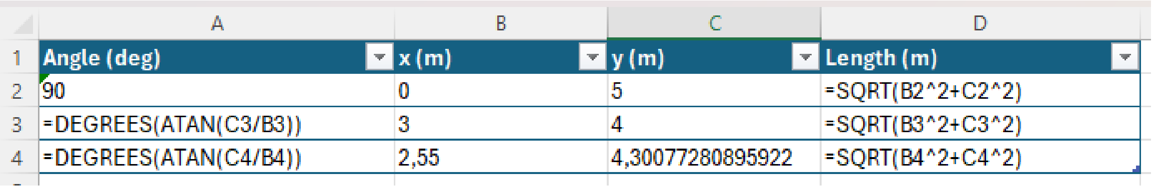
In the event of having elements taller and wider than this, there are solutions to still be able to transport these elements. Veidekke Prefab used special support rests in order to tilt the elements so that they would fit within the transportation vehicles. If the vehicle is to be imagined with x-axis along the width of the truck, y-axis along the height, and z-axis along the depth, the necessary tilt of the elements can be found from a Goal Seek analysis in MS Excel.

Imagine a 5 m long element that is oriented 90 degrees, i.e in an upright position. This clearly exceeds the 4,5 m restriction. By orienting the element to an approximate 53 degrees angle, the height would be reduced to 4 m, and the width becomes 3 m. Now the width restriction is exceeded. A planar view of the x-y plane of the imaginary element is shown in figure 17. Instead, a Goal Seek analysis in Excel for a given width of 2,55 m and length of 5 m yields a result of a 59,34-degree inclination. The height would have to be roughly 4,3 m, therefore both axis restrictions are satisfied. The calculation and formulas are shown in figure 15 and 16 respectively. Placing an element with an inclination of 59-degrees means that we will need to support the element so that gravitational forces do not make it slide off the vehicle.



	A	B	C	D
1	Angle (deg)	x (m)	y (m)	Length (m)
2	90	0	5	5
3	53,13	3	4	5
4	59,34	2,55	4,301	5,000

Figure 15: Goal Seek analysis has been used on cell D4 to be equal to 5 when cell C4 is changed. The result is shown above



	A	B	C	D
1	Angle (deg)	x (m)	y (m)	Length (m)
2	90	0	5	=SQRT(B2^2+C2^2)
3	=DEGREES(ATAN(C3/B3))	3	4	=SQRT(B3^2+C3^2)
4	=DEGREES(ATAN(C4/B4))	2,55	4,30077280895922	=SQRT(B4^2+C4^2)

Figure 16: Formulas used in Figure 1. Formulas for column D is basic Pythagoras

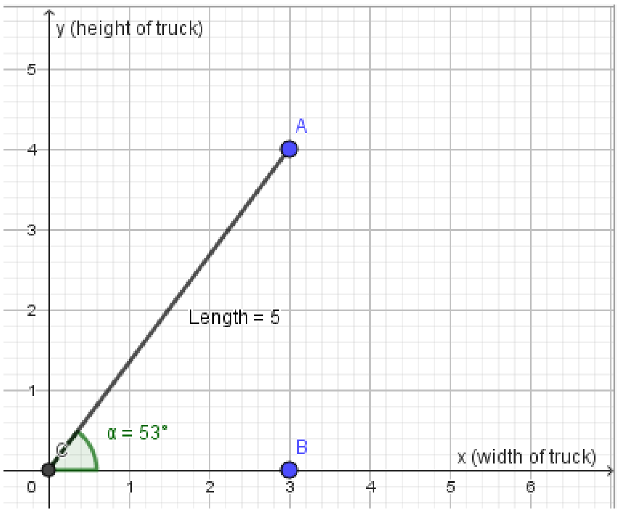


Figure 17: Height restriction is satisfied, but the width restriction is exceeded

Moreover the transportation, sufficient handles for cranes to lift the elements are required. Some additional steel reinforcement may be used in order to ensure adequate capacity of the element to withstand the axial forces acting on the element at the lifting point.

When an element is lifted airborne by a crane, there are two main forces to consider: the lifting tension of the cable, and the gravitational force. Both forces point out of the element, so that the element is subjected to tension. Reinforcement in the element must be designed for the construction purpose, as well as for the installation phase. Commonly, handles such as prestressed strands or cable loops are used as lifting points for elements (Building and Construction Authority, 2023, p. 9). Example lifting handles in a construction element can be found in figure 18 and 19. It is not recommended to use the reinforcement bars as lifting points, unless they are specifically designed to withstand the induced tension (Building and Construction Authority, 2023, p. 9).

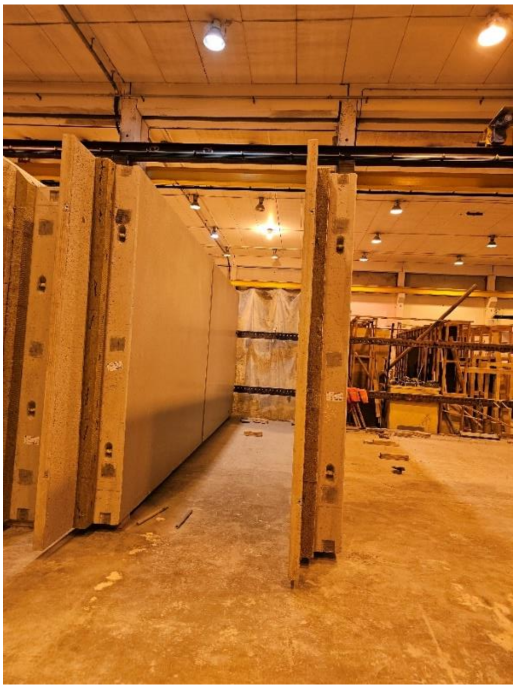


Figure 18: Lifting handles for concrete slab, constructed at Veidekke Prefab. Taken on 05.02.2024, at Klepp

Figure 19: Close up of lifting handles for concrete slab, stored at Veidekke Prefab. Taken on 05.02.2024, at Klepp

Though tilting the elements on the loading truck seems like a good solution, it raises another problem. A tilted element will take up more volume on the truck than stacking the elements more smoothly. Therefore, one should only need to use oversized elements if absolutely necessary. The most advantageous would be to standardize some elements which are more optimal for production, shipping and installation. The elements constructed at Veidekke Prefab are easily stackable, whilst also performing well structurally. They are also able to customize their element design to fit a buyer’s needs. Though Veidekke Prefab would like to use standardized elements for production optimalization, that is not always possible due to differences in the individual projects. The customer wants precise elements, which the manufacturer then needs to adapt to. Thus, standardisation of elements is theoretically most optimal, but not too common in real world practice.

For prefabricated elements in transient situations, Standard Norge (2023) section 4.3.3.6 recommends considering a transverse horizontal force equal to 1.5% of the self-weight of the element (no page number). This is to cover out of plane effects due to dynamic action, i.e. transporting the element, and due to vertical deviation. The latter is to ensure stability of the element when traveling along a sloped road. When trucks are driving up- and downhill, the resultant self-weight force is acting non-perpendicular to the moving direction. The force can be split into two components (or three if the road is inclined perpendicular to the driving direction) in the x and y direction. Thus, resulting in a horizontal force acting along the moving direction of the truck. See figure 20 and 21 below.

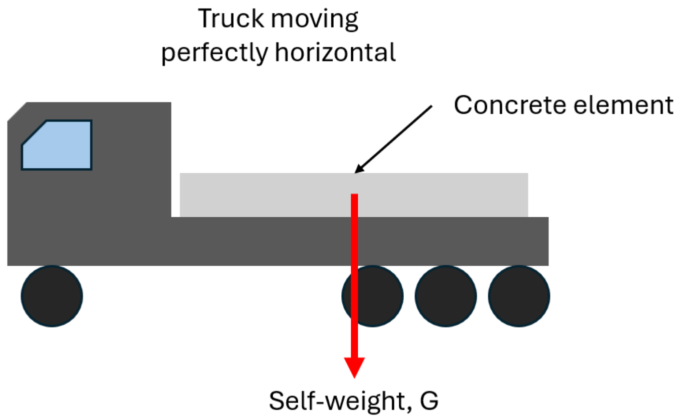


Figure 20: Gravitational force acting on element during transportation

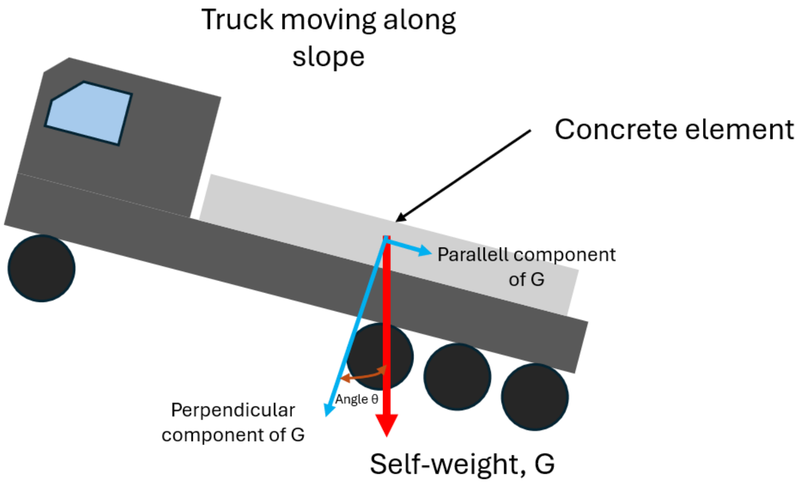


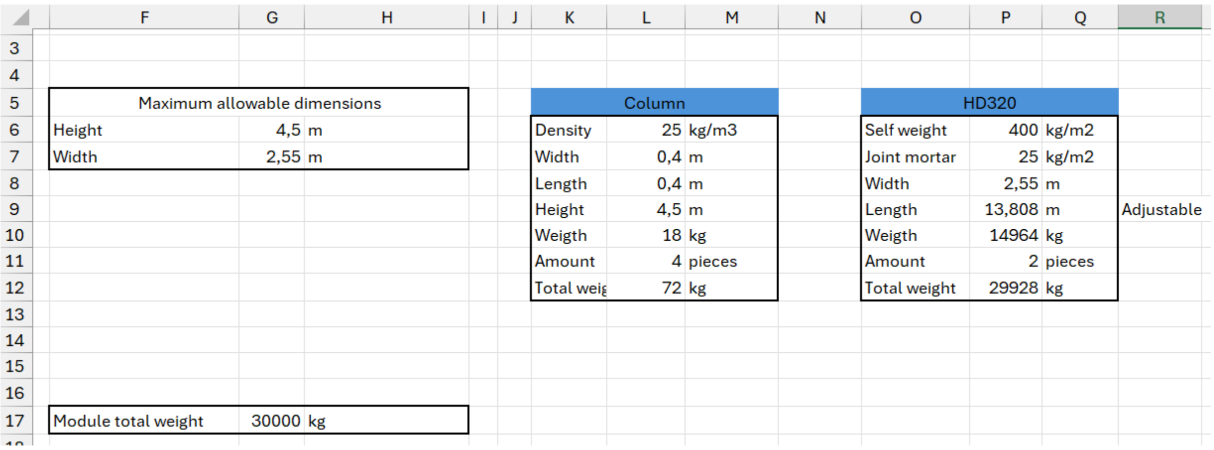
Figure 21: Gravitational force components acting on element during uphill transportation

3.3. Prefabricated modules

One difficulty that is present for precast modules, is transporting them to the construction site. A conversation with experts at Veidekke Prefab revealed that the maximum allowable carrying capacity of transportation trucks is 30 tonnes. Usually, it is preferred to be slightly below this load for safety reasons.

Furthermore, there are some dimension restrictions in Norway for transporting objects on the roads. For starters, the maximum allowable height to transport through tunnels is 4,5m and the maximum allowable width is 2,55 m. A Goal Seek analysis in Excel results in the maximum length of the modules can then be approximately 13,8 m.

The context for this calculation is that the density of concrete columns with rebar is 25 kg/m^3, a sample cross section of the column is set to be 400x400 mm^2. Max height is 4,5 m. There are 4 columns. An HD320 has been considered for the floor and roof of the modules. Weights for hollow decks are found from NOBI. (2016). For HD320, the weight is 400 + 25 kg/m^2. Maximum width is set to 2,55m. There are two of these. Thus, the goal seek analysis is set to seek what the length of the module can be, in order to reach the maximum allowed weight of 30 tonnes. Calculations and formulas can be found in figure 22 and 23 respectively.



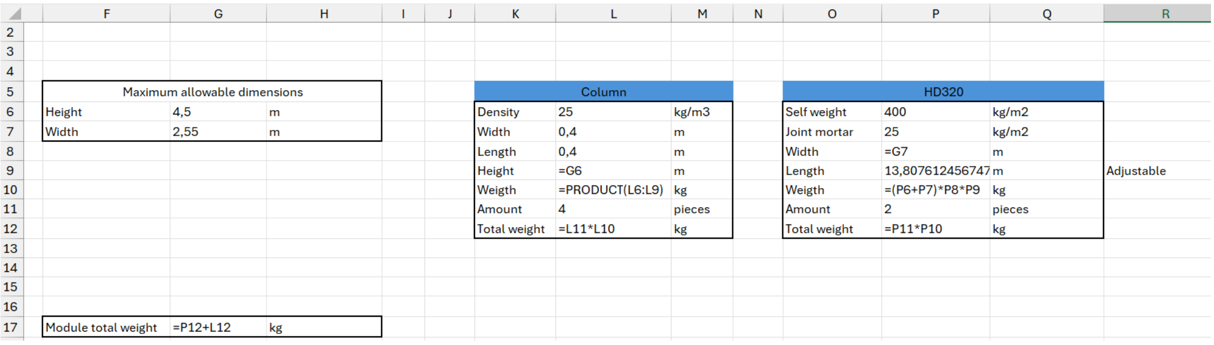
Maximum allowable dimensions		
Height	4,5	m
Width	2,55	m

Column		
Density	25	kg/m3
Width	0,4	m
Length	0,4	m
Height	4,5	m
Weigth	18	kg
Amount	4	pieces
Total weig	72	kg

HD320			
Self weight	400	kg/m2	
Joint mortar	25	kg/m2	
Width	2,55	m	
Length	13,808	m	Adjustable
Weigth	14964	kg	
Amount	2	pieces	
Total weight	29928	kg	

Module total weight	30000	kg

Figure 22: Maximum length of module with HD320, considering 30 tons maximum weight



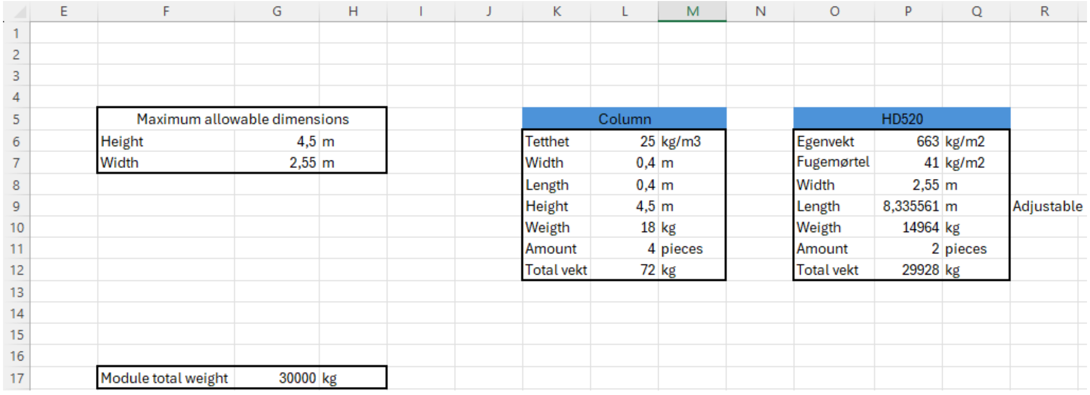
Maximum allowable dimensions		
Height	4,5	m
Width	2,55	m
Module total weight	=P12+L12	kg

Column		
Density	25	kg/m3
Width	0,4	m
Length	0,4	m
Height	=G6	m
Weigth	=PRODUCT(L6:L9)	kg
Amount	4	pieces
Total weight	=L11*L10	kg

HD320			
Self weight	400	kg/m2	
Joint mortar	25	kg/m2	
Width	=G7	m	
Length	13,807612456747	m	Adjustable
Weigth	=(P6+P7)*P8*P9	kg	
Amount	2	pieces	
Total weight	=P11*P10	kg	

Figure 23: Formulas used in figure 21

The result shows that modules of appropriate heights and widths can still satisfy the dimension requirements in Norway. This calculation was repeated once more by considering an HD520, which has a self-weight of 663 + 41 kg/m^2. The same Goal Seek analysis was done to reach 30 tonnes, and the result indicated a maximum length of 8,33 m. This is satisfactory for a general-purpose module. Calculations and formulas can be found in figure 24 and 25 respectively.

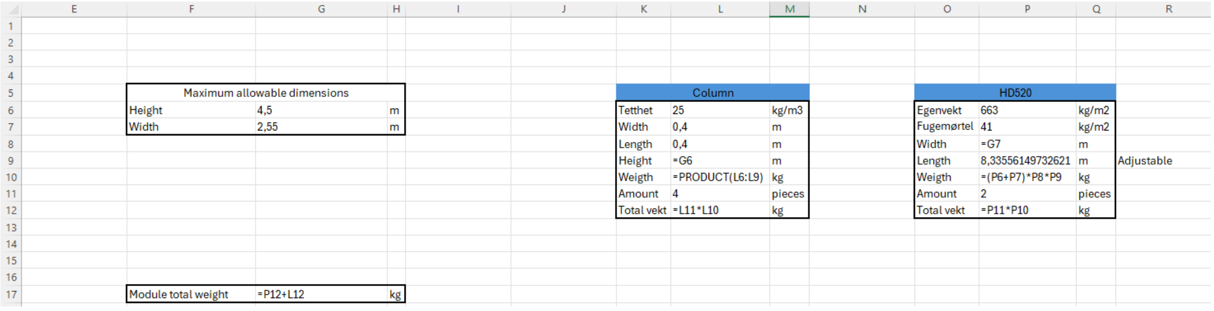


Maximum allowable dimensions		
Height	4,5	m
Width	2,55	m
Module total weight	30000	kg

Column		
Tetthet	25	kg/m3
Width	0,4	m
Length	0,4	m
Height	4,5	m
Weigth	18	kg
Amount	4	pieces
Total vekt	72	kg

HD520			
Egenvekt	663	kg/m2	
Fugemørtel	41	kg/m2	
Width	2,55	m	
Length	8,335561	m	Adjustable
Weigth	14964	kg	
Amount	2	pieces	
Total vekt	29928	kg	

Figure 24: Maximum length of module with HD520, considering 30 tons maximum weight



Maximum allowable dimensions		
Height	4,5	m
Width	2,55	m
Module total weight	=P12+L12	kg

Column		
Tetthet	25	kg/m3
Width	0,4	m
Length	0,4	m
Height	=G6	m
Weigth	=PRODUCT(L6:L9)	kg
Amount	4	pieces
Total vekt	=L11*L10	kg

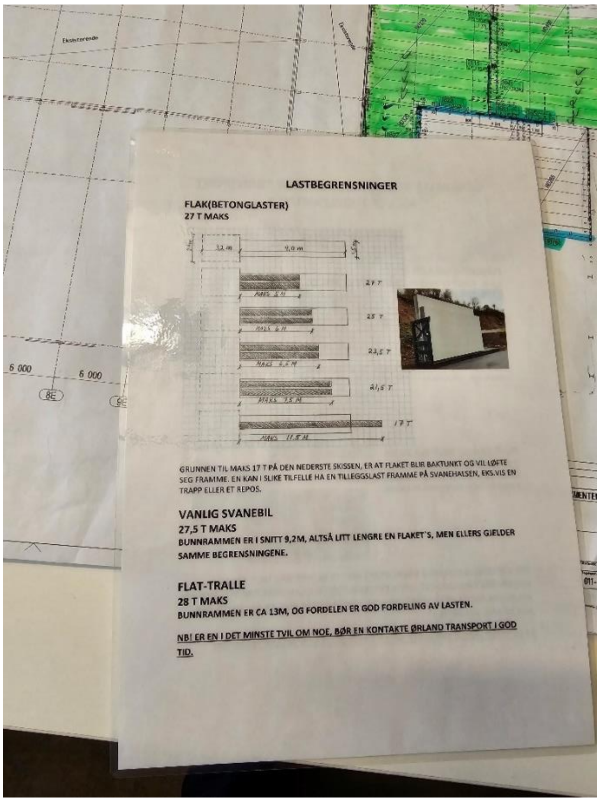
HD520			
Egenvekt	663	kg/m2	
Fugemørtel	41	kg/m2	
Width	=G7	m	
Length	8,33556149732621	m	Adjustable
Weigth	=(P6+P7)*P8*P9	kg	
Amount	2	pieces	
Total vekt	=P11*P10	kg	

Figure 25: Formulas used in figure 23

3.3.1. Veidekke Prefab Guidelines for maximum weight on trucks

A module with the calculated length of 8,33 m satisfies the 30-ton maximum in Norway. In the Norwegian laws it is stated that trucks of length 24 m with a total weight above 30 ton need to have stabilizers (Bruksforskriften, 1990, § 5-5). If not, the maximum height of the transport is 4 m. Meaning that our module would not fit properly in a truck with no stabilizers. Modules shorter than 4 m can still be transported.

Veidekke Prefab was generous enough to share a document specifying their common arrangements for loading trucks with prefabricated elements. See figure 26 below.



LASTBEGRENSNINGER

FLAK(BETONGLASTER)
27 T MAKS

GRUNNEN TIL MAKS 17 T PÅ DEN NEDERSTE SKISSEN, ER AT FLAKET BLIR BAKTUNKT OG VIL LØFTE SEG FRAMME. EN KAN I SLIKE TILFELLE HA EN TILLEGGSLAST FRAMME PÅ SVANEHALSEN, EKS.VIS EN TRAPP ELLER ET REPOS.

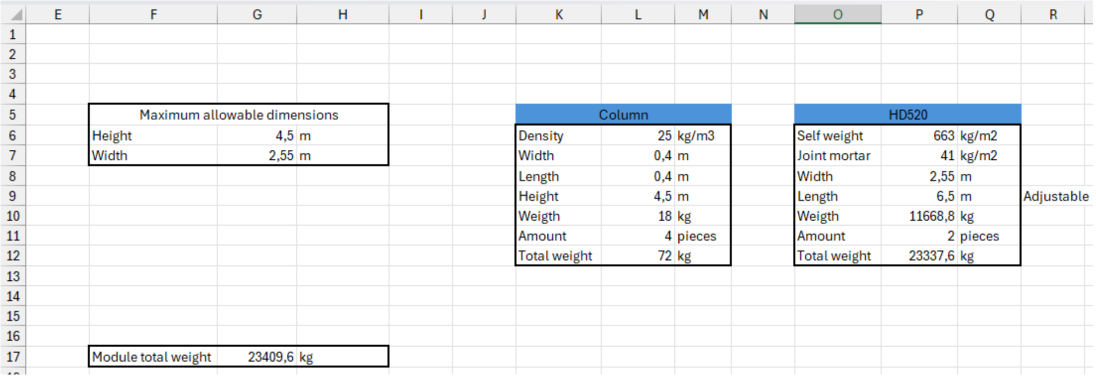
VANLIG SVANEBIL
27,5 T MAKS
BUNNRAMMEN ER I SNITT 9,2M, ALTSÅ LITT LENGRE EN FLAKET`S, MEN ELLERS GJELDER SAMME BEGRENSNINGENE.

FLAT-TRALLE
28 T MAKS
BUNNRAMMEN ER CA 13M, OG FORDELEN ER GOD FORDELING AV LASTEN.

NB! ER EN I DET MINSTE TVIL OM NOE, BØR EN KONTAKTE ØRLAND TRANSPORT I GOD TID.

Figure 26: Load restrictions from Veidekke Prefab. Text in Norwegian. Taken on 05.02.2024, at Klepp

By assuming no modules need a length greater than 6.5 m, a quick calculation can be computed to see if it matches their weight of 23.5 tonnes in figure 25 above. The calculation and formulas can be found in figure 27 and 28 respectively.



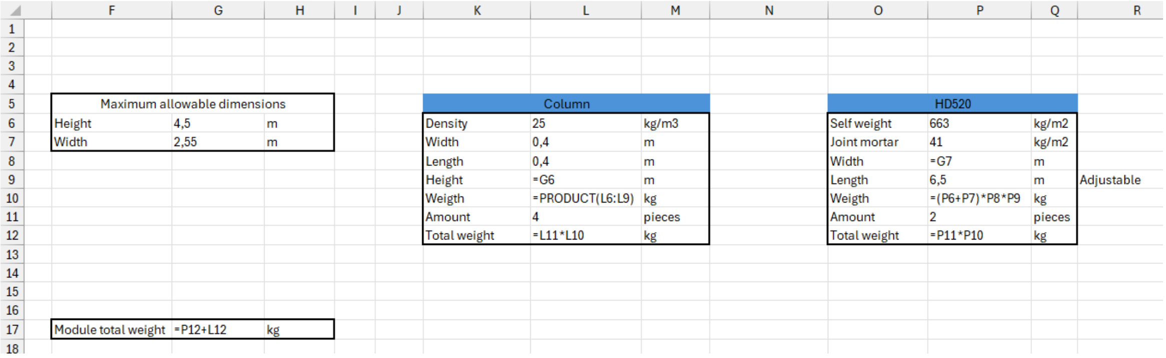
Maximum allowable dimensions		
Height	4,5	m
Width	2,55	m

Column		
Density	25	kg/m3
Width	0,4	m
Length	0,4	m
Height	4,5	m
Weigth	18	kg
Amount	4	pieces
Total weight	72	kg

HD520			
Self weight	663	kg/m2	
Joint mortar	41	kg/m2	
Width	2,55	m	
Length	6,5	m	Adjustable
Weigth	11668,8	kg	
Amount	2	pieces	
Total weight	23337,6	kg	

Module total weight	23409,6	kg

Figure 27: Weight of 6.5 m module



Maximum allowable dimensions		
Height	4,5	m
Width	2,55	m

Column		
Density	25	kg/m3
Width	0,4	m
Length	0,4	m
Height	=G6	m
Weigth	=PRODUCT(L6:L9)	kg
Amount	4	pieces
Total weight	=L11*L10	kg

HD520			
Self weight	663	kg/m2	
Joint mortar	41	kg/m2	
Width	=G7	m	
Length	6,5	m	Adjustable
Weigth	=(P6+P7)*P8*P9	kg	
Amount	2	pieces	
Total weight	=P11*P10	kg	

Module total weight	=P12+L12	kg

Figure 28: Formulas used in figure 26

The weight is acceptable. Therefore, modules of dimensions 2.55x6.5x4.5 m are transportable with standard trucks, and still satisfy all weight and dimensional requirements in Norway.

Ro et al. (2021) regards prefabricated modular construction to be faster, more efficient and safer for workers. A downside is the limitations stemming from the inherent transportation problem due to the sizes of modules (Ro et al., 2021). Specifically, modular construction “impose limits on construction, e.g., related to module size” (Ro et al., 2021). Therefore, a challenging aspect of modular construction, is limitation of sizing the modules for structural performance, whilst allowing the modules to be transported without significant damage.

3.3.2. Transportation

For dimensional planning of modules, chapter 5 of Lawson et al. (2014) go into greater detail of recommendations and typical solutions. It is noted that the "The module length is generally not as important for transportation as the width, except where site access is difficult" (Lawson et al., 2014, p. 70). More detail about the widths for this thesis' case study is given later in "9. Principles of modular construction". Generally, the widths of the modules will be influenced by transportation requirements (Lawson et al., 2014, p. 70).

During transportation, the modules must be protected from weather effects such as water ingress while allowing vapour to pass through (Lawson et al., 2014, p. 235). A protective shroud should cover the module during storage, transportation and installation (Lawson et al., 2014, p. 235). Lawson et al. (2014) show an illustration of an example shroud on page 236.

3.3.3. Transient error

When transporting the module, it is of utmost importance that the module is properly secured and carried to the place of installation. If the module is subject to damages, an entire module may need significant repair or replacement. This could further lead to hold up in the installation sequence (Realprojectives, 2019). Which in turn would impose further costs on the project due to delays and additional labour hours.

3.3.4. Factory fabrication

An important factor in mix design of concrete for modular design is the strength of the concrete during de-moulding (Lawson et al., 2014, p. 179). The cast module is usually removed from the mould after 12 to 24 h after casting. Therefore, manufacturers need to consider this to maximise efficiency of the factory fabrication of modules. Various methods, such as cement accelerators, rapid hardening cement, steam curing and electrical heating, can be used to speed up the hardening process so the mould can be re-cast with a new module (Lawson et al., 2014, p. 179). Table 13.1 page 180 in Lawson et al. (2014) show the typical strength of concrete when de-moulding and after 28 days. It is common to use C35/45 concrete for precast concrete modules (Lawson et al., 2014, p. 179). The authors have considered the standards given in Eurocode 2 of the British standards BS EN 1992-1-1 and BS EN 1992-1-2 (Lawson et al., 2014, p. 180), which is the British equivalent of the Norwegian standards given in NS EN 1992-1-1 and NS EN 1992-1-2.

3.3.5. Service interfaces

A lot of services inside the modules can be installed and tested off-site before finally connecting them together with other modules on-site (Lawson et al., 2014, p. 203). Service installation in traditional concrete casting is generally time consuming (Lawson et al., 2014, p. 203). These services include electrical work and piping which is generally distributed horizontally and vertically within the module, but it also includes lifts and stairs which can also be fabricated in modular form (Lawson et al., 2014, p. 203). Under-floor heating can also be added to the module manufacturing process if required (Lawson et al., 2014, p. 204).

Some services can be manufactured within the concrete walls by using conduits (Lawson et al., 2014, p. 204). This may be beneficial for some electrical work or piping, but there is also a possible downside of being less de-mountable. In other words, it is more difficult to de-construct and place new services into the walls, because the entire module must be lifted to reach the conduits. An advantage of placing the services into conduits is that it is more "visually acceptable and tamper resistant … than surface-mounted electrical distribution" (Lawson et al., 2014, p. 204). For water services, it is common to place these as vertical rises in the bathroom modules. Lawson et al. (2014) also recommend placing the bathroom pods adjacent to each other, which gives another added benefit of allowing the vertical risers to installed in pairs of modules rather than separately in each one (Lawson et al., 2014, p. 204).

Examples of frame modules with services and the service layout can be found on page 208 and 207 respectively in Lawson et al. (2014). An example of conduit placement in a precast concrete element mould from Veidekke Prefab can be found in figure 29.

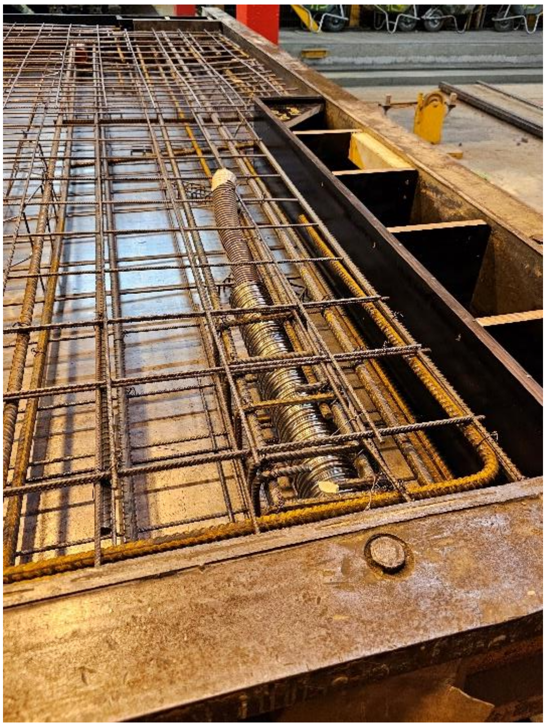


Figure 29: Mould used by Veidekke Prefab for use of conduit in precast concrete elements. Taken 05.02.2024

3.4. Discussion related to casting, installation and transportation

The most notable points from Chapter 3 are summarised in table 1 below. The advantages and disadvantages are noted in a keyword formatted table below to get a better overview of which factors and qualities to consider for each construction method.

Table 1: Summary of Chapter 3

Factor or quality	Traditional Casting	Precast elements	Prefabricated modules
Reachability for tight spaces	Good	No, but can be ignored if project is planned carefully	No, but can be ignored if project is planned carefully
Element construction	On-demand casting, can fix element mistakes on-site	Dependant on deliveries	Dependant on deliveries
Inventory	On-site inventory must fit all equipment and materials. No need to include big space for storage of elements.	Some inventory for storage of elements. Can use on-site mini factories if desired. Site must be fitted to include installation cranes.	No inventory for storage, modules are connected directly from transport Site must be fitted to include installation cranes.
Weather effect	Weather effects is unfavourable Freezing and Thawing cycles need more attention in Norway. Total Betong mention	Controlled environment in off-site factory lead to ignorance of weather effects	Controlled environment in off-site factory lead to ignorance of weather effects

	small measures reduce this risk.		
Transportation	Transportation of equipment.	Stack elements for efficient transport. Must keep size within transport limitation. Bigger elements take more volume of trucks due to inclination	Size and weight of modules make it unfavourable to stack modules. One module at a time should be transported. Difficulty to transport modules of sufficient dimension and still achieving required structural performance
Lifting and installing	Install directly, no lifting points required	Additional steel for lifting points must be considered Must be designed for induced tension during lifting.	Additional steel for lifting points must be considered Must be designed for induced tension during lifting.
Damages	Only one element would need re-casting	Only one element would need replacement	Damage of module would create big holdup in the entire project

4. Customizability

For each construction to have some uniqueness to it, there is often a desire for some customizability to be applied to the construction. Some construction methods are easier to customize than others, but they all share some level of custom touch to the element design.

4.1. Traditional casting

Traditional casting often uses slightly less finishing design than the other construction methods. Usually, the appearance of the construction mainly stems from the outer facades. There is also a point to be made about rolling a design pattern over the newly cast concrete to create a more unique look for the elements. The shape of the elements is however highly adaptable to change, because the framework is not used as reusable moulds. Each cast element requires a specific mould which is laid out before casting. The moulds are cut and fitted so the elements will fit the exact desired shape in the place of installation.

4.2. Precast elements

The precast elements which Veidekke Prefab uses proved to be highly customizable and can be changed to match a significant number of element designs. Each mould can be varied through each iteration of the manufacturing process to match a new element. Finishing panels can also be added to the elements for a selected finishing look in the hardened concrete. Examples of these finishes are shown in figures 30-33.

Figure 30: Outside finished for prefabricated elements at Veidekke Prefab. Taken on 05.02.2024, at Klepp

Figure 31: Pattern designs for prefabricated elements at Veidekke Prefab. Taken on 05.02.2024, at Klepp

Figure 32: Pattern design for prefabricated elements at Veidekke Prefab. Taken on 05.02.2024, at Klepp

Figure 33: Pattern design for prefabricated elements at Veidekke Prefab. Taken on 05.02.2024, at Klepp

By using wooden panels with magnetic fasteners, it is possible to alter the shape, slope and lengths of each surface of the element. As a result, construction by prefabricated elements is a highly customizable construction method. The panels used can be seen figures 34 and 35 below.

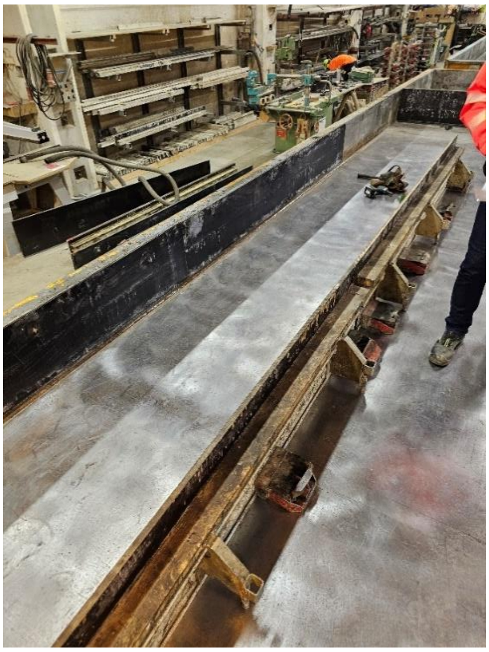


Figure 34: Wooden panels are stacked and fastened magnetically to the mould for desired length. Taken on 05.02.2024, at Klepp

Figure 35: Sloped wooden panels, cut for desired surface design. Taken on 05.02.2024, at Klepp

4.3. Prefabricated modules

Modules should be designed to be easily repetitive and produce. Less variety is preferred, because bigger changes lead to more time and cost needed for customization of each module. Which "reduces, and potentially defeats, the time and cost advantages" (Realprojectives, 2019). Though modules can be varied somewhat, similar to variations observed in precast elements, modules are of bigger size and therefore need more work to adapt to customization. It is preferred to keep modules of similar size, material, and geometry for the advantages to be apparent. Frame systems of modules could be an effective solution due to the repetitiveness, while façade finishing can be added for the custom appearance. For manufacturers, it is desired to keep some standardisation of components for efficiency (Lawson et al., 2014, p. 63).

4.4. Discussion of customizability

To get a better understanding of factors and qualities to consider for customizability of the construction elements, see table 2 below. The table shows a short summary of Chapter 4. Each construction method differs from how they are able to alter the dimensions and finished of the element. The table below gives a clearer picture of the differences between each method.

Table 2: Summary of Chapter 4

Factor or quality	Traditional Casting	Precast elements	Prefabricated modules
Custom pattern	By rolling pattern over newly cast concrete	By pattern panels which is applied to mould	Custom modules reduce the advantages of faster construction by reducing the repetitiveness of modular construction. Is possible, but not recommended practice.
Dimensions	Each mould created for each specific element. Desired dimensions are easily achieved.	Highly adaptable factory moulds. Desired dimensions can be achieved, but standardisation is recommended.	Best to use the same dimensions for the moulds to increase repetitiveness
Outside finish	Facades	Facades	Facades

5. Cost and time efficiency

For any construction project, build owners are interested in the most optimal construction with regards to project cost and time efficiency in accordance with the progress plan. These documents are important to have ready when delivering the project proposal.

5.1. Traditional casting

In the time of writing this thesis, there is an ongoing road construction project of which participation is currently involved. The project consists partly of a new round-about which is quite large in size. Some associates at Total Betong are responsible for casting the concrete deck of the round-about. On 25.03.2024, they started and finished casting the entire deck. Though this does not align precisely with the focus of this thesis, it is deemed noteworthy to highlight the vast amount of concrete they were able to place. With approximately 60 concrete workers, they casted about 1750 m^3 in one full day. The construction also included many hours of work before placing the concrete. Mainly casting and securing the underground walkway and placing of reinforcement. Presentation of the deck can be found on Total Betong's website. Furthermore, the associates confirm that this is their biggest casting project in the history of the company. A picture from the project can be seen in figure 36.

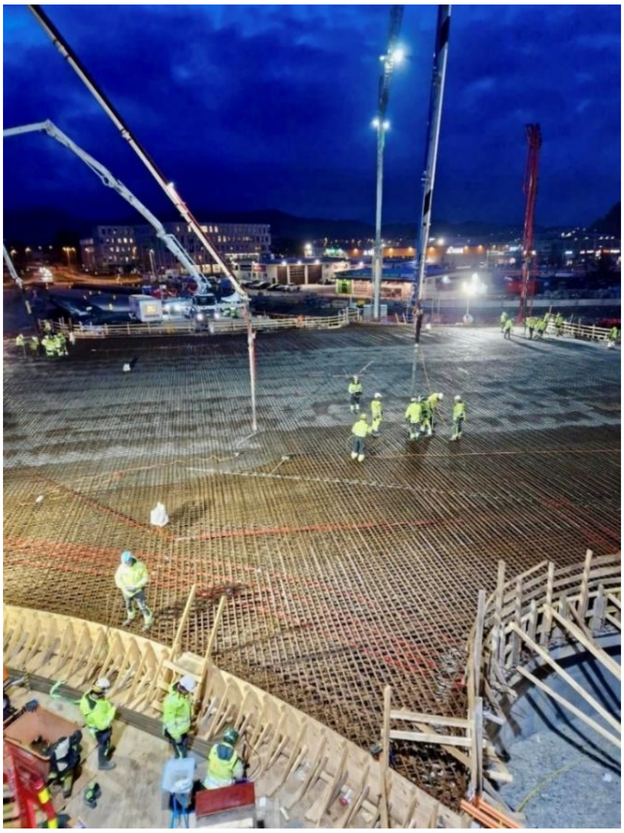


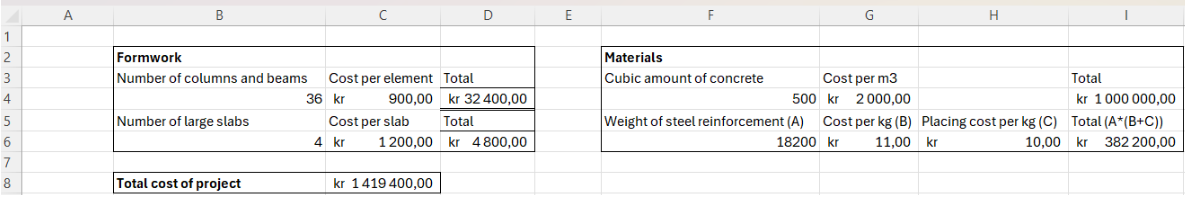
Figure 36: 1750 m^3 concrete cast by Total Betong. Retrieved from Total Betong. (2024)

To get a better understanding of the costs connected to casting this element, Total Betong said that "Volume per Person" would not be realistic. Instead, dividing the volume by the amount of labour hours, which was 13,5, would be better. Still, there are a lot of factors which is not included. For the case study of this thesis, the costs in the table below would be a better estimate. Note that these costs are not exact and only used as an estimate for the thesis.

Table 3: Simplified cost of construction cast-in-place elements. Numbers from Total Betong

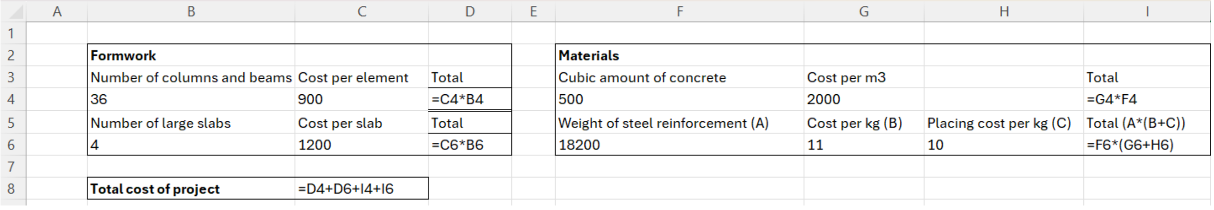
Work	Cost per unit
Concrete work	2000 NOK per m^3
Steel reinforcement	11 NOK per kg
Placing of reinforcement	10 NOK per kg
Formwork cost	800-1200 NOK per element

These costs give a simplified understanding of the work needed to create an element by traditional methods. Realistically, other factors must be considered, such as administrative costs, transportation costs, labour salary and so on. The totals of the simplified costs connected to the case study building is found in figure 37. Formulas can be found in figure 38



	A	B	C	D	E	F	G	H	I
1									
2		**Formwork**				**Materials**			
3		Number of columns and beams	Cost per element	Total		Cubic amount of concrete	Cost per m3		Total
4		36	kr 900,00	kr 32 400,00		500	kr 2 000,00		kr 1 000 000,00
5		Number of large slabs	Cost per slab	Total		Weight of steel reinforcement (A)	Cost per kg (B)	Placing cost per kg (C)	Total (A*(B+C))
6		4	kr 1 200,00	kr 4 800,00		18200	kr 11,00	kr 10,00	kr 382 200,00
7									
8		**Total cost of project**	kr 1 419 400,00						

Figure 37: Total cost of project using numbers from Total Betong. Calculation of steel and concrete amounts can be found in Appendix A



	A	B	C	D	E	F	G	H	I
1									
2		**Formwork**				**Materials**			
3		Number of columns and beams	Cost per element	Total		Cubic amount of concrete	Cost per m3		Total
4		36	900	=C4*B4		500	2000		=G4*F4
5		Number of large slabs	Cost per slab	Total		Weight of steel reinforcement (A)	Cost per kg (B)	Placing cost per kg (C)	Total (A*(B+C))
6		4	1200	=C6*B6		18200	11	10	=F6*(G6+H6)
7									
8		**Total cost of project**	=D4+D6+I4+I6						

Figure 38: Formulas used in calculations in Figure 37

The total cost of the project using traditional concrete casting is, according to the estimates from Total Betong, is about 1 419 400 NOK.

5.2. Precast elements

Veidekke Prefab also showcased their efficient factory for making precast elements. During a tour with them, they confirmed that the main factors for choosing precast elements, was the time saved, cost reduction and the efficiency which they achieve (Veidekke Prefab, personal communication, 05.02.2024).

For precast elements to be an efficient solution, the workers and the factory need to be specialized and well-coordinated. The tour at Veidekke Prefab proved that this can be done to a large extent. They also said that their factory could produce between 350-400 m^3 of concrete elements per day(Veidekke Prefab, personal communication, 05.02.2024).

5.2.1. ENECA Comparison

Specialists at ENECA have made some results after conducting a comparative analysis of a reinforced concrete frame using cast-in-place and precast concrete elements (ENECA, 2023). The study features a multi-storey building with the same foundation for both cases. The result shows that the use of precast elements could vastly decrease the labour hours required and the construction time needed (ENECA, 2023). The cost of traditional cast concrete per m^2 is only around 5% higher than using precast concrete (ENECA, 2023). By their study, it would take almost 5 times more labour hours and 210 more days to finish the modelled building using cast-in-place methods. Results from the comparison can be found in figure 39 and 40 below.

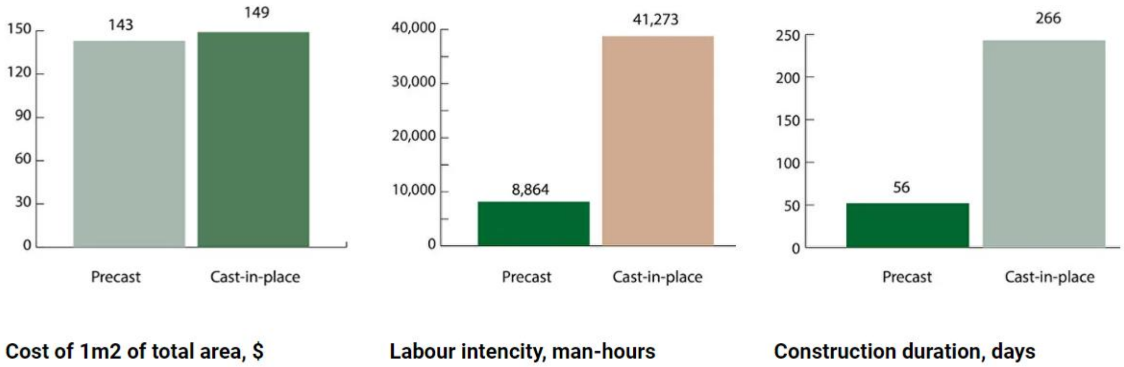


Figure 39: Comparison of m^2 concrete cost, labour hours and construction duration by ENECA. Acquired on 08.03.2024 from ENECA, (2023)

Furthermore, the study distinguishes the cost components in each case. In both cases, the material cost is by far the most dominant (ENECA, 2023). Following the material costs are the salary for workers and machine costs as the second and third most costly components of the buildings total value (ENECA, 2023).

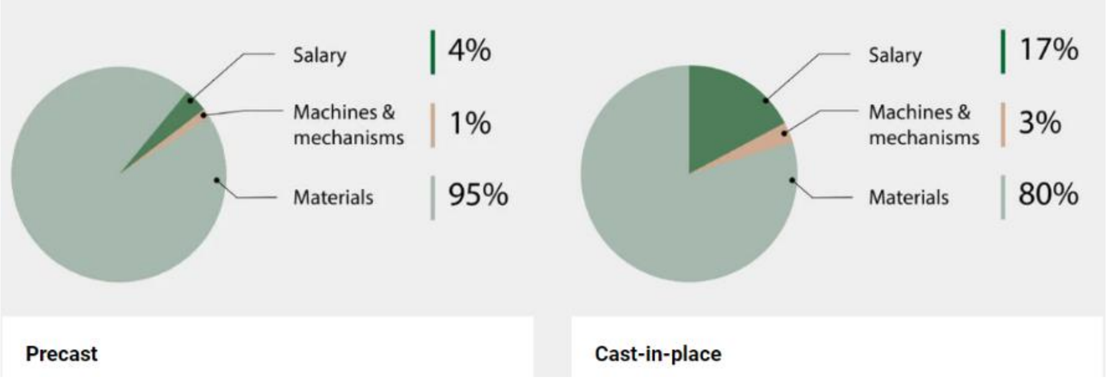


Figure 40: Cost component comparison by ENECA. Acquired on 08.03.2024 from ENECA, (2023)

5.2.2. Transportation cost

Some studies have discussed the potential barriers for use of off-site construction. An instance of this is observed by Rahman (2014) who argued that "the logistics problem was the major technical barrier" (Ji et al., 2018). Furthermore, Jaillon and Poon (2008) found that there was a "higher initial costs along with the transportation costs of prefabricated components to be the two major economic constraints" (Ji et al., 2018). Meaning that use of precast elements will include a higher cost of transportation, compared to the use of traditional cast-in-place methods. This further implies that distance between the construction site and the factory should be reduced to lower the unavoidable transportation cost.

5.3. ISY Calculus – Cast-in-place vs Precast

Through ISY Calculus, a software for projecting the cost of a project, it is possible to compare prices of different standard elements. The in-built element register allows for inspection of element attributes, such as dimensions, material and standard price for these elements. A few selected elements are compared in the table below. All numbers are from element register 202302.

Table 4: Cost of selected linear elements from ISY Calculus element register 202302

Element	**Unit cost of cast-in-place element per m (in NOK)**	**Unit cost of precast element per m (in NOK)**
B45 concrete beam, b x h = 200 x 500 mm, 180 kg steel per m^3 concrete	2758.71	3104.20
B45 concrete beam, b x h = 200 x 700 mm, 180 kg steel reinforcement per m^3 concrete	3732.64	3104.20
B45 concrete column, 400x400 mm, 180 kg steel reinforcement per m^3 concrete	4000.42	4573.52
B45 concrete column, 500x500 mm, 180 kg steel per m^3 concrete	5431.81	4573.52

Table 5: Pricing of selected planar elements from ISY Calculus element register 202302

Element	Unit cost of cast-in-place element per m^2 (in NOK)	Unit cost of Hollow-core equivalent precast element per m^2 (in NOK)
B30 concrete decks, thickness 200 mm, 120kg steel reinforcement per m^3 concrete	2137.58	1348.82
B30 concrete decks, thickness 220 mm, 120kg steel reinforcement per m^3 concrete	2256.83	1427.29

As the numbers suggest, the cost of precast elements is generally lower when the element size increases. For small elements, cast-in-place concrete is the more economical alternative. Still, one must consider that the element register may not be fully accurate. From the register, it is clear that there is no direct comparative alternative for the linear elements, because they are not named or distinguished in the same way as for traditional concrete elements. The precast elements only show one general price for beams and columns, which may not be the identical cross-section of the cast-in-place element. The tables still give an idea of which price ranges can be expected for cast-in-place and precast elements.

5.4. Prefabricated modules

There are several advantages to construction by precast modules. Similar to precast elements, modular construction requires less construction time than traditional casting. This is mostly due to the efficiency of on-site preparation happening alongside factory fabrication (Realprojectives, 2019). While the modules are hardening in a factory, workers can prepare the construction site by laying foundation, clearing space or assemble other modules. When the workers are ready, a new module can be transported and installed as part of the construction immediately. Furthermore, Lawson et al. (2014) note that "The primary economic benefit is the speed of the construction process" (p. 237).

Precast modular construction also have the added benefit of reduced material waste in factory fabrication (Great Magtech Electric Co, 2023) (Lawson et al., 2014, p. 237). There are a lot of situations that can happen on-site which can spill or invalidate some of the material used. However, fabrication in a controlled environment results in a better control of materials and more efficient factory processing, thus minimizing wastage (Lawson et al., 2014, p. 41). Lawson et al. (2014) further specify that the materials needed in off-site construction can be up to 20% less than for traditional construction (p. 237). This is due to more efficient bulk ordering of materials and less site damage (Lawson et al., 2014, p. 237).

The decreased construction time together with less waste product, also adds to the reduced cost of modular construction. Fewer labour workers are required, less time is needed, but the workers must be specialized in the modular construction method. The exact cost of the specialization opposed to the savings of total working hours are not explicitly analysed in this paper.

Some researchers note that modular construction may save cost by 20% (Thai et al., 2020). Labour cost itself can be saved up to 25% (Realprojectives, 2019). However, the transportation cost, which is a major area for modular construction, can have a higher initial cost than traditional methods (Ji et al., 2018). This is due to the higher number of deliveries needed to transport the materials to the facility, then later transporting the modules to the installation place. For this reason, relative distance to the production facility is a major variable cost when considering the cost effectiveness of modular construction. Lawson et al. (2014) also note that modular construction benefit from a greatly reduced transportation and equipment cost, as opposed to traditional construction methods (Lawson et al., 2014, 237).

A variety of case studies and design recommendations can be found in "Design in Modular Construction" by Lawson, R. Ogden, R and Goodier, C. In their study, it is found that the installation rate of modular construction can be observed to be between 6 to 10 modules installed per day, with the lifting distance and crane capacity being the main factors (Lawson et al., 2014, p. 41).

Another cost saving factor for modular construction, is the lack of formwork and scaffolding being required for the build (Lawson et al., 2014, p. 41). This results in saving cost by reducing the necessary on-site resources, together with reducing on-site construction programmes (Lawson et al., 2014, p. 41).

The analysis by Lawson et al. (2014) gives a numerical representation of the efficiency of modular factory fabrication. Lawson refers back to Mullen (2011) and his book "Factory design for Modular Home Building" for the numbers used (Lawson et al., 2014, p. 237). The conclusion of the study is that timber-module factories which produced 1000 modules per year, generally required about 250 man-hours per module (Lawson et al., 2014, p. 238). The modules in question have a floor area of 50 to 60 m^2, which is generally larger than most European systems (Lawson et al., 2014, p. 238). It is not possible to directly compare the labour hours between timber and concrete modules, but this can still be used as an estimate for how many hours a contractor can expect to require for a project.

5.5. Discussion of cost and time efficiency

Table 6 below show a shortened comparison of the research connected to cost and time efficiency of each construction method. To get a better idea of which factors to consider when discussing how optimal each method is, the comparison below gives a clearer picture.

Table 6: Summary of Chapter 5

Factor or quality	Traditional Casting	Precast elements	Prefabricated modules
Production efficiency	1750 m^3 in 13.5h was the largest project for Total Betong. Can produce more if necessary, but more labour workers are required.	300-400 m^3 per day. Specialized and well-coordinated workers is necessary to achieve this.	6-10 modules per day. 4-5 man-hours per m^2 floor area.
ENECA Comparison	More labour hours. Slightly higher cost per m^2. More construction days.	Less labour hours. Slightly lower cost per m^2. Less construction days.	N/A
Transportation cost	N/A	Transportation of material + Shipping of elements. Highly dependent on relative distance to construction site. Not as high if on-	Transportation of material + Shipping of modules. Highly dependent on relative distance to construction site.

		site mini factories are used, but then weather effects must be considered for quality. Multiple elements can be stacked to reduce the number of trips needed.	Fewer modules can be stacked, possibly leading to more trips required. Difficult to compare with elements because many elements will form one module anyways.
On-site and factory efficiency	Workers must wait to cast elements until foundation is created.	Foundation can be made while elements are being constructed elsewhere.	Foundation can be made while modules are being constructed elsewhere.
Material waste	Spillage and some unforeseen waste must be accounted for.	Controlled environment, exact amount of concrete needed. Less waste.	Controlled environment, exact amount of concrete needed. Less waste.
ISY Calculus element cost	Lower for smaller elements. Hollow-cores are generally more expensive.	Lower for bigger elements. Hollow-cores are generally cheaper.	N/A
On-site resources	Necessary.	Necessary, but reduced.	Basic equipment, but vastly reduced.

6. Inspection and safety control

6.1. Traditional casting

After the mix has hardened into structural concrete, the element is ready for quality control. For on-site casting, this control has to be performed quickly after hardening, so that the work can continue to expand on the element. For instance, a new column cannot be placed onto a slab before the slab has been controlled for safety. The inspection happens on-site, and considers any defects in the element.

6.2. Precast elements

Inspection and safety control of precast elements share mostly all attributes with controlling prefabricated modules. To name a few similarities, factory fabricated elements and modules share a disconnection to weather effects. I.e. wind, temperature and relative humidity do not affect the quality of the casted element because of the controllable conditions of a factory. Furthermore, the elements can be inspected and controlled for cracks before transporting and installing the elements. Meaning that the elements are cleared for installation, thus leading to a safer construction site when the elements arrive. The cold climate in Norway make prefabrication an advantageous construction method as opposed to traditional cast-in-place methods.

6.3. Prefabricated modules

Factory fabrication of modules is more convenient and a safer manufacturing alternative which also leads to better quality control (Thai et al., 2020). Traditional casting is often done in tight and messy spaces around the construction site, which can be difficult to manage. This problem is not observed in module construction, because it is easier to inspect and control the module before transporting it to site (Thai et al., 2020). The workspace can therefore be considered as much safer for workers, due to the separation of on-site work and factory fabrication. The safety of the on-site construction process is enhanced because labour-intensive formwork installation and striking, material handling etc. is eliminated (Lawson et al., 2014, p. 41).

Manufacturers of prefabricated modules do not need to consider environmental factors when casting in a controlled facility. The relative humidity upon casting plays a significant role in the hardening process for concrete. A study by Almusallam (2001) concluded that environmental factors such as increased exposure temperature, increased wind velocity and decreased relative humidity lead to faster water evaporation, faster shrinkage strain and bigger cracks (Great Magtech Electric Co, 2023). The factors affecting the errors can be vastly reduced by using a controlled environment to precast modules rather than on-side casting. Ventilation can be manipulated for optimal hardening of concrete, and the roof ensures excessive rainwater in the hardening mix. The reduced weather effects thus leads to a higher level of quality control of the modules (FORTRESS Protective Buildings, 2022).

Studies by Lawson et al. (2014) show that "Precast concrete elements achieve higher accuracy and quality than in situ concrete" (Lawson et al., 2014, p. 41). This is of course applicable to both precast element construction and prefabricated modular construction. The reason for this increased quality, is said to come from the in-house concrete production, which assures a consistent supply and control of materials. This further leads to better colour, texture and performance of the concrete element (Lawson et al., 2014, p. 41). An added benefit of higher-level quality control is the reduction of reworking and delays due to insufficient quality of modules (Lawson et al., 2014, p. 225). This also influences the economic side of modular construction, because the "improved quality of manufactured units … saves in on-site checking and reworking" (Lawson et al., 2014, 238).

6.4. Discussion of inspection and safety control-

A safe and stable working environment is crucial to all construction projects. Contractors must follow rules and regulations for health, safety and environment and ensure that the working conditions are well suited for the on-site workers. A summary of the key points discussed in Chapter 6 regarding inspection and safety-control are presented in table 7 below.

Table 7: Summary of Chapter 6

Factor or quality	**Traditional Casting**	**Precast elements**	**Prefabricated modules**
Quality control	Must be done before connecting new elements onto the previous.	Can be done before and after transportation. Easier to perform because it is not placed in the place of installation.	Can be done before and after transportation. Easier to perform because it is not placed in the place of installation.
Safety of workspace	Workers and elements are both on-site, must be careful around the non-hardened element. Incidents can occur.	Elements are mostly separated from on-site workers, therefore they are safe.	Modules are mostly separated from on-site workers, therefore they are safe.
Quality of product	Must consider weather effects. Faster water evaporation, faster shrinkage strain and bigger cracks.	Weather do not affect the element. Higher accuracy and quality than in-situ.	Weather do not affect the module. Higher accuracy and quality than in-situ.

7. Applicability

With the population steadily increasing in many parts of the world, the use of high-rise buildings are preferred over low-to-medium-rise buildings, especially for metropolises (Wang et al., 2020). Norway has a wide spread of citizens, where some live in more urban areas like Randaberg, while others live in populous cities such as Oslo on the opposite coast. Deciding which construction method to use in the different areas depends on the applicability of each method.

7.1. Traditional casting

Traditional concrete casting is the most common building technique used in Norway (Total Betong, personal communication, 10.04.2024). It ensures structural integrity and is highly adaptable to any changes or revisions made during the construction period. In real world practice, there can be a number of revisions which would render prefabricated alternatives costly and inefficient. Furthermore, prefabricated alternatives are not as attractive in the Norwegian construction marked as it is now (Total Betong, personal communication, 10.04.2024).

7.2. Precast elements

Precast frame structures are mostly common for single-storey industrial buildings, car parks and low-rise office buildings (Lawson et al., 2014, p. 42). This construction method combines beams, columns, floors, shear walls and special components to create the frame of the structure (Lawson et al., 2014, p. 42). The use of precast elements will depend on whether the cranes have enough capacity and range to carry all the elements to their place of installation (Total Betong, personal communication, 10.04.2024). Veidekke Prefab confirm that they have made buildings with primarily prefabricated elements up to 10 stories tall, with about 4 m tall stories (Veidekke Prefab, personal communication, 05.02.2024).

7.3. High rise modular buildings

In his paper “A review on modular construction for high-rise buildings”, Thai et al. (2020) discuss the benefits of modular construction in high-rise building. Though the applications “are very limited” (Thai et al., 2020), there is “great potential for real world applications of modular construction in high-rise buildings” (Thai et al., 2020). The paper further states that there is a lack of “strong structural systems and joining techniques to ensure structural integrity, overall stability, and robustness of an entirely modular building” (Thai et al., 2020). Furthermore, Thai et al. (2020) state that “the benefits of modular construction will be maximised for high-rise applications due to the increased number of repeated modules” (Thai et al., 2020).

Still, modular buildings are commonly built as low-to-medium-rise. This is mostly due to the “knowledge gap regarding the structural design of modular high-rises” (Pan et al., 2021). There is a significant gap in research regarding design of concrete modular high-rise buildings, which further hinders the applications of this construction method. High-rise buildings would require concrete cores to contain the overall stability of the building, while the modules can be designed to carry vertical loads (Pan et al., 2021). Horizontal loads would be carried to the cores to reduced structural failure in the modules (Pan et al., 2021). Lawson & Richards. (2010) also mention the technique of clustering modules around a core to provide stability (section 2). Typical arrangements of modules around a concrete core can be found in figure 3 in Pan et al. (2021).

This seems to have been a viable solution in more recent structures. For instance, a 16-storey residential building was built using this exact concept. Therefore, placing vertical load bearing modules around a concrete core is suitable for high-rise modular buildings (Lawson et al., 2014, p. 14). A picture of this building can be found on page 14 in Lawson et al. (2014).

The book also includes a description of the tallest modular building, which was a 32-storey residential building with 350 apartments. The building required 930 modules and covered an area of 30,000 m^2 (Lawson et al., 2014, p. 14). Further case studies can be found in "Design in Modular Construction".

Buildings with a high number of repetitive room design is best opted for using modular construction methods. Lawson et al. (2014) list hotels, prison and secure accommodations as the most common applications of modular construction (Lawson et al., 2014, p. 42). Hotels may use a corridor-type layout (Lawson et al., 2014, p. 43), where the internal walls can be painted for a desired finishing look. Prison cell blocks can be manufactured as single modules with walls and roof so that the roof of the cell below forms the floor of the cell above (Lawson et al., 2014, p. 44). A foundation layer must be placed before the first module is installed at the first floor.

Bathroom pods can also be casted as prefabricated concrete modules with piping and electrical work pre-installed before installation. These modules can weigh up to 4 tonnes (Lawson et al., 2014, p. 44), which is significantly lighter than the common room modules. Commonly, room modules weight between 20 to 40 tonnes each (Lawson et al., 2014, p. 42), with 20 being the most common weight of modular units. The pods use thinner concrete walls and a floor with single-layer steel mesh reinforcement for a reduced total weight. To efficiently place these modules, it is recommended to place these pods back-to-back around the service riser, with a maximum of four being grouped at one area of the slab (Lawson et al., 2014, p. 44).

7.4. Discussion of applicability

Which construction method to use depend on how well suited the method is for a particular project. Factors such as building location and the height of the building play a significant role in deciding which method will be optimal. The most important factors and qualities discussed in Chapter 7 is highlighted in the comparison presented in table 8 below.

Table 8: Summary of Chapter 7

Factor or quality	Traditional Casting	Precast elements	Prefabricated modules
Building height	Low, medium and high.	Single-storey industrial buildings, car parks and low-rise office buildings. Veidekke constructed 10 storeys building with precast elements.	Potential for high-rise, but low to medium rise is most common.
Adapts to revisions	Yes. Changes can be made during construction.	Revisions will hurt the progress plan.	Revisions will hurt the progress plan.
Common Norwegian practice	Yes.	To some degree. Used in some constructions, or as a mix of precast and and in-situ cast.	Very little or in small parts. Business have used modules sometimes, but not to the same degree as with full volumetric frame modules.
Construction type	All types can be constructed.	Industrial buildings, car parks and low-rise office buildings most common.	Buildings with a high number of repetitive rooms. Such as prisons, hotels and secure accommodations.

8. Design codes of concrete

An example of design calculations for a critical beam and column is computed using Smath in Appendix A. The calculation of design reinforcement for concrete elements conform to Eurocode 2 NS-EN 1992-1-1:2004+A1:2014+NA:2021. Calculations of self-weights and imposed loads conform to Eurocode 1 NS-EN 1991-1-1:2002+NA:2019. Wind loads conform to NS-EN 1991-1-4:2005+NA:2009. Lastly, snow loads conform to NS-EN 1991-1-3:2003+A1+NA. References for the calculations are present in Appendix A. Rights to use these standards are given by a purchased student subscription through the University of Stavanger.

There are many standards designated to precast concrete elements. For calculation of design resistances, the same aforementioned standards apply. There are some corrections or additions in the precast standards. For instance, in NS-EN 13225:2013 Prefabricated concrete elements – Linear construction elements [Translated from Norwegian], section 4.3.3.1 connects the calculation of mechanical resistance of a precast element to Eurocode 2 NS EN 1992-1-1:2004. Section 4.3.3.1 also specify that section 4.3.3.4 of NS EN 1992-1-1:2004 is to be ignored. Therefore, calculation of capacity of precast concrete elements and cast-in-place elements are computed with the same standards, with minor adjustments. For this reason, the calculation for the case study apply to all three construction methods. Lawson et al. (2014) also mentions that the structural design of precast concrete modules is the same as for in-situ cast reinforced concrete (Lawson et al., 2014, p. 179).

8.1. Structural module design

For concrete modules, some guidelines have been given in Lawson et al. (2014, Chapter 13). As opposed to element design, modular construction carry loading through reinforced concrete walls (Lawson et al., 2014, p. 179). Element construction on the other hand often carry load through beam and column combinations. The use of concrete modules has several benefits, including additional fire resistance, acoustic separation, concealed service distribution, internal and external finishes to walls and thermal mass to assist in controlling internal temperatures (Lawson et al., 2014, p. 179). During the research process of this study, there was no official guidelines for design of modules.

9. Principles of modular construction

Lawson et al (2014, p. 63-78) highlight some general and specific principles related to planning of modular construction building. The chapter covers several types of modular buildings, construction layout and dimensions of some example structures. For instance, the book covers grid planning for different building types. The case study for this thesis is a 3-storey office building. Module lengths for office buildings typically range between 6 to 12 m with increments of 600 mm (Lawson et al., 2014, p. 70). The internal planning dimensions for office buildings of 1500 mm is widely used (Lawson et al., 2014, p. 69). Furthermore, internal module width for offices is 3.6 m (Lawson et al., 2014, p. 70), which is only indicative. The true dimensions may vary depending on the needs of the building. External modules are generally "250 to 300 mm wider than their internal dimensions" (Lawson et al., 2014, p. 70).

9.1. Example layout of case study using modular form

In order to fit as many modules of the same size as possible, the width of the building has been increased from 17.4 m to 17.6 m. As previously stated, the office modules can have lengths between 6 and 12 m. Thus allowing the length of the building to stay the same, with only minor adjustment to the width. An example layout of the building using corridor design with a stabilizing core can be seen in figure 41 below.

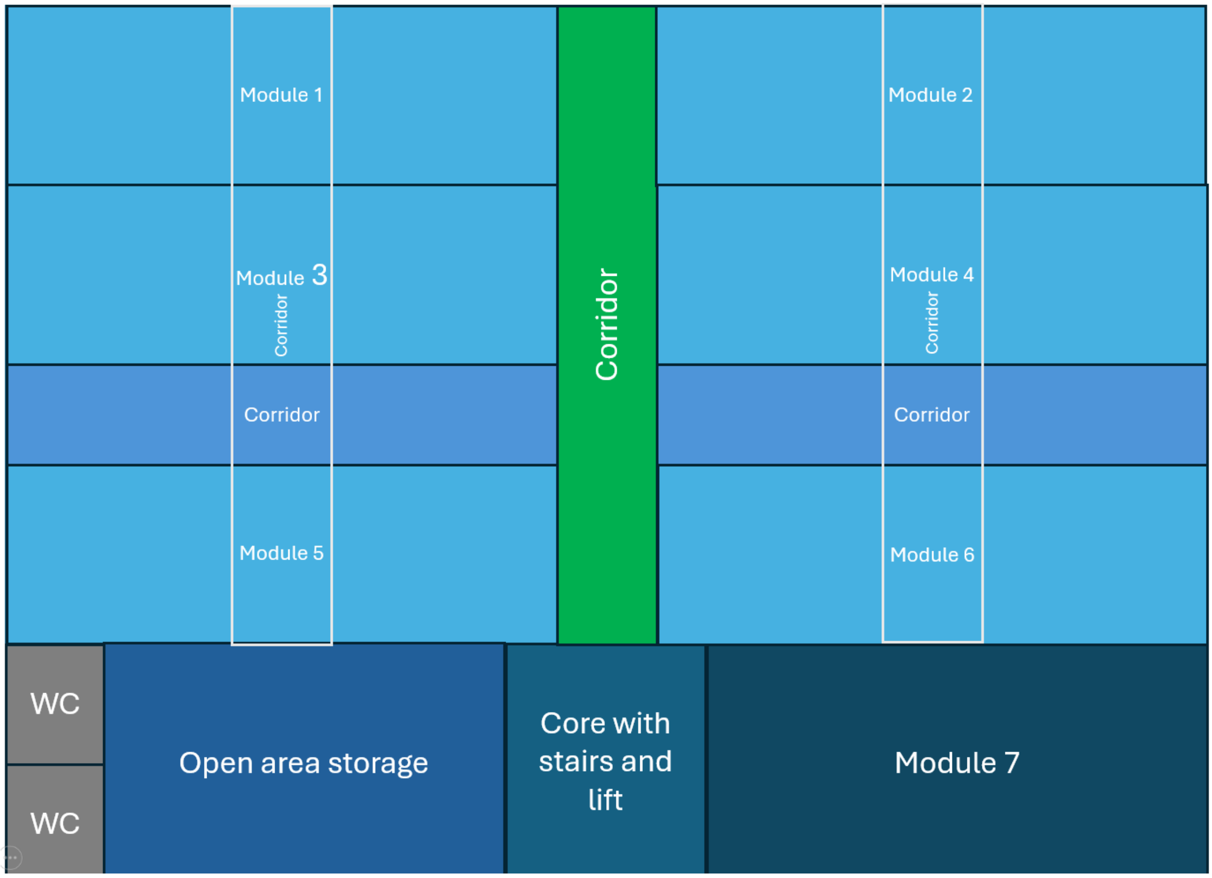


Figure 41: Modular layout of office building using a corridor type arrangement with stabilizing core. Length as dimension from left to right in image, width as dimension from bottom to top in image

Greater detail about the modules can be found in table 9 below.

Table 9: Details of modular layout of office building

Module	**Dimensions in metres (L x W x H)**	**Conforms to**	**Description**
1-6	3.6 x 11 x 4	Module width and length for offices, page 70 in Lawson et al. (2014)	Two separate offices with a corridor splitting the two apart
Corridor (blue)	11 x 2 x 4	One side less than 2,55 m for transport	Corridor which allows access to the other office modules
Corridor (green)	2 x 12.8 x 4	One side less than 2,55 m for transport	Corridor for access to the building after entering from the core. May require division into two modules
Core	4 x 2.4 x 4	One side less than 2,55 m for transport	Core with stairs and lift. Access from the bottom floor to the top floor. Module consists of two modules of given dimension to form the core. Alternatively, it can be cast traditionally for structural integrity
WC	2 x 2.4 x 4	Lawson et al. (2014) page 52 for typical bathroom module dimensions	Bathroom pod
Open area storage	8 x 2.4 x 4	One side less than 2,55 m for transport	Combination of two modules to form one room used for storage.
Module 7	10 x 2.4 x 4	One side less than 2,55 m for transport	Meeting room. Combines two modules of given dimension two form one room

The modules can be stacked vertically three times to fit the storeys of the case study building. This layout is not necessarily the optimal layout, but it works for simplicity of the case study. An alternative is to set the "Open area storage" module to have full length in floor 1 and 3, and remove it entirely in floor 2. The removed module in floor 2 can then be replaced by a much larger bathroom area for the whole building.

For this layout to be used in three floors, the number of modules required is three times the modules in figure 41. For this project, it becomes:

Office modules – 18

Corridor modules (blue) – 6

Corridor modules (green) – 3

WC pods – 6

Meeting room modules (module 7) – 3

Core modules – 3, or traditionally cast the entire core

Total amount of modules – 41

Assuming the modules can be installed within the range of 6 to 10 modules per day, this computes to a total installation time of 5 to 7 days. With each unit requiring an approximate investment of £2000 (Lawson et al., 2014, p. 238), this totals to £82 000 or approximately 1 115 423.15 NOK (CoinMill, 17.04.2024). Compared to the cost discussed in section 5.1 of 1 419 400 NOK, this is a reduction of 21.4%. This is consistent with the theoretical cost reduction given by Lawson et al. (2014, p. 237), which was 20%.

10. Structural performance

It is without a doubt necessary to include the structural performance of the building when considering the most optimal construction method for a project. Structural performance includes the stability, integrity and robustness of the building when subjected to the design loading. This study focuses specifically on the structural performance achieved by joining and connection methods.

10.1. Connections

The joining method used in each construction method is a distinguishing parameter for all three methods. Cast-in-place concrete rely on direct joining and anchoring of elements. The two prefabricated methods can use a variety of joining methods, including anchoring, plate-to-plate connection and bolted connections. The performance of the entire frame structure relies heavily on the performance of the connection. For instance, the L'Aquila earthquake in 2009 gave collapses to entire buildings due to insufficient anchorage at connections (Chang et al., 2023). Another study of an earthquake in Turkey showed that "connections that lack moment-resisting capacity can cause joint damage and result in the collapse of a structure" (Chang et al., 2023). The hazard level for Norway is set to medium, implying a 10% chance of potentially damaging earthquakes within the next 50 years (ThinkHazard, 2021). For this reason, calculations for anchoring and plate connection is not included in Appendix A. The importance of sufficient connecting methods is also significant for use of modular construction. Ro et al. (2021) state that "Structural performance and serviceability can be ensured if the modules are connected sufficiently".

10.1.1. Traditional casting

Traditional concrete casting often uses direct joining and anchoring of elements. The connections must be designed to achieve an overall structural integrity and stability of the construction. The anchorage length can be computed using the guidelines in Standard Norge. (2021, section 8).

10.1.2. Precast elements

Similar to other construction methods, the connection used are "particularly important for overall structural performances" (Chang et al., 2023). The components of the building is joint by either mechanical devices, or by on-site cast joints (Chang et al., 2023). To ensure structural performance of a precast concrete building, it is necessary to design and assemble sufficient joints between elements.

Chang et al (2023) makes a clear point regarding the failure of precast concrete buildings. The authors mention that "It is difficult to ensure a precast building with the same integrity as the cast-in-situ buildings, because failures may develop along connections to components" (Chang et al., 2023). The study is specifically focused on the failure of precast structures due to earthquakes. Precast concrete elements must conform to NS-EN 13369:2023 or above, but there is no assurance of earthquake design resistance for this construction method. Which is why seismic action has not been accounted for in the case study of this thesis.

10.1.3. Prefabricated modules

For modular buildings, there is a "lack of strong structural systems and joining techniques to ensure structural integrity, overall stability, and robustness" (Thai et al., 2020). Sufficient joining techniques of modules is therefore critical for the performance of modular construction to be a viable option. Also, the lack of design guidelines (Thai et al., 2020) further reduces the confidence of the construction industry to adapt to this method of construction.

A study by Ro et al. (2021) dealt with difficulties of connecting module units by bolted plates. In their review, they state that this connection "may suffer from alignment issues and corrosion problems" (Ro et al., 2021). Another issue for precast concrete modular systems is that "there is difficulty grouting the sleeves when splicing reinforcing bars" (Ro et al., 2021). The connections between modules are especially important in modular construction, because it "strongly influence the overall structural stability and robustness of the assembly of modules" (Lawson et al., 2014, p. 214).

The inherit structural integrity of a module leads to advantages for the design reinforcement needed. A study by Wenke, J. M. and Dolan, C. W. stated that modular units are inherently stable and therefore need less reinforcement to achieve sufficient structural integrity (Wenke & Dolan, 2021, p. 68). Single elements would need specific additional reinforcement to control the overall integrity of the building. Modules however are generally more stable than groupings of single elements.

The study further cites research concluding that corner connections of modules create structural integrity of the overall building (Wenke & Dolan, 2021, p. 68). The building is then able to absorb the energy from abnormal failure and transfer it throughout the structure. Finally, Wenke & Dolan (2021) compare the behaviour of this modular building method to traditional cast-in-place concrete buildings and precast concrete panel construction (p. 68).

Lawson et al. (2014) also note some benefits of the modular construction method related to their structural performance. For one, they have found that modules have "Higher construction tolerances than in on-site construction" (Lawson et al., 2014, p. 41). Furthermore, using concrete modules also bring inherent benefits due to their "fire resistance, sound insulation and thermal capacity" (Lawson et al., 2014, p. 41).

10.1.4. Performance of modular system

A flexure and shear test were performed by Ro et al. (2021) which compared the structural performance of a precast concrete modular specimen and a monolithic beam. The result shows the modular specimen to achieve 88% of the structural performance of the monolithic beam. By ACI 318-19, this is equivalent to 102% of the calculated strength (Ro et al., 2021). Meaning that their proposed bolted connection with plates may be an improvement to the performance of modular systems. The proposed connection can be seen in figure 2 and 3 in Ro et al. (2021).

Furthermore, the experiments showed conclusive results regarding the structural performance of a modular system using this connections method. Ro et al. (2021) concludes his paper by saying "using a bolted connecting plate ensured splicing performance and had excellent structural performance" (Ro et al., 2021). Thus, regarding the modular system to meet the structural requirements.

This connection method was also used in the recent renovation of Kiwi, Randaberg by ØsterHus AS (ØsterHus AS, personal communication, 31.01.2024). A conversation with the project manager, Johannes Hovda, lead to the finding of the joining method used. He described the connections to be of the U and I plated with fillings between (ØsterHus AS, personal communication, 31.01.2024), similar to what Ro et al. (2021) described. Hovda mentioned the installation process as smooth, swift and efficient for their need (ØsterHus AS, personal communication, 31.01.2024).

10.2. Modular design principles

The guidelines highlighted by Lawson et al. (2014) provide a lot of research focused on modular design principles. For instance, it is noted that the load capacity of reinforced concrete walls used in modular construction is very high, thus making high-rise buildings less of an issue. Furthermore, it is common to allow the combination of the roof, of a module below, with the floor of the module above, to form the separating slab for each storey.

The main load bearing element of prefabricated modular buildings is the vertical reinforced concrete walls. The modular structures are "very resistant to lateral loads" (Lawson et al., 2014, p. 182) and the walls and slabs are "inherently robust and can easily meet the requirements for structural integrity by appropriate reinforcement detailing" (Lawson et al., 2014, p. 183).

“Horizontal stability is provided by the walls of the modules” (Lawson et al., 2014, p. 179) and pairs of rooms can be separated within the module itself. Thus, allowing one unit to form multiple rooms, such as a double office module. Thin walls of 125 to 150 mm are common, with the additional benefit of forming a double wall with adjacent modules (Lawson et al., 2014, p. 179).

10.3. Discussion of structural performance

Common for all three methods, is the connection method being the determining factor for overall structural performance of the construction. The three methods may use different connection types, but they must all be designed to withstand forces and achieve structural safety. Researchers point to the existence of earthquakes to be a common failure for many constructions. This should therefore be considered. Norway is located such that there is a very small chance of destructive earthquakes occurring. Table 10 below give a clearer comparison between the three construction methods with regards to the structural performance discussed in Chapter 10.

Table 10: Summary of Chapter 10

Factor or quality	**Traditional Casting**	**Precast elements**	**Prefabricated modules**
Connection type	Direct joining and anchoring. Easy to grout connection sleeves.	Plates and bolts with filling. Easy to grout connection sleeves.	U and I bolted plates. Difficult to grout connection sleeves.
Guidelines	Equations and recommendations from Standard Norge. (2021) section 8, p. 131 and Larsen et al. (2003)	Equations and recommendations from Standard Norge. (2021) section 8 and Larsen et al. (2003)	Lack guidelines for modular connection.
Additional reinforcement	Anchoring.	Connection reinforcement.	Less reinforcement needed to achieve stability. There is an inherent structural stability of modules.

11. Practical perspective

A conversation with experienced project managers at Total Betong revealed a lot about the real-world applications of traditional casting and prefabricated methods. This discussion is voice recorded in Norwegian and took place at their offices on Bryne.

Krister Austarheim and Espen Solberg at Total Betong confirm some of the previously listed advantages of prefabricated elements. Like cost saving, time saving, better safety control and the early quality inspection possible in manufactured elements (Total Betong, personal communication, 10.04.2024). They also agree that prefabricated methods are a great alternative under optimal circumstances. Most notably if there is a guaranteed delivery schedule (Total Betong, personal communication, 10.04.2024). In some cases where they have considered prefabricated elements, they have found that is was slightly cheaper, but it is generally not considerably more expensive to use cast-in-place methods (Total Betong, personal communication, 10.04.2024). Finally, they also confirm that they have used a combination of prefabricated elements and cast-in-place concrete in cases where traditional methods have not been sufficient for the entire construction (Total Betong, personal communication, 10.04.2024).

Even though they show enthusiasm for use of modular building techniques and prefabricated element constructions, they have some real-world practice of what works well in the Norwegian marked. For one, there is a lack of attractiveness and practical solutions for prefabricated alternatives in Norway. There are variations in weather and soil which hinders the desired standardisation of prefabricated methods (Total Betong, personal communication, 10.04.2024). It would be difficult to standardise a complete module, because of the regional differences.

Next, there are cases where the build owner and architects simply do not like the repetitive form of modular constructions. The build owner is the one who decides which method to use, and they are generally more comfortable with traditional methods.

Lastly, traditional casting is preferred because of their ability to adapt to change and revisions in the construction plan without 1) hindering the progress plan and 2) adding additional costs to the project (Total Betong, personal communication, 10.04.2024). This will of course not be necessary if the plans are complete before the construction with no plans to change anything. Sufficient planning before construction may render prefabricated methods to be a more suited construction method (Total Betong, personal communication, 10.04.2024). Still, there is no way to guarantee deliveries, even with good planning. There is too much uncertainty and too little room for revision with prefabricated methods. Therefore, cast-in-place is the most reliable method of construction.

12. Conclusion and discussion

Each construction method have their own advantages and disadvantages to consider when deciding which method of construction will be most optimal for a given project. Traditional casting is most commonly used and trusted in Norway, but it may be more practical to use prefabricated alternatives in metropolises. Furthermore, there is more wastage to consider for traditional methods, and the environment plays a factor in the hardening stage of the concrete mix. Still, small measurements allow traditional methods to dominate the Norwegian construction market.

For precast concrete elements, optimal transportation will be a deciding factor for the economical perspective of the project. The elements must be made to fit the dimensional and weight requirements on Norwegian roads. Also, it is more efficient for manufacturers to have a set of standardised elements for more efficient casting for bigger projects. Precast elements are flexible and customizable, and more adaptable to change than for modular construction. For any revision or mistake in the progress plan, only one or a few select elements must be redesigned and cast. Modular construction suffer from having to replace and entire module, which can take days to prepare.

Similar to precast elements, modular construction allows for off-site casting and construction of the module. This further allows for a safer on-site workspace and easier quality control of the unit. Lawson et al. (2014) have provided great research focused on the applicability of modular construction in other countries. It is evident that modular construction is efficient elsewhere, but the method is limited in Norway due to the lack of trust and flexibility in the market. Practically, traditional methods are advantageous with regards to the current trends.

There is a lot to be said about the theoretical savings of prefabricated alternatives as opposed to the common in-situ cast methods in Norway. For one, there is a good market with few competitors to start a prefabricated business. Advantages include time savings, cost savings and good structural performance. However, it is not a common construction method in Norway, which renders it less trustworthy. The mountains may prove it to be difficult to transport elements or modules across larger distances. Furthermore, the Norwegian climate may be difficult to create standardised modules or elements. Additionally, businesses would need to invest a lot into factories for a process that may not be profitable. Previously existing businesses have gone bankrupt after only a few years of practice. Lastly, Total Betong make a good point on what is achievable versus what is practical. They agree that prefabrication would be a great method, but that real practice include revisions in the progress plan. These revisions are problematic for prefabricated construction methods, because they are not adaptable to change. Thus, adding to the total project cost.

Even though traditional casting methods seems to be more expensive, they are practical and known to work in the Norwegian market. The build owner decides which method to use, and it is most often traditional methods that come out on top. It is of utmost importance that the practice used in construction is safe. Build owners are familiar with traditional methods, and architects are usually not a fan of precast methods. If prefabricated elements or modules are to take over the Norwegian market, further research and standardisation must be conducted.

Prefabricated modules have big dimensions, higher weight and are less stackable for transportation than precast elements. The existing methods of combining traditional in-situ cast elements with precast elements could be the best solution with the current technology and practice to date. However, there is potential for a gradual change in the market to consider more prefabricated alternatives with growing research.

13. Further research

This thesis includes several simplifications to the case study. From the research conducted on the different construction methods, there are a broad range of factors which should be considered and added to the research. These points are highlighted in a bullet point list below.

- Standardised design modules with some room for flexibility
- Standardised connection methods with sufficient capacity
- Internal humidity and airflow in modular building
- Sway of construction by Force Method or Unit Load Method
- Optimalisation of designed dimensions and reinforcement in modular form
- Layout of production factory for reinforced concrete modules
- Further investigation of the structural behaviour, stability and robustness of modular buildings
- Sustainability and energy efficiency of modular buildings
- Roof modules with solar panels and green energy integration
- Deconstruction and reconstruction of modular buildings

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Appendix A – Design element calculation and cost calculation

This page is reserved any notes and comments connected to the calculations below. Calculations start on the next page.

Parts of the thesis include formulas and requirements gathered from the course BYG220 - Concrete Constructions at the University of Stavanger. Lectures and notes from this course are refrenced from personal communication with the lecturer of 2023, Dr. Samindi Samarakoon (PhD). Said parts are noted from attending her lectures in the spring semester of 2023. Samindi is a professor at the Faculty of Science and Technology at the Department of Mechanical and Structural Engineering and Materials Science at the university.

$L := 27\ \text{m}$
$B := 17{,}4\ \text{m}$
$H := 12{,}675\ \text{m}$

For building dimensions, see figure 1 to 4

Height of building:
$z := H = 12{,}675\ \text{m}$

$A_{floor} := L \cdot B = 469{,}8\ \text{m}^2$

The following snow load calculation refers to NS-EN 1991 - 1 - 3 : 2003 + A1:2015 + NA:2018.

Snow load:

$S := \mu_i \cdot C_e \cdot C_t \cdot S_k$ (Standard Norge, 2018, p. 18)

$C_e := 1$ (Standard Norge, 2018, p. 20)

$C_t := 1$

Randaberg

$S_{k,0} := 1{,}5\ \frac{\text{kN}}{\text{m}^2}$ (Standard Norge, 2018, p. 4 of National Annex)

$H_g := 150\ \text{m}$ (Standard Norge, 2018, p. 4 of National Annex)

$\delta S_{k,max} := 0{,}5\ \frac{\text{kN}}{\text{m}^2}$ (Standard Norge, 2018, p. 4 of National Annex)

Altitude above sea level is 29.4m for Randaberg (Kartverekt, 2024).

Since the altitude above sea level is less than H.g: (Standard Norge, 2018, p. 2 of National Annex)

$S_k := S_{k,0} = 1{,}5\ \frac{\text{kN}}{\text{m}^2}$

Consider monopitched roof at angle 0 degrees

$\mu_i := 0{,}8$ (Standard Norge, 2018, p. 6)

$$\boxed{S := \mu_i \cdot C_e \cdot C_t \cdot S_k = 1{,}2\ \frac{\text{kN}}{\text{m}^2}}$$

Characteristic snow load $\psi_{0,s} := 0{,}7$ $\psi_{1,s} := 0{,}5$ $\psi_{2,s} := 0{,}2$ (Standard Norge, 2018, p. 17)

Design snow load: $S_d := 1{,}5 \cdot \psi_{0,s} \cdot S = 1{,}26\ \frac{\text{kN}}{\text{m}^2}$

This concludes the design snow load calculation, and thus also the end of referring to NS-EN 1991 - 1 - 3 : 2003 + A1:2015 + NA:2018

For the calculation of wind load, NS-EN 1991 - 1 - 4 : 2005 + NA : 2009 has been used

Wind load:

Basic wind velocity:

$v_b := c_{dir} \cdot c_{season} \cdot v_{b,0}$ (Standard Norge, 2024, p. 18)

$c_{dir} := 1$ No specific direction (Standard Norge, 2024, p. 9 of National Annex)

$c_{alt} := 1$ (Standard Norge, 2024, p. 9 of National Annex)

$c_{season} := 1$ Recommended value (Standard Norge, 2024, p. 9 of National Annex)

$c_{prob} := 1$ Conservative value (Standard Norge, 2024, p. 9 of National Annex)

$v_{b,0} := 28\ \frac{\text{m}}{\text{s}}$ (Standard Norge, 2024, p. 5 of National Annex)

Mean wind velocity:

Area 1 region

$H_0 := 900\ \mathrm{m}$

$H_{topp} := 1500\ \mathrm{m}$ (Standard Norge, 2024, p. 10 of National Annex)

$H < H_0$ results in

$v_b := v_{b,0} = 28\ \frac{\mathrm{m}}{\mathrm{s}}$

Terrain category 2 (Table NA.4.1)

$k_r := 0{,}19$

$z_0 := 0{,}05\ \mathrm{m}$ (Standard Norge, 2024, p. 12 of National Annex)

$z_{min} := 4\ \mathrm{m}$

Roughness factor:

No hill. Orography factor is 1, see (Standard Norge, 2024. p. 16 of National Annex)

$z_{max} := 200\ \mathrm{m}$

$c_0 := 1$

$z_{min} < z \ \ and \ \ Z < z_{max}$

$c_{r,B} := k_r \cdot \ln\left(\frac{z}{z_0}\right) = 1{,}052$ (Standard Norge, 2024, p. 19)

$v_{m,B} := c_{r,B} \cdot c_0 \cdot v_b = 29{,}448\ \frac{\mathrm{m}}{\mathrm{s}}$ Mean wind velocity at construction site (Standard Norge, 2024, p. 19)

There is a change in roughness. Category 0 located 1.15 km from contstruction site. Table NA.4.1

$k_{r,A} := 0{,}16$

$z_{0,A} := 0{,}003\ \mathrm{m}$ (Standard Norge, 2024, p. 12 of National Annex)

$z_{min,A} := 2\ \mathrm{m}$

$c_{r,A} := k_{r,A} \cdot \ln\left(\frac{z}{z_{0,A}}\right) = 1{,}336$ (Standard Norge, 2024, p. 19)

$v_{m,A} := c_{r,A} \cdot c_0 \cdot v_b = 37{,}403\ \frac{\mathrm{m}}{\mathrm{s}}$ Mean wind at coastal area (Standard Norge, 2024, p. 19)

There is an increase in terrain roughness less than 10km from the construction site. The terrain category increases from the coastal area A to the construction site B.

$n_{cat} := 2 - 0 = 2$

$x_B := 1{,}15\ \mathrm{km}$

$$v_{m,B1} := \max\left(\begin{bmatrix} 10^{-0{,}04 \cdot n_{cat} \cdot \log10\left(\frac{x_B}{10\ \mathrm{m}}\right)} \cdot v_{m,B} \\ v_{m,A} \end{bmatrix}\right) = 37{,}403\ \frac{\mathrm{m}}{\mathrm{s}}$$

(Standard Norge, 2024, p. 13 of National Annex)

Peak velocity wind preassure:

$q_p := k_1 \cdot k_2 \cdot k_3 \cdot c_{dir}^{\ 2} \cdot c_{alt}^{\ 2} \cdot c_{season}^{\ 2} \cdot c_{prob}^{\ 2} \cdot q_{p,0}$ (Standard Norge, 2009, p. 1 in Veiledning)

$v_{b,0} := 28\ \frac{\mathrm{m}}{\mathrm{s}}$ Catergory 2 $z = 12{,}675\ \mathrm{m}$

$q_{p,0} := 1200 \frac{N}{m^2}$

$k_1 := 1$ for flat terrain (Standard Norge, 2009, p. 6 in Veiledning)

No steep terrain

$k_2 := 1$ V.5 (Standard Norge, 2009, p. 12 in Veiledning)

For n = 2, A sone category 0, positive n, xB = 1.15km, consider Table V.1 a) for factor k3 (Standard Norge, 2009, p. 14 in Veiledning)

$k_{3,1} := 1{,}3$

$k_{3,2} := 1{,}10$

Interpolate for k3

$$\frac{k_{3,2} - k_{3,1}}{2{,}5 - 0{,}5} = \frac{k_{3,2} - k_3}{2{,}5 - 1{,}15}$$

This gives:

$$k_3 := -\left(\frac{\left(k_{3,2} - k_{3,1}\right) \cdot (2{,}5 - 1{,}15)}{2{,}5 - 0{,}5} - k_{3,2}\right) = 1{,}235$$

Thus the peak wind preassure is

$$\boxed{q_p := k_1 \cdot k_2 \cdot k_3 \cdot c_{dir}^{\ 2} \cdot c_{alt}^{\ 2} \cdot c_{season}^{\ 2} \cdot c_{prob}^{\ 2} \cdot q_{p,0} = 1482 \frac{N}{m^2}}$$

Wind action on building:

Bulding height less than 15m -> $C_{sd} := c_s \cdot c_d$

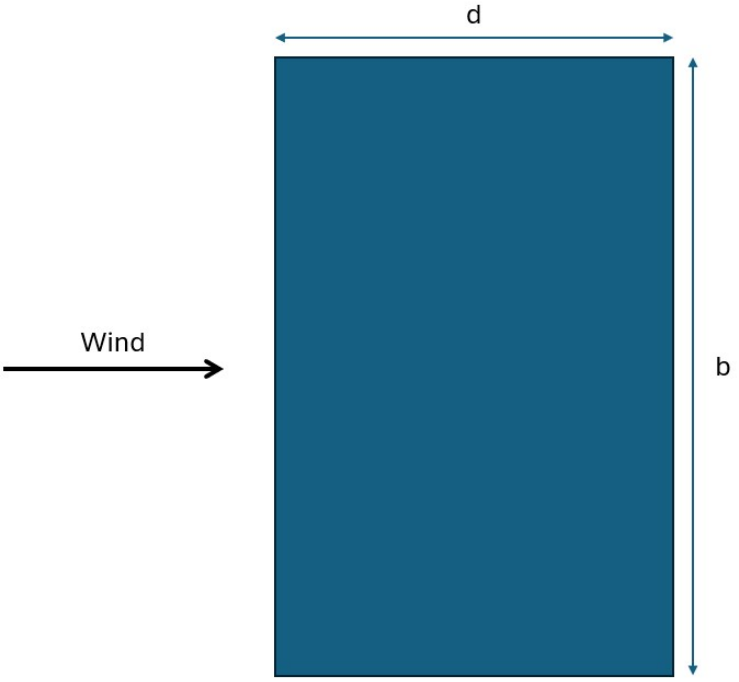
Preassure coefficient on vertical wall $C_{sd} := 1$ (Standard Norge, 2024, p. 28)

$b := 27\ m$

$d := 17{,}4\ m$

$h := H = 12{,}675\ m$

$\frac{h}{d} = 0{,}728$



$h < b$

See figure 7.4 in Standard Norge. (2024) page 35

$z_e := h = 12{,}675\ \mathrm{m}$

All walls have a reference area greater than 10 m2

$e := \min\left(\begin{bmatrix} b \\ 2 \cdot h \end{bmatrix}\right) = 25{,}35\ \mathrm{m}$

$e > d$ See figure 7.5 in Standard Norge. (2024) page 36

Length of zones A and B

$ZoneA := \dfrac{e}{5} = 5{,}07\ \mathrm{m}$

$ZoneB := d - \dfrac{e}{5} = 12{,}33\ \mathrm{m}$

For preassure coeffiecients C.pe in Zone A and Zone B, the values are identical for h / d ratios equal to one and less than or equal to 0.25. For D and E zones, must interpolate

Thus

$c_{pe,10,A} := -1{,}2$ (Standard Norge, 2024, p. 37)

$c_{pe,10,B} := -0{,}8$

$$\frac{0{,}8 - 0{,}7}{1 - 0{,}25} = \frac{0{,}8 - C_{pe,10,D}}{1 - \dfrac{h}{d}}$$

$$C_{pe,10,D} := -\left(\frac{(0{,}8 - 0{,}7) \cdot \left(1 - \dfrac{h}{d}\right)}{1 - 0{,}25} - 0{,}8\right) = 0{,}764$$

$$\frac{-0{,}5 - (-0{,}3)}{1 - 0{,}25} = \frac{-0{,}5 - C_{pe,10,E}}{1 - \dfrac{h}{d}}$$

$$C_{pe,10,E} := -\left(\frac{(-0{,}5 - (-0{,}3)) \cdot \left(1 - \dfrac{h}{d}\right)}{1 - 0{,}25} - (-0{,}5)\right) = -0{,}428$$

Since h / d ratio is less than one, note 3 in section 7.2.2 says to multiply the resultant force by 0.85
(Standard Norge, 2024, p. 37)

$k_{correlation} := 0{,}85$

Find peak wind preassure at reference height z.e (is same as z here)

Surface area of zone D and E

$A_{ref,DE} := L \cdot H = 342{,}225\ \mathrm{m}^2$

To find wind load on the building at zones D and E, must find C.pe for D and E zones. Linear interpolation.

Preassure on building:

$\boxed{q_{w,k} := \left(\left|C_{pe,10,D}\right| + \left|C_{pe,10,E}\right|\right) \cdot q_p = 1765{,}624\ \dfrac{\mathrm{N}}{\mathrm{m}^2}}$ $\boxed{F_w := k_{correlation} \cdot q_{w,k} \cdot A_{ref,DE} = 513{,}605\ \mathrm{kN}}$

Loads on critical beam element in section 2 floor 1:

3 floors

Columns: 610x610 mm $l_{col} := 610\ \text{mm}$ $H_{col} := 4\ \text{m}$

Beams: 400x600 mm $b_{beam} := 400\ \text{mm}$ $h_{beam} := 600\ \text{mm}$ $L_{beam} := 8{,}2\ \text{m}$

Slabs: 225 mm thickness $t_{slab} := 225\ \text{mm}$

All elements consider B35 concrete and B500NC reinforcement

Self weights:

Density of concrete with reinforcement:

$$\rho := (24+1)\ \frac{\text{kg}}{\text{m}^3} = 25\ \frac{\text{kg}}{\text{m}^3}$$ (Standard Norge, 2019, p. 32)

$$g := 9{,}81\ \frac{\text{m}}{\text{s}^2}$$ Gravitational constant

Self weight per floor

$$G_{k,beam,floor} := \rho \cdot b_{beam} \cdot h_{beam} \cdot L_{beam} \cdot 3 \cdot g = 1{,}448\ \text{kN}$$

$$G_{k,col,floor} := \rho \cdot l_{col} \cdot l_{col} \cdot H_{col} \cdot 9 \cdot g = 3{,}285\ \text{kN}$$

$$G_{k,slab,floor} := \rho \cdot t_{slab} \cdot L \cdot B \cdot 1 \cdot g = 25{,}924\ \text{kN}$$

Imposed loads:

Considering first storey as fitness center, above floors as office area

Floor 1 Category C4 - Areas wtih physical activities
Floor 2 as Catefory B - Office Area

(Standard Norge, 2019, p. 21)

$$q_{k,1} := 5\ \frac{\text{kN}}{\text{m}^2}$$ (Standard Norge, 2019, p. 22)

$$q_{k,2} := 3\ \frac{\text{kN}}{\text{m}^2}$$

ψ factors:

Cat $\psi_0 := 0{,}7$ $\psi_{1,B} := 0{,}5$ $\psi_{2,B} := 0{,}3$ (Standard Norge, 2016, p. 2 of National Annex)

Cat C $\psi_{1,C} := 0{,}7$ $\psi_{2,C} := 0{,}6$

Reduced imposed load on beams due to area:

$$\alpha_A := \min\left(\begin{bmatrix} \frac{5}{7} \cdot \psi_0 + \frac{A_0}{A} \\ 1 \end{bmatrix}\right)$$ (Standard Norge, 2019, p. 3 of National Annex)

$A_0 := 15\ \text{m}^2$ (Standard Norge, 2019, p. 3 of National Annex)

$A := \frac{1}{2} \cdot L \cdot \frac{1}{2} \cdot B = 117{,}45\ \text{m}^2$ Contienous beams, area equal to loaded area of span

$$\alpha_A := \min\left(\begin{bmatrix} \frac{5}{7} \cdot \psi_0 + \frac{A_0}{A} \\ 1 \end{bmatrix}\right) = 0{,}628$$

Does not meet the requierements of the equation to be greater than both ψ.0 and 0.6. Therefore reduction factor set to be equal to ψ.0 (Standard Norge, 2019, p. 3 of National Annex)

$\alpha_A := \psi_0 = 0,7$

$\alpha_A > \psi_0 \quad \alpha_A > 0,6$ These are both meant to be "greater than or equal to" signs, but the program limits me to only use greater than signs.

Reduced imposed load on beam due to storeys:

$n_{storeys} := 3$

$$\alpha_n := \frac{2 + \left(n_{storeys} - 2\right) \cdot \psi_0}{n_{storeys}} = 0,9$$ (Standard Norge, 2019, p. 4 of National Annex)

Section NA 6.3.1.2 specify that only one reduction factor may be used at a time. To be conservative, use highest value α.n

Loaded area

$A_{load,beam} := \frac{1}{2} \cdot L \cdot B = 234,9\ \mathrm{m}^2$

$G_{k,beam,floor} := \rho \cdot b_{beam} \cdot h_{beam} \cdot L_{beam} \cdot 3 \cdot g = 1,448\ \mathrm{kN}$

$G_{k,col,floor} := \rho \cdot l_{col} \cdot l_{col} \cdot H_{col} \cdot 9 \cdot g = 3,285\ \mathrm{kN}$

Loading type

Snow $\quad S_{k,beam} := S \cdot \frac{A_{load,beam}}{B} = 16,2\ \frac{\mathrm{kN}}{\mathrm{m}}$

Wind $\quad F_w = 513,605\ \mathrm{kN}$

Imposed $\quad q_{k,imp} := q_{k,2} \cdot \frac{A_{load,beam}}{B} = 40,5\ \frac{\mathrm{kN}}{\mathrm{m}}$

Self weight $\quad G_{k,self} := \frac{3 \cdot \rho \cdot t_{slab} \cdot A_{load,beam} \cdot g + 6 \cdot G_{k,col,floor} + 3 \cdot G_{k,beam,floor}}{B} = 3,617\ \frac{\mathrm{kN}}{\mathrm{m}}$

Design vertical load:

$$q_{6,10a} := 1,35 \cdot G_{k,self} + 1,5 \cdot \psi_0 \cdot q_{k,imp} \cdot \alpha_n + 1,5 \cdot \psi_{0,s} \cdot S_{k,beam} = 60,166\ \frac{\mathrm{kN}}{\mathrm{m}}$$

$$q_{6,10b} := 1,2 \cdot G_{k,self} + 1,5 \cdot q_{k,imp} \cdot \alpha_n + 1,5 \cdot \psi_{0,s} \cdot S_{k,beam} = 76,026\ \frac{\mathrm{kN}}{\mathrm{m}}$$

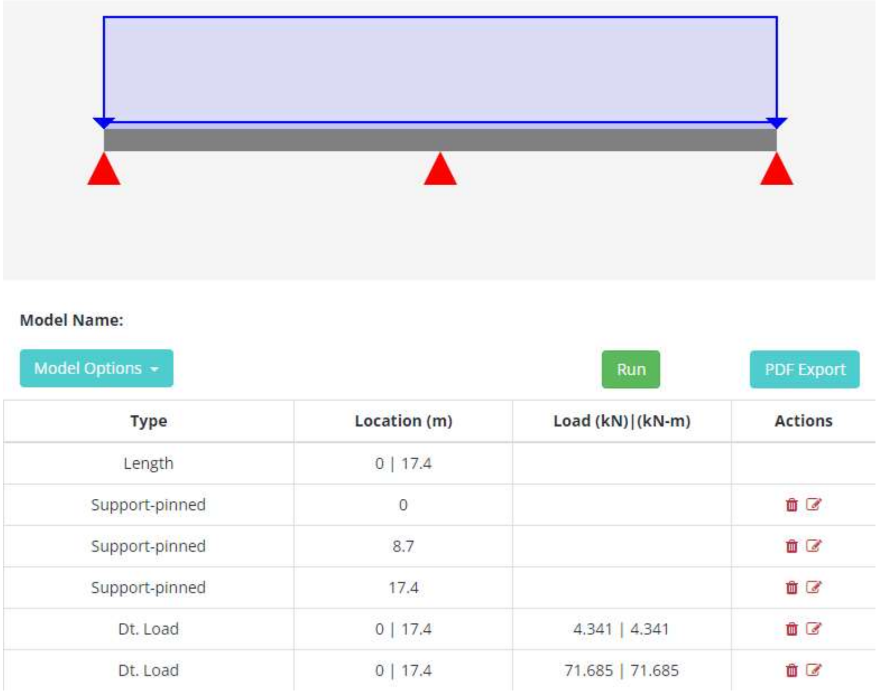
(Standard Norge, 2016, p. 12)

$$q_d := \max\left(\begin{bmatrix} q_{6,10a} \\ q_{6,10b} \end{bmatrix}\right) = 76,026\ \frac{\mathrm{kN}}{\mathrm{m}}$$

Model column to beam connection as pin supports

$\boxed{G_{ed} := 1,2 \cdot G_{k,self} = 4,341\ \frac{\mathrm{kN}}{\mathrm{m}}}$ $\boxed{Q_{ed} := 1,5 \cdot q_{k,imp} \cdot \alpha_n + 1,5 \cdot \psi_{0,s} \cdot S_{k,beam} = 71,685\ \frac{\mathrm{kN}}{\mathrm{m}}}$

Case 1



Model Name:

Type	Location (m)	Load (kN)|(kN-m)	Actions
Length	0 | 17.4		
Support-pinned	0		🗑 ✎
Support-pinned	8.7		🗑 ✎
Support-pinned	17.4		🗑 ✎
Dt. Load	0 | 17.4	4.341 | 4.341	🗑 ✎
Dt. Load	0 | 17.4	71.685 | 71.685	🗑 ✎

Calculations taken from OptimalBeam. (n.d).

Reactions

Location: 0 (m), Force Reaction = -248.0348 (kN)

Location: 8.7 (m), Force Reaction = -826.7828 (kN)

Location: 17.4 (m), Force Reaction = -248.0348 (kN)

Shear Diagram

(Max +ve)Shear Load (kN): 413.391,

Location (m): 8.700

(Max -ve)Shear Load (kN): -413.391,

Location (m): 8.700

Moment Diagram

(Max +ve)Moment Load (kN-m): 404.607,

Location (m): 3.263, 14.137

(Max -ve)Moment Load (kN-m): -719.301,

Location (m): 8.700

Calculations taken from OptimalBeam. (n.d).

Case 2

Model Name:

Type	Location (m)	Load (kN)|(kN-m)	Actions
Length	0 | 17.4		
Support-pinned	0		🗑 ✎
Support-pinned	8.7		🗑 ✎
Support-pinned	17.4		🗑 ✎
Dt. Load	0 | 17.4	4.341 | 4.341	🗑 ✎
Dt. Load	0 | 8.7	71.685 | 71.685	🗑 ✎

Calculations taken from OptimalBeam. (n.d).

Reactions

Location: 0 (m), Force Reaction = -287.0135 (kN)

Location: 8.7 (m), Force Reaction = -436.9956 (kN)

Location: 17.4 (m), Force Reaction = 24.8162 (kN)

Shear Diagram

(Max +ve)Shear Load (kN): 287.014,

Location (m): 0.000

(Max -ve)Shear Load (kN): -374.413,

Location (m): 8.700

Moment Diagram

(Max +ve)Moment Load (kN-m): 541.767,

Location (m): 3.776

(Max -ve)Moment Load (kN-m): -380.186,

Location (m): 8.700

Calculations taken from OptimalBeam. (n.d).

Case 3 would be a symmetrically flipped version of case 2. Therefore only these two cases considered

Maximum shear and moment in case 1

$M_{ed} := 719,301\ \text{kN m}$

$V_{ed} := 413,391\ \text{kN}$

Design of beam to withstand above actions:

Material properties:

$f_{ck} := 35\ \text{MPa}$ B35 concrete

$f_{ctm} := 3,2\ \text{MPa}$ (Standard Norge, 2021, p. 29)

$E_{cm} := 34\ \text{MPa}$

$f_{yk} := 500\ \text{MPa}$ Yield strength of steel B500NC

$\gamma_c := 1,5$ (Standard Norge, 2021, p. 24)

$\gamma_s := 1,15$

$\alpha_{cc} := 1$ Recommended value. (Standard Norge, 2021, p. 34)

$$f_{cd} := \frac{\alpha_{cc} \cdot f_{ck}}{\gamma_c} = 23,333\ \text{MPa}$$ (Standard Norge, 2021, p. 34)

$$f_{yd} := \frac{f_{yk}}{\gamma_s} = 434,783\ \text{MPa}$$ (Standard Norge, 2021, p. 40)

Select rebar size as:

$\varnothing_s := 8\ \text{mm}$ Stirrup bar size 8mm

$\varnothing_l := 25\ \text{mm}$ Longditudinal bar size 25mm

$\varnothing_t := 25\ \text{mm}$ Transeverse bar size 25mm

$A_8 := \pi \cdot \varnothing_s^{\,2} = 201,062\ \text{mm}^2$

$A_{25} := \pi \cdot \varnothing_l^{\,2} = 1963,495\ \text{mm}^2$

Spacing of bars:

$$a_h := \max\left(\begin{bmatrix} 2 \cdot \varnothing_l \\ 20\ \text{mm} \end{bmatrix}\right) = 50\ \text{mm}$$ Horizontal spacing

$$a_v := \max\left(\begin{bmatrix} 1,5 \cdot \varnothing_s \\ 20\ \text{mm} \end{bmatrix}\right) = 20\ \text{mm}$$ Vertical spacing

$a_v < 32\ \text{mm}$

(Samarakoon, personal communication, 2023)

Nominal cover depth:

$c_{nom} := c_{min} + \delta c_{dev}$ (Standard Norge, 2021, p. 49) Recommended value for δc,dev i 10mm $\delta c_{dev} := 10\ \text{mm}$ (Standard Norge, 2021, p. 52)

$$c_{min} := \max\left(\begin{bmatrix} c_{min,b} \\ c_{min,dur} \\ 10\ \text{mm} \end{bmatrix}\right)$$ (Standard Norge, 2021, p. 49)

$c_{min,b} := \varnothing_s = 8\ \text{mm}$

Exposure class XC3 and c,min.b 12, 50 year construction life

$c_{min,dur} := 25\ \text{mm}$ (Standard Norge, 2021, p. 7 of National Annex)

$$c_{min} := \max\left(\begin{bmatrix} c_{min,b} \\ c_{min,dur} \\ 10\ \text{mm} \end{bmatrix}\right) = 25\ \text{mm}$$

$c_{nom} := c_{min} + \delta c_{dev} = 35\ \text{mm}$

$d := h_{beam} - c_{nom} - \varnothing_s - \frac{1}{2} \cdot \varnothing_l = 544{,}5\ \text{mm}$ Assumming one lay of reinforcement bars needed in section. If 2 layers are needed, redo calculation of depth d

$k := \dfrac{M_{ed}}{b_{beam} \cdot d^2 \cdot f_{ck}} = 0{,}173$ (Samarakoon, personal coommunication, 2023)

$k > 0{,}167$ Section must be doubly reinforced to withstand moment

$d' := c_{nom} + \varnothing_s + \frac{1}{2} \cdot \varnothing_l = 55{,}5\ \text{mm}$

$\dfrac{d'}{d} = 0{,}102$ $\dfrac{d'}{d} < 0{,}171$ Ok, compression reinforcement will yield (Samarakoon, personal coommunication, 2023)

Steel reinforcement to withstand bending moment

$M_{bal} := 0{,}167 \cdot b_{beam} \cdot d^2 \cdot f_{ck} = 693{,}171\ \text{kN m}$ (Samarakoon, personal coommunication, 2023)

$A'_s := \dfrac{M_{ed} - M_{bal}}{(d - d') \cdot f_{yd}} = 122{,}903\ \text{mm}^2$ Compressive reinforcement (Samarakoon, personal coommunication, 2023)

$A_s := \dfrac{M_{bal}}{0{,}82 \cdot d \cdot f_{yd}} + A'_s = 3693{,}627\ \text{mm}^2$ Tensile reinforcement $A_{s,req} := A_s = 3693{,}627\ \text{mm}^2$ (Samarakoon, personal coommunication, 2023)

Number of bars
Compressive side $\dfrac{A'_s}{A_{25}} = 0{,}063$ Rounds to 1 bar being needed, choose 2 bars for stability

Tensile side $\dfrac{A_s}{A_{25}} = 1{,}881$ Select 2 bars

$Spacing := \dfrac{b_{beam} - 2 \cdot c_{nom} - 2 \cdot \varnothing_s - 2 \cdot \varnothing_l}{2} = 132\ \text{mm}$

$Spacing > a_h$ Spacing between bar is sufficient

$A_{s,t} := 2 \cdot A_{25} = 3926{,}991\ \text{mm}^2$

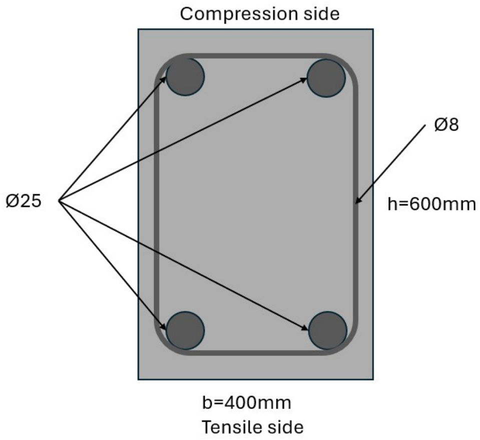
Checking minimum and maximum tensile reinforcement

$$A_{s,min} := \min\left(\begin{bmatrix} 0{,}26 \cdot \dfrac{f_{ctm}}{f_{yk}} \cdot b_{beam} \cdot d \\ 0{,}0013 \cdot b_{beam} \cdot d \end{bmatrix}\right) = 283{,}14\ \text{mm}^2$$ (Standard Norge, 2021, p. 152)

$$A_{cs} := b_{beam} \cdot h_{beam} = 2{,}4 \cdot 10^5\ \text{mm}^2$$

$$A_{s,max} := 0{,}04 \cdot A_{cs} = 9600\ \text{mm}^2$$ (Standard Norge, 2021, p. 152)

$A_{s,min} < A_{s,t}$ *and* $A_{s,t} < A_{s,max}$ OK, Reinforcement is sufficient for moment capacity



Spacing of stirrups to withstand shear

Shear envelope not considered. Design shear force from shear diagram

$\varphi := 22\ \text{deg}$

$\alpha_{cw} := 0{,}36$

$$V_{Rd,max} := \frac{\alpha_{cw} \cdot b_{beam} \cdot d \cdot \left(1 - \dfrac{f_{ck}}{250\ \text{MPa}}\right) \cdot f_{ck}}{\cot(\varphi) + \tan(\varphi)} = 819{,}725\ \text{kN}$$ (Standard Norge, 2021, p. 89)

$V_{ed} = 413{,}391\ \text{kN}$ No shear envelope

Near middle support:

$$\frac{A_{s,w}}{S_1} = \frac{V_{ed}}{0{,}78 \cdot d \cdot f_{yk} \cdot \cot(\varphi)} = 0{,}787\ \text{mm}$$

$$A_{s,w} := 2 \cdot A_8 = 402{,}124\ \text{mm}^2$$

Rearrange for S.1

$$S_1 := \frac{A_{s,w}}{\left(\dfrac{V_{ed}}{0{,}78 \cdot d \cdot f_{yk} \cdot \cot(\varphi)}\right)} = 511{,}272\ \text{mm}$$

$S_{1,max} := 0{,}6 \cdot (d - d') = 293{,}4\ \text{mm}$ (Samarakoon, personal communication, 2023)

Using minimum shear ratio to find largest spacing

$$\rho_{w,min} := \frac{0{,}1 \cdot \sqrt{\dfrac{f_{ck}}{\text{MPa}}}}{f_{yk}}$$ (Standard Norge, 2021, p. 19 of National Annex) (1)

$$\rho_w := \frac{A_{sw}}{S_{max} \cdot b_{beam}}$$ (Standard Norge, 2021, p. 156) (2)

For (1) and (2) to be equal, set them to be equal and solve for S.max

$$S_{max} := \frac{A_{s,w} \cdot \frac{f_{yk}}{\mathrm{MPa}}}{0{,}1 \cdot \sqrt{\frac{f_{ck}}{\mathrm{MPa}}} \cdot b_{beam}} = 849{,}642\ \mathrm{mm}$$

$$S'_{stirrup} := \min\left(\begin{bmatrix} S_1 \\ S_{1,max} \\ S_{max} \end{bmatrix}\right) = 293{,}4\ \mathrm{mm}$$

Select spacing 290mm

$$\boxed{S_{stirrup} := 290\ \mathrm{mm}}$$

Deflection control by span/depth ratio:

$A_{s,req} = 3693{,}627\ \mathrm{mm}^2$ $A_{s,prov} := 4 \cdot A_{25} = 7853{,}982\ \mathrm{mm}^2$

$$\rho := \frac{A_{s,req}}{b_{beam} \cdot d} = 0{,}017$$ (Standard Norge, 2021, p. 156) Shear reinforcement ratio for tension

$$\rho' := \frac{A'_s}{b_{beam} \cdot d} = 0{,}001$$ (Standard Norge, 2021, p. 156) Shear reinforcement ratio for compression

$$\rho_0 := \sqrt{\frac{f_{ck}}{\mathrm{MPa}}} \cdot 10^{-3} = 0{,}006$$ (Standard Norge, 2021, p. 127) $d = 544{,}5\ \mathrm{mm}$

$\rho_0 < \rho$

Use equation 7.16b

$K := 1{,}3$ Table 7.4N for end of contineuous one way deck. (Standard Norge, 2021, p. 128)

$$\delta_{lim} := K \cdot \left(11 + 1{,}5 \cdot \sqrt{\frac{f_{ck}}{\mathrm{MPa}}} \cdot \frac{\rho_0}{\rho - \rho'} + \frac{1}{12} \cdot \sqrt{\frac{f_{ck}}{\mathrm{MPa}}} \cdot \sqrt{\frac{\rho'}{\rho_0}}\right) = 18{,}661$$ (Standard Norge, 2021, p. 127)

$$\delta_{lim,mod} := \delta_{lim} \cdot \frac{A_{s,prov}}{A_{s,req}} = 39{,}68$$

$$\delta_{prov} := \frac{L_{beam}}{d} = 15{,}06$$

$\boxed{\delta_{prov} < \delta_{lim,mod}}$ Ok! Deflection is controlled

Move over to column
Design reinforcement of column

$G_{ed} := 1,2 \cdot G_{k,self} = 4,341 \ \frac{\text{kN}}{\text{m}}$ $\quad Q_{ed} := 1,5 \cdot q_{k,imp} \cdot \alpha_n + 1,5 \cdot \psi_{0,s} \cdot S_{k,beam} = 71,685 \ \frac{\text{kN}}{\text{m}}$

$N_{ed} := \left(G_{ed} + Q_{ed}\right) \cdot \frac{L_{beam}}{2} = 311,706 \ \text{kN}$

$h_{col} := 610 \ \text{mm}$

$b_{col} := 610 \ \text{mm}$

$A_{col} := h_{col} \cdot b_{col} = 3,721 \cdot 10^5 \ \text{mm}^2$

Same bars as for beams

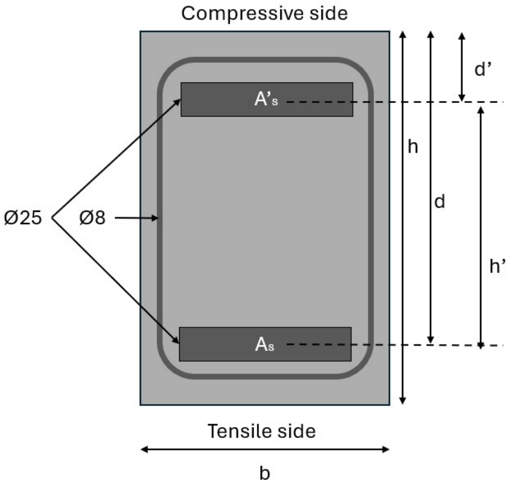
$\varnothing_1 = 25 \ \text{mm}$

$\varnothing_s = 8 \ \text{mm}$

Then d and d' are the same

$d = 544,5 \ \text{mm}$

$d' = 55,5 \ \text{mm}$



Assume no second order moment effect due to column being short.

Eccentricity

$e_0 := \max\left(\begin{bmatrix} \frac{h_{col}}{30} \\ 20 \ \text{mm} \end{bmatrix}\right) = 20,333 \ \text{mm}$ (Standard Norge, 2021, p. 83)

$M_{ed,min} := N_{ed} \cdot e_0 = 6,338 \ \text{kN m}$ $\quad M_{ed,min} < M_{ed,col}$ Ok!

The minimum moment gives a necessary reinforcement less than 1 but greater than 0. Thus we would need some reinforcement, but not quite as much as calculated below. For stability, 4 bars should be used regardless with one in each corner. Furthermore, moment due to wind action and seismic action should be considered. For simplicity, the design moment will be set to 300kNm. The true value of the moment can be calculated using the previously calculated wind velocity preassure togheter with a design seismic load on the column.

For now, consider moment on column as 300kNm

$M_{ed,col} := 300 \ \text{kN m}$

Consider unbraced column. The same column which suppors the vertical actions also provide resistance against horizontal (wind) actions, the column can be considered unbraced (Elliot, 2017, p. 7)

$h' := h_{col} - 2 \cdot c_{nom} - 2 \cdot \varnothing_s - 2 \cdot \frac{1}{2} \cdot \varnothing_1 = 499 \ \text{mm}$

$\frac{h'}{h_{col}} = 0,818$

Then

$n := \frac{N_{ed}}{f_{cd} \cdot A_{col}} = 0,036$ (Standard Norge, 2021, p. 70) $\quad m := \frac{M_{ed}}{f_{cd} \cdot A_{col} \cdot h_{col}} = 0,136$ (Samarakoon, personal communication, 2023)

Consider m-n diagram for height ratio of 0.8, n = 0.04 and m = 0.14

$\omega := 0,15$ (Samarakoon, personal communication, 2023)

$A_{s,col} := \frac{\omega \cdot A_{col} \cdot f_{cd}}{f_{yd}} = 2995,405 \ \text{mm}^2$ (Samarakoon, personal communication, 2023)

$\frac{A_{s,col}}{A_{25}} = 1,526$ Use two bars

$A_{s,col,prov} := 2 \cdot A_{25} = 3926,991 \ \text{mm}^2$

$A'_{s,col,prov} := A_{s,col,prov} = 3926,991\ \mathrm{mm}^2$ Tension and compression reinforcement are symmetric

$\varnothing_{min} := 10\ \mathrm{mm}$

$\varnothing_l > \varnothing_{min}$ Ok! (Standard Norge, 2021, p. 20 of National Annex)

Minimum and maximum reinforcement

$$A_{s,min,1,col} := \min\left(\begin{bmatrix} \dfrac{0,2 \cdot A_{col} \cdot f_{cd}}{f_{yd}} \\ \dfrac{0,5 \cdot N_{ed}}{f_{yd}} \end{bmatrix}\right) = 358,462\ \mathrm{mm}^2$$

(Standard Norge, 2021, p. 20 of National Annex)

$$A_{s,min,col} := \max\left(\begin{bmatrix} 0,01 \cdot A_{col} \\ A_{s,min,1,col} \end{bmatrix}\right) = 3721\ \mathrm{mm}^2$$

(Standard Norge, 2021, p. 20 of National Annex)

$A_{s,col,tot} := A_{s,col,prov} + A'_{s,col,prov} = 7853,982\ \mathrm{mm}^2$

$A_{s,col,tot} > A_{s,min,col}$ *OK*

$A_{s,max,col} := 0,08 \cdot A_{col} = 29768\ \mathrm{mm}^2$ (Standard Norge, 2021, p. 162)

$\boxed{A_{s,col,tot} < A_{s,max,col}}$ Ok!

Transeverse reinforcement;:

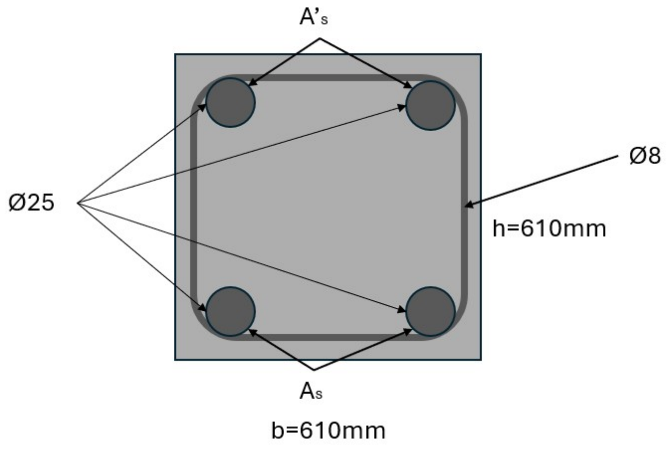
$$\varnothing_{s,min} := \max\left(\begin{bmatrix} 6\ \mathrm{mm} \\ \dfrac{1}{4} \cdot \varnothing_l \end{bmatrix}\right) = 6,25\ \mathrm{mm}$$

(Standard Norge, 2021, p. 162)

$\varnothing_s > \varnothing_{s,min}$

$$S_{cl,t,max} := \min\left(\begin{bmatrix} 15 \cdot \varnothing_l \\ h_{col} \\ b_{col} \\ 400\ \mathrm{mm} \end{bmatrix}\right) = 375\ \mathrm{mm}$$

(Standard Norge, 2021, p. 20 of National Annex)



Checking axial capacity of designed column:

Neutral axis in center.

$N_{Rd} := f_{cd} \cdot A_{s,col,prov} \cdot b_{col} \cdot h_{col} + f_{sc} \cdot A'_{s,col,prov} + f_{sc} \cdot A_{s,col,prov}$

$f_{sc} := \varepsilon_{c2} \cdot E_{rfc}$

(Samarakoon, personal communication, 2023)

$E_{rfc} := 200 \text{ GPa}$ For reinforced concrete. (Standard Norge, 2021, p. 41)

$\varepsilon_{c2} := 0,002$ (Standard Norge, 2021, p. 29)

$f_{sc} := \varepsilon_{c2} \cdot E_{rfc} = 400 \text{ MPa}$ (Samarakoon, personal communication, 2023)

$N_{Rd} := f_{cd} \cdot A_{col} + f_{sc} \cdot A'_{s,col,prov} + f_{sc} \cdot A_{s,col,prov} = 11823,926 \text{ kN}$

$N_{ed} = 311,706 \text{ kN}$

$\boxed{N_{Rd} > N_{ed}}$ Ok!

Notice that the axial capacity is much higher than the design load. The columns could possibly be more economical by reducing the cross sectional area. One proposal (without calculation) would be to use a 300x300 column. Steel reinforcement might need to increase, but there is sufficient space in the cross section to increase steel area. The initial dimension of 610x610 columns was decided due to restraint in the Revit 2023 program. Limitations excluded any other column dimensions. Thus, the 610x610 was decided to be used so that the calculations matches the Revit model.

For further research, one could consider the column to resist axial force and biaxial bending. However, for the simplicity, the column is only desiged to resist the axial compression from snow load, live load and dead load. The wind action and seismic action is considered to be carried by facade,

The calculation has also been checked with Ø16 and Ø12 bars. The minimum reinforcement needed is close to the calculated reinforcement, no matter which bar size is used. The cross section of the column is determining factor for the reinforcement area needed in the design.

Pricing of tradiitional cast concrete according to numbers from Total Betong:

Volume of elements:

Columns: 610x610 mm $l_{col} := 610\ \mathrm{mm}$ $H_{col} := 4\ \mathrm{m}$

Beams: 400x600 mm $b_{beam} := 400\ \mathrm{mm}$ $h_{beam} := 600\ \mathrm{mm}$ $L_{beam,full} := 2 \cdot L_{beam} = 16{,}4\ \mathrm{m}$

Slabs: 225 mm thickness $t_{slab} := 225\ \mathrm{mm}$ $L = 27\ \mathrm{m}$ $B = 17{,}4\ \mathrm{m}$

$$V_{beam} := b_{beam} \cdot h_{beam} \cdot L_{beam,full} = 3{,}936\ \mathrm{m}^3$$

$$V_{col} := l_{col} \cdot l_{col} \cdot H_{col} = 1{,}488\ \mathrm{m}^3$$

$$V_{slab} := t_{slab} \cdot L \cdot B = 105{,}705\ \mathrm{m}^3$$

Number of elements:

$n_{col} := 9 \cdot 3 = 27$ 9 columns per floor, 3 floors

$n_{beam} := 3 \cdot 3 = 9$ 3 beams per floor, 3 floors

$n_{slab} := 1 \cdot 3 + 1 = 4$ 1 slab per floor, 3 floors, plus foundation

$$V'_{concrete,total} := V_{beam} \cdot n_{beam} + V_{col} \cdot n_{col} + V_{slab} \cdot n_{slab} = 498{,}431\ \mathrm{m}^3$$

Round to 500 m3 for easier calculation and extra concrete in case of on-site errors

$$\boxed{V_{concrete,total} := 500\ \mathrm{m}^3}$$

Steel reinforcement needed:

$\rho_{steel} := 7850\ \frac{\mathrm{kg}}{\mathrm{m}^3}$ (Standard Norge, 2021, p. 40)

Beams:
4Ø25 along the beams length

$$V_{s,beam,r} := 4 \cdot A_{25} \cdot L_{beam,full} = 0{,}129\ \mathrm{m}^3$$

$$n'_{stirrup,beam} := \frac{L_{beam,full}}{s_{stirrup}} = 56{,}552$$

Rounds to 57 stirrups per beam

$$n_{stirrup,beam} := 57$$

Length of stirrups:

$$L_{stirrup,beam} := 2 \cdot \left(h_{beam} - 2 \cdot c_{nom}\right) + 2 \cdot \left(b_{beam} - 2 \cdot c_{nom}\right) = 1{,}72\ \mathrm{m}$$

$$V_{s,beam,r,2} := A_8 \cdot L_{stirrup,beam} \cdot n_{stirrup,beam} = 0{,}02\ \mathrm{m}^3$$

Volume of steel in all beams is then:

$$V_{steel,beam,total} := n_{beam} \cdot \left(V_{s,beam,r,2} + V_{s,beam,r}\right) = 1{,}337\ \mathrm{m}^3$$

Columns:
4Ø25 in all columns

$V_{steel,col,r} := 4 \cdot A_{25} \cdot H_{col} = 0{,}031\ m^3$

Stirrups placed at 375mm from eachother

$$n'_{stirrup,col} := \frac{H_{col}}{S_{cl,t,max}} = 10{,}667$$

Round to 11 stirrups

$n_{stirrup,col} := 11$

Stirrup length, simplify as perfect rectangular stirrup. Realistically it should be a rounded rectangle with slighly less circumfrence

$L_{stirrup,col} := 4 \cdot \left(h_{col} - 2 \cdot c_{nom}\right) = 2{,}16\ m$

$V_{steel,col,r2} := n_{stirrup,col} \cdot A_8 \cdot L_{stirrup,col} = 0{,}005\ m^3$

Total in all columns:

$V_{steel,col,total} := n_{col} \cdot \left(V_{steel,col,r} + V_{steel,col,r2}\right) = 0{,}977\ m^3$

Amount of steel reinforcement needed in kg:

$W'_{steel,total} := \rho_{steel} \cdot \left(V_{steel,beam,total} + V_{steel,col,total}\right) = 18163{,}895\ kg$

$\boxed{W_{steel,total} := 18200\ kg}$

For use in cost calculation of steel, use rounded number to 18200kg steel

Numbers are further used in figure 37