



# **PREFABRICATED FOUNDATIONS FOR HOUSING**

## **APPLIED TO ROOM MODULES**

DOCTORAL THESIS

By:

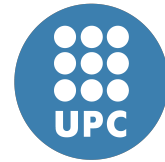
**ESTER PUJADAS GISPERT**

Supervised by:

**PROF. DR. JOSEP IGNASI DE LLORENS**

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Barcelona, November 2015



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A thesis submitted in fulfilment of the requirements for the degree of Doctor of Architecture at the UPC University.

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“Ultreia!!”: Keep going! Walk further! This was an old pilgrim greeting along the Camino de Santiago, a long trail that crosses Spain to Santiago de Compostela. Along that route, I learned a lot about myself and life. This thesis have been a kind of path for me, not through fields, villages, cites or mountains, but through knowledge.

## Acknowledgments

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I am absolutely sure that this thesis would not have been the same without their help.

Ester Pujadas



## **Abstract**

Room module buildings have been the subject of extensive literature, but few buildings have actually been built. However, the numbers are now high enough to carry out an on-site analysis, in order to confirm or refute the expectations of fully or nearly fully prefabricated structures. It was surprising that traditional or on-site foundations were used for this kind of highly industrialized building, instead of taking advantage of the benefits of prefabrication. In some cases, the fact that the foundations were not prefabricated led to problems that had an impact on the construction schedule, costs and quality of the entire building.

Information was gathered on room modules housing buildings built in Catalonia constructed during or after 2008. Information was also gathered on prefabricated and semi-prefabricated foundations available on the market that could be implemented to these buildings. The person/s responsible in each building was asked why foundations were not prefabricated. Companies and others involved in the construction of foundations on-site, semi-prefabricated foundations and prefabricated foundations were also asked this question. Then, three foundations were selected to analyse the feasibility or not of precast foundations in room module buildings studying economic costs, the embodied energy and CO<sub>2</sub> equivalent emissions. It was realised that the conclusions of the thesis were not only applicable to this specific type of building, but also to other prefabricated buildings.

In Spain, basically a foundation is chosen because of its initial price. This vision of the work is partial. But if the vision were more general, considering all the items of the work even the expensive unforeseen events, its final quality-durability, to be on time, the accuracy and the environmental issues, the scale would tip in favour depending on the case. It is important to have in mind that every foundation has an optimal application scope that makes it competitive. But it is true that there is not much variety of precast foundations systems for housing in Spain, there is a big misinformation about prefabricated foundations and semi-prefabricated foundations and a lack of acceptance, confidence and interest to use them that will be approached next.

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# 1. Introduction. Objectives. Method

## 1.1. Introduction

The Spanish property bubble (1997-2006) [Campos, 2008, p. 20] had a major impact on the construction sector. Construction had extended "*beyond its possibilities*", which resulted in a surplus of empty dwellings that the market could not absorb. In addition, demand for new construction and prices both tumbled.

During the years of the property bubble, the rate of construction work was high. However, in most cases, the high activity did not lead to optimization or reconsideration of the construction methods used in Spain to date, "*But to build in a traditional way, but without craftspeople, and to promote signature buildings*" [Salas, 2009].

In this slightly disheartening context, some companies emerged that set out to prefabricate dwellings, to offer a product with a better price-quality ratio. They assured that prefabricated dwellings would be faster to build, reduce unexpected costs and delays, cut the accident rate in the sector, improve the working conditions of workers, and would be more sustainable, among other factors.

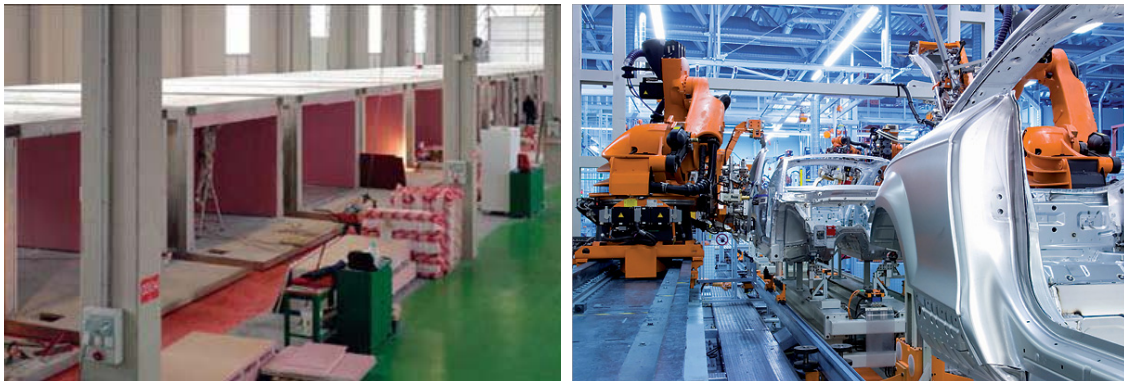


Figure 1. Prefabricated room module buildings. These are highly industrialized buildings. [http://territori.gencat.cat/web/.content/home/12\\_butlletins/butlleti\\_d\\_innovacio\\_i\\_recerca\\_num\\_4-x/imatges/04/incasol\\_noticia\\_1\\_imatge\\_2.jpg\\_646983608.jpg](http://territori.gencat.cat/web/.content/home/12_butlletins/butlleti_d_innovacio_i_recerca_num_4-x/imatges/04/incasol_noticia_1_imatge_2.jpg_646983608.jpg) Figure 2. Their production could be compared to car manufacture: streamlining processes, high productivity, precision, mechanized techniques and mass construction, among other factors <http://www.audiworld.com/news/07/ingolstadt-plant/production/header.jpg>

In recent years, room module buildings have been constructed in Catalonia. It was decided to take advantage of this circumstance to study prefabs in the field. This thesis began by studying a

specific problem found with room module buildings, which will be described below. The conclusions of the thesis are not only applicable to this specific type of building, but also to other prefabricated buildings.

It was surprising that traditional or cast-in-place foundations were used for this kind of highly industrialized building, instead of taking advantage of the benefits of prefabrication. In some cases, the fact that the foundations were not prefabricated led to problems that had an impact on the construction schedule, costs and quality of the entire building.



**Figures 3 & 4. These are some of the foundations that are constructed for room module buildings. Figure 3 shows a ground slab constructed on-site. Figure 4 illustrates an isolated footing [Jiménez, 2010], which was also built on-site.**

A clear example is that of A1-14 (p. 79 to 80). In this case, the foundations were constructed on-site, and connectors were welded onto the foundations. However, when the prefabricated modules arrived at the construction-site, it was found that they did not fit on the connectors. What had gone wrong? The connectors were not in exactly the right position.

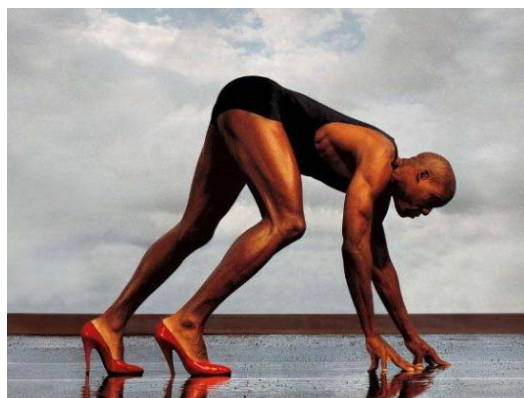


**Figure 5. The connectors were cut off using an angle grinder, because they were not positioned in exactly the right place (A1-14). Figure 6. Prefabricated pads were positioned over the foundations that had been constructed on-site. These prefabricated pads had the connectors set in place in the factory (A1-16).**

In fact, works constructed on-site tend to be less accurate and precise than prefabricated constructions [Tectónica, 1997]. This may lead to problems of dimensional tolerance between the on-site and prefabricated works. In the case of A1-14, construction was halted for several days to find the right solutions and implement them (Figure 5). However, stopping construction works has a cost, as will be explained later in Chapter 6 (Data).

In other cases studied, to avoid these kinds of dimensional problems, the foundations were either semi-prefabricated or a prefabricated element with the connectors set out in the factory was placed over the foundation (Figure 6). Normally, the mechanisms for positioning these elements are laborious, and have a considerable impact on the construction schedule and final costs of the construction work.

To illustrate the significance of this problem, I would like to refer to an image from an advertisement that came out several years ago. The advert showed a runner in the starting position. The runner had probably trained hard and was in shape, but he was wearing high-heeled shoes. Unfortunately, he had not chosen the right footwear to achieve his full potential in the race. He might even have injured himself. The result of this unfortunate choice would have had an impact on the runner's objective.



**Figure 7. This runner has not chosen the right footwear to achieve his full potential in the race.**

<http://www.alasparavolar.es/tag/publicidad-efectiva/>

A similar situation occurs when unsuitable foundations are used. A lot of energy can be invested in making the building faster to build, higher quality, cheaper and more sustainable, among other factors. However, an inappropriate choice can delay the entire construction work, lead to the emergence of numerous incidental items that increase construction costs, decrease the quality of the end product, and cause a series of problems that will be explained later. To what extent does it make sense to prefabricate a dwelling if some of the effort is lost when unsuitable foundations are used?

In addition, given the problem of dimensional tolerances between cast-in-place and prefabricated works, it is not clear why prefabricated foundations are not used for prefabricated buildings, particularly as prefabricated foundations are available on the market. However, there is not as much variety in the Spanish market as in other European countries, such as the United Kingdom or Holland.

A literature search was carried out to investigate why prefabricated foundations are not used for dwellings. However, very little information was found on this subject. One of the most direct references was made by Bujang Kim Huat, a lecturer at Universiti Putra Malaysia. He stated that *"Cost is usually the most important factor affecting the choice of a foundation system and the nature of construction, but where rapid construction and quality assurance of construction are sufficiently important, these may be the factors which tip scales in favour of precast foundation system (...) The answer to this question does not lie in technology, but perhaps in the human psyche, which resists change even when the change is known to be to one's advantage"* [Huat, 2003].

This thesis examines why prefabricated foundations are not used in dwellings, and whether it is feasible and sensible to use them. The aim was for the research to have a positive impact on future buildings in Spain.

The thesis is divided into eight chapters. Below, the objectives, hypothesis and the method are described. In Chapter 2 (Background), the benefits of prefabricated foundations are examined, as are the reasons why are not the foundations of dwellings precast. In the Chapter 3 (Case studies), room module buildings in general, and the cases or buildings under analysis, are described. In Chapter 4 (Foundations), some of the prefabricated foundations and semi-prefabricated foundations that are available in the Spanish and international markets and can be used for dwellings are discussed. In Chapter 5 (The reasons given for not using prefabricated foundations in the case studies), reasons for avoiding prefabricated foundations are presented. In Chapter 6 (Data), three real foundations that were cast-in-place or semi-prefabricated are compared with their prefabricated versions. The viability of precast foundations is calculated from different perspectives: economic cost, energy cost and greenhouse gas emissions. In Chapter 7 (Discussion of the results), the information and data are discussed. Finally, in Chapter 8 (Conclusions), the conclusions of this research are presented, along with the factors that would facilitate the introduction of precast foundations for Spanish dwellings, and potential future research related to this thesis.



## 1.2. Objectives

### a) Main objectives

- Discover why aren't precast foundations used in prefabricated dwellings.
- Analyse the feasibility of precast foundations for prefabricated housing (through the study of room module buildings).
- Analyse whether precast foundations are more expensive than those that are cast-in-place in Spain.
- Analyse whether precast foundations are more environmentally friendly than those that are cast-in-place. Calculate the embodied energy (MJ) and greenhouse gas emissions (kilogrammes of CO<sub>2</sub> equivalent) in the construction of foundations.

### b) Additional objectives

- Record existing prefabricated and semi-prefabricated foundations.
- Influence future constructions.

## 1.3 Hypothesis

- Prefabricated foundations can be used in room module buildings for housing.
- It is economically viable to use precast foundations in room module buildings for housing in Spain.
- Precast foundations have less embodied energy and emit less greenhouse gas emissions.

## 1.4. Method

### a) Gathering information about room module buildings and creating a data sheet on each one

Information was gathered on prefabricated room module buildings of various types built in Catalonia. An Internet and literature search was carried out to find examples of room module buildings that met the following requirements:

- Constructed during or after 2008
- Designed as dwellings
- Room module buildings
- Constructed with wood, steel, concrete or a combination of these materials

Then, people who were involved with the construction works were contacted and asked for information. If possible, the construction site was visited, particularly during the stage in which



the foundations were built or when the modules were placed over the foundations. Examples that did not meet the above criteria or cases in which the informant did not provide enough information for the study were excluded.

In all the cases selected, as much information as possible was gathered, and then a data sheet was created to summarize each case. These sheets can be found in Appendix 1 and contain the following information:

- Light room module ( $< 4\text{kN/m}^2$ ) or heavy room module ( $\geq 4\text{kN/m}^2$ ).
- Whether the module transmits point or distributed loads over the foundations or beams.
- Type and materials of the module structure.
- Weight of the module ( $\text{kN/m}^2$  floor surface).
- Deformability. T1: modules comprised of frames with rigid junctions without building envelopes or with flexible building envelopes that are not associated with the structure and do not restrict deformation. T2: modules comprised of panels or frames with rigid junctions, with deformation restricted by building envelopes. [DB SE, 2009]
- Year that the construction was completed.
- Ground floor plan, building section / elevation and foundation plan. In some cases also details and images.
- Determining factors in the construction of foundations.

#### **b) Gathering information about prefabricated foundations available on the market**

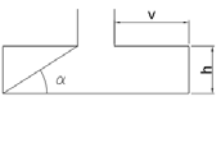
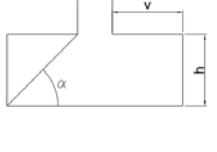
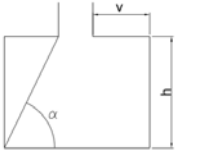
A literature search was undertaken, catalogues and the Internet were consulted, and Spanish and international experts were asked about prefabricated foundations. In addition, factories and sites where prefabricated foundations are produced were visited.

Foundations were selected with the following characteristics:

- They could be used with prefabricated dwellings.
- They are prefabricated or semi-prefabricated.
- They are mainly made of precast concrete, steel, wood, plastic or a combination of these.
- They are made by Spanish or international manufacturers.

A data sheet was created to summarize information on each of these prefabricated foundations. These sheets can be found in Appendix 2 and contain the following information:

- A description of the foundation.
- Shallow or deep foundation [DB SE-C, 2007].
- Prefabricated or a semi-prefabricated foundation.
- The main material or materials used in the foundation.
- The load that the foundation can bear (kN or kN/m).
- The type of loads that the foundation transmits to the soil: point or distributed.
- Type of soil according to the table bellow.

Soils	Soft	Medium	Hard
<b>Suitable soil</b>	Soft clays Soft silts Silty clays Clayey silts	Compacted clays Medium sand	Carbonated clay Compacted sand Gravel Rock
<b>Permissible pressure</b>	0.1 – 0.15 (or 0.20) N/mm <sup>2</sup>	0.15 (or 0.20) – 0.30 N/mm <sup>2</sup>	≥ 0.30 N/mm <sup>2</sup>
<b>Soil deformability</b>	$E < 10 \text{ N/mm}^2$	$10 \leq E \leq 100 \text{ N/mm}^2$	$E > 100 \text{ N/mm}^2$
<b>Type of footing</b>			
<b>Dimensions</b>	$v > 2h$ $\alpha < 27^\circ$	$0.5h \leq v \leq 2h$ $27^\circ \leq \alpha \leq 63^\circ$	$v < 0.5h$ $\alpha > 63^\circ$

**Table 1. Adequacy of shallow foundations.**

- The most common measurements for this foundation.
- Its own weight.
- The dimensional tolerances. What deviation is permitted when this foundation is constructed?
- The stages in the construction of this foundation.
- The machinery required to assemble the foundation at the construction-site.
- The advantages of using this foundation.
- The disadvantages of using this foundation.
- Additional information.

- Whether the foundation has specific, fixed measurements and cannot be adapted / Whether the precast foundation is flexible and can be adapted to each case / Whether the precast foundation is made to measure for a specific case.
- Whether the height of the foundation can be adjusted once it has been constructed on-site.
- How many workers who are specialized in the foundation are required to construct it?
- What resources are required to construct it? None / water and / or electricity.
- Is noise generated when the foundation is constructed? No / Yes, but only a little; the operators do not need to wear headphones / Yes, and the operators must wear headphones.
- Is it difficult to lay this foundation when there is a water table? No / No, if measures are taken (for example, an impermeable membrane is used) / Yes, there will be difficulties.
- Are obstacles (such as rock) a problem when this foundation is laid? No / No, not if measures are taken (for example, the site is first excavated) / Yes, obstacles do cause problems.
- Does the fact that the soil may freeze represent a problem? No / No, not if measures are taken (the site is excavated to a certain depth) / Yes, it is a problem.
- Any other problems that may occur when the foundation is assembled or semi-prefabricated.
- Is this foundation reusable? No / Partly / Depends on the case / Yes

### **c) Gathering reasons why foundations are not prefabricated**

For this section, the person/s responsible in each case was contacted and asked why prefabricated foundations had not been used. Normally, the informants were architects, engineers, construction companies, the owner and/or geologists, depending on the case. Companies and others involved in the construction of foundations on-site, semi-prefabricated foundations and prefabricated foundations were also asked.

### **d) Selecting case studies**

Three case studies were selected: A1-10, A1-16 and A1-14. As mentioned previously, this research began by studying a problem that affected room module buildings. However, the topic of the thesis covers most prefabricated buildings.

The three selected case studies met the following criteria:

- Constructed during or after 2008.



[Sastre, 2015]. Then, the dimensions were determined using the works *Estructuras de formigó armat: predimensionament i càlcul de seccions* (Reinforced steel structures: determining dimensions and calculating sections) [Gómez, 2013] and *EHE-08. Instrucció de hormigón estructural* (Instructions for structural concrete) [EHE-08, 2011]. The precast piles were calculated using the *Documento Básico SE-C Seguridad estructural. Cimientos* (Basic Document SE-C Structural Safety. Foundations) [DB SE-C, 2007].

- The dimensions of the footing of case A1-14 were determined using a formula from the book *Cimentaciones de hormigón armado* (Reinforced concrete foundations) [Jiménez, 2010]. In addition, in the case of A1-14, we also used the *Normativa de construcción sismoresistente. Parte general y edificación* (Regulations for earthquake-resistant construction. General part and construction) (NCSE-02) [NCSE-02, 2009].

#### **h) Calculate the budget for the selected parts (on-site)**

The measurements and budgets were provided for the three cases. However, to standardize, they were recalculated using the BEDEC database [ITeC, 2015] and prices for 2015. In fact, many of the items from the original budgets proceeded from this database.

It was considered that excavated soil is transported 30 km to other construction works and reused. In addition, it was assumed that waste is transported 30 km to licensed facilities for soil and waste [Kellenberger, 2009]. Existing soil and waste transport items from the database were adjusted to a distance of 30 km. (For more information please see Appendix 3).

#### **i) Calculate the budget for the selected parts (prefabricated)**

Most of the prefabricated budget items were also found in the BEDEC database [ITeC, 2015], as many of the tasks are the same as those required to build foundations on-site, such as excavation and transport of soil. The database only includes a few items for precast foundations, so the information was complemented with the following data. (For more information please see Appendix 3):

- The BEDEC database does not include precast concrete piles of square section. Therefore, this item from BEDEC database was considered: "*Driving precast concrete piles, with a diameter of 30 cm*". Only the price of the precast pile ( $\varnothing$  30 cm) has been changed of this item for the price of a precast pile (30 x 30 cm). An ABB joint was also included. Data on the precast pile (30 x 30 cm) was provided by a Spanish precast pile

company. It was also considered that breaking a precast pile of circular section is similar in costs to breaking a precast pile of square section.

- For linear elements in the cases of A1-10 and A1-16 (semi-ground beam, precast ground beams, precast tie beams [Jiménez, 2010], precast pads and precast continuous footings, Spanish and international companies were asked how much it would cost to make a 10-m beam that could support a load of 110.89 kN/m. The average of the figure given for a rectangular section beam by two Spanish companies was used. However, the cost of each foundation will vary depending on several factors, including the quantity of reinforcing steel that is used, the company that prefabricates it and its dimensions. Nevertheless, whatever the foundation is like, there will always be some fixed costs (production, factory operation, design and various others) that will be higher than the cost of the materials themselves.
- For the small precast footings used in A1-14, a prefabricated model in stock in Spain could not be found. Consequently, a factory that uses molds for pillars was asked how much it would cost to make a precast footing. Out of all the data provided by the company, only the price of the small footing was considered. The costs of transport or assembly were not taken into account.
- It was considered that precast foundations were transported 155 km from the factory to the building site [QPA, 2008].
- To calculate the assembly of precast foundations, it was assumed that they were equal to other elements in the BEDEC database. For example, the assembly of precast foundations of projects A1-10 and A1-16 (except piles) was similar to that of precast beams: they are all linear precast foundations and some are  $\geq 5$  tonnes. It was assumed that the assembly of the precast isolated footing of project A1-14 was similar to that of a precast inspection chamber. Its weight is  $< 5$  tonnes.
- Like the foundations on-site, it was considered that soil is transported 30 km to other construction works and reused. In addition, it was considered that waste is transported 30 km to licensed facilities for soil and waste [Kellenberger, 2009]. Existing soil and waste transport items were adjusted from the database to a distance of 30 km.

#### **j) Calculate the kilogrammes of reinforcing steel**

The amount of steel affects the environmental impact of the foundation. To calculate the reinforcing steel used in the selected parts of foundations constructed on-site, the documents provided by those responsible for the construction were consulted. However, calculations had to be made to determine the amount of reinforcing steel used in precast foundations. They were

made on the basis of regulation *EHE-08. Instrucción de hormigón estructural* (EHE-08. Instructions on structural concrete) [EHE-08, 2011].

#### **k) Calculate the environmental impact**

The environmental impact of the selected foundation parts was calculated on the basis of two indicators: "*Cumulative energy demand: material production embodied energy*; and *global warming potential (CO<sub>2</sub> equivalent)*. *Global warming is the contribution to atmospheric absorption of infrared radiation leading to increase in global temperature. The impact method has been developed by the Intergovernmental Panel Climate Change (IPCC), is based on a 100 year scenario and reported as Carbon Dioxide equivalents*" [<http://www.grantadesign.com/products/data/ecoinvent.htm>, 2015] (Accessed: 05/11/2015). Calculations were carried out using the SimaPro software [SimaPro, 2015], with the Ecoinvent v3 database [Ecoinvent, 2015].

The extraction, production and transport of materials from the production site to the construction site or factory were taken into account. The following distances for materials were considered [Kellenberger, 2009]: cement (75 km), admixtures (100 km), gravel and sand (45 km) and reinforcing steel (131 km), construction steel (188 km) and sawn timber (48 km).

The foundation construction processes and the associated machinery were also considered, as well as the depreciation of mold or formwork. In the case of precast foundations, the transport of the foundation from the factory to the construction site [QPA, 2008] and its assembly was also taken into account.

The environmental impact of each of the items in the budgets explained above in sections h and i was also calculated. To calculate what each item included, the specifications in the BEDEC database were consulted. The diesel consumption of construction work machinery (MJ) was calculated from BEDEC database. The lorry consumption was taken from the Ecoinvent v3 database [Ecoinvent, 2015]. The proportioning of concrete was provided by two Spanish concrete companies, and verified with the regulations [EHE-08, 2011]. The impact of admixtures was taken from <http://efca.info/publications.html> (Accessed: 25/10/2015). The impact of materials and processes was looked up in the Ecoinvent v3 database. All of this data was calculated with SIMAPRO software [SIMAPRO, 2015]. Therefore, MJ and kilogrammes of CO<sub>2</sub> equivalent were associated with each construction item. The values for all the budget items were then added together to obtain the environmental impact.

The Ecoinvent database only includes one precast concrete that is reinforced and not specifically designed for foundations. Therefore, the environmental impact of precast concrete for foundations was calculated. To do this calculation, the materials, processes, machinery and time needed to construct a precast isolated footing of 1.60 x 1.60 and a precast beam of 0.4 x 0.55 x 10.00 metres were taken into account. The beam was not designed for foundations, but was constructed in the same way. The impact of the mold was considered, and a depreciation rate of 250 uses was established. In addition, the distances of the materials were used, drawn from Kellenberger [Kellenberger, 2009]. The rebar was not considered, as it is calculated separately for each foundation. It was found that the concrete of the precast beam and the isolated footing had a similar impact. Most precast foundations in the three cases would have been produced in molds similar to those of precast beams. Therefore, the environmental impact of prefabricated beams (MJ and kilogrammes of CO<sub>2</sub> equivalent) was considered for all precast foundations in the three cases.

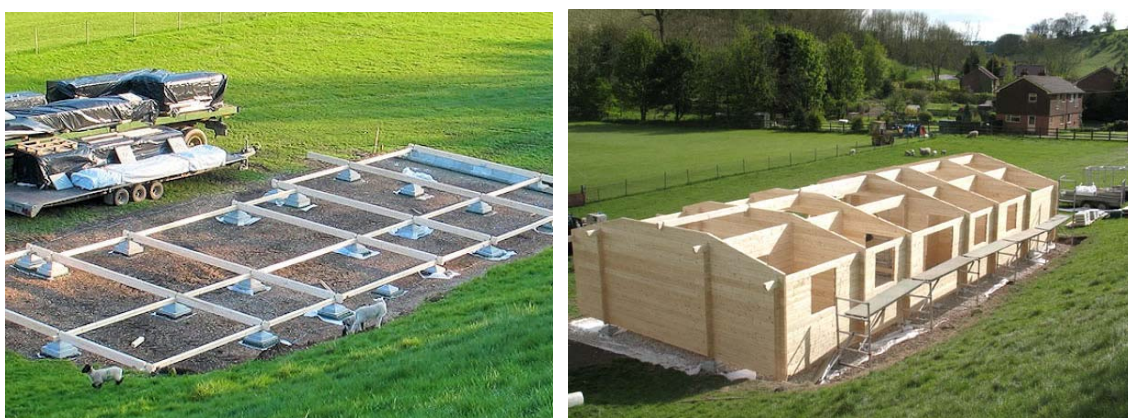


## 2. Background

### 2.1. Which factors benefit from prefabricated foundations?

#### a) Low-rise buildings

*"For tall and heavy buildings, prefabricating the foundation components may not be economical due to the high loads involved. (...) It is contended that industrialization of foundations for low-rise light-weight buildings is technically feasible and can lead to considerable savings"* [Krishna, 1972, p. 4 & 6].



Figures 9 & 10. A precast foundation for one or two floor dwellings that can currently be found on the market. [https://www.swiftfoundations.co.uk/swift\\_plinth/](https://www.swiftfoundations.co.uk/swift_plinth/)

#### b) Volume

*"Precast foundation system is the most suitable alternative for mass scale construction particularly in residential schemes"* [Huat, 2003]. *"These advantages are more pronounced when the systems are installed in large volumes"* [Wren, 2012, p. 1344 & 1345].

#### c) Speed

Prefabricated foundations reduce the construction time: *"Components are manufactured off-site and installed on-site with a significant time saving on traditional house foundation construction methods."* [Wren, 2012]. On the one hand, you do not have to wait for the concrete to reach the required resistance. *"Another precondition was that making the foundation could be made as fast as possible. For these reason a casted foundation made of concrete was not preferred, because this takes several days to build and cure"* [Moonen and Hermans, 2013, p.14]. On the other hand, construction of the foundation is not halted due to bad weather: *"A major justification for industrialized foundations is the time delay resulting from inclement weather."*

[Krishna, 1972, 4]. In addition, *"all the parts arrive on-site in a completed state, and practically the only thing that needs to be done is join them together. The time that is saved can be used by development companies to return any bank loans they have taken out, and reduce their financial exposure. (...) This also reduces the time during which neighbours may be affected by the construction work, and cuts down on related transport"* [López, 2015].



**Figure 11.** *"The drawings alone for an average housing development have been speeded up by at least 500% due to this software and a typical phase of a housing site, which would have taken an engineer 2 days to complete all 3 processes, now takes about ½ hour."* [<http://www.van-elle.co.uk/Downloads/Smartfoot%20Brochure.pdf>, 2015] **Figure 12.** An automatic rebar bending machine. The machinery has high performance and precision. **Figure 13.** *"All the parts arrive on-site in a completed state, and practically the only thing that needs to be done is join them together."* [<http://www.van-elle.co.uk/Downloads/Smartfoot%20Brochure.pdf>]

#### d) Cost

*"The price of prefabrication is fixed, and therefore the costs are more controlled"* [López, 2015]. In addition, *"reduce costs when resources are scarce, or remote areas"* [CRC Construction Innovation, 2007]. Viswanath stated that industrialization of foundations could cut the costs of dwellings and make them more affordable: *"Furthermore, industrialized foundations which result in over-all savings can help industry to produce low-cost houses so urgently needed for low-income groups"*. [Krishna, 1972, p. 8].

#### e) Quality

*"In general, prefabricated items are quality products that have been checked by the factory. Staff are specialized, and the materials are of better quality, as is the construction process. There are less possibilities of human error on-site, as each part's position is marked. As a result, the product offers more certainty in construction times, costs and quality, is more durable, and leads to fewer unexpected incidents"* [López, 2015]. *"Accuracy is another major benefit (...) (+/- 3mm) and the software has significantly reduced the margin for human error particularly"* [<http://www.van-elle.co.uk/Downloads/Smartfoot%20Brochure.pdf>, 2015].



Figure 14. Staff are specialized. <http://www.van-elle.co.uk/Downloads/Smartfoot%20Brochure.pdf>

Figure 15. Each part's position is marked. Figure 16. "Accuracy is another major benefit" [\[http://www.van-elle.co.uk/Downloads/Smartfoot%20Brochure.pdf, 2015\]](http://www.van-elle.co.uk/Downloads/Smartfoot%20Brochure.pdf)

#### f) The human factor

Prefabricated buildings provide "better working conditions, staff have less risk of accident and the work is more stable, with learning and promotion opportunities (...) In addition, fewer construction groups are involved, which simplifies management" [López, 2015]. The volume of work is more constant: "Industrialized foundations can help even out the seasonal fluctuations in the housing industry. Because of the lesser construction activity, builders hire less labour during winter. However, they have to hire extra labour during the remaining months" [Krishna, 1972, p. 6].

#### g) Transport

No specific information was found on how transport affects prefabricated foundations. However, information was found on how transport affects prefabricated components and modular dwellings. In the University of Bath's *Inventory of Carbon & Energy* it is stated that the "delivery distance of precast is 155 km by road" [Hammond, 2011]; which takes into account the QPA report [QPA, 2008]. According to the authors of a paper entitled *Sustainable precast concrete foundation system for residential construction* [Yu et al., 2008], precast concrete basement walls are feasible when they are delivered at distances of around 200 km from the factory: "As PFC panels are bulky and heavy, transportation is costly. Economical range for the delivery radius of a PCF plant is about 200 km." According to a book entitled *Components and systems* [Staib, 2008, p. 46 & 47], "the value of a building element and the costs of transporting it determine the economical transport radius." It is considered that the "economic transport radius" of building elements comprised of "heavy, raw building materials e.g. prefabricated reinforced concrete elements (...) is up to 100 km approx." For building elements of "middle-weight, raw building materials e.g. prefabricated steel elements (...) the economic transport radius (...) is up to approx. 300 km". And for building elements of

*"completely finished elements e.g. sanitary blocks, mobile homes (...) the economic transport radius (...) is up to approx. 1000 km".*

#### **h) Sustainability**

*"Prefabricated buildings are more sustainable in terms of the amount of resources and energy used, and have less impact on the land. The production of components within a factory enables resources to be controlled more completely. Over-dimensioning of sections is avoided, and reuse is promoted; the parts are not demolished but dismantled. This also means that parts can be exchanged or replaced more easily "* [López, 2015].

According to Cliff Wren [Wren, 2012], there is an increasing interest in precast modular foundation systems: *"The introduction of the Code for Sustainable Homes (DCLG, 2009) has seen an increase in the use of modular off-site foundation systems (...) The emphasis of many of the leading ground engineering specialists has therefore been to explore and develop new systems that assist building contractors to achieve a higher code rating than would be realised by using traditional 'dig and dump' foundations."* In this paper, he describes various modular systems of prefabricated foundations and others that are semi-prefabricated. These systems are normally formed by foundations and the floor. Wren mentions that *"most modular foundation systems require no trench excavation (...) The modular system is value-engineered to eliminate waste. It contributes to the sustainable design in new construction by substantially reducing the use of natural resources and subsequently the embodied carbon footprint of the building when compared to more traditional foundations"* [Wren, 2012]. According to Wren, some modular systems could substantially reduce the emissions of CO<sub>2</sub> to the atmosphere: *"To give an example, consider the following: 'traditional' trench-fill foundations for an average house (having a footprint of 80 m<sup>2</sup>) will release 45 tonnes of CO<sub>2</sub> into the atmosphere. A modern composite reinforced concrete and galvanized steel foundation system will release 11 tonnes, a reduction of 75%. Even greater percentage reductions are calculated for water and raw materials usage"* [Wren, 2012, p. 1345].

Prefabricated structures *"facilitate the incorporation of sustainable solutions"* [CRC Construction Innovation, 2007]. Precast foundations can also be made from recycled materials. The Faas Moonen team designed footings using demolition materials, in order to support a wooden bungalow on a campsite. *"The foundation can also be completely removed at the end of its life time."* Precast foundations may also contribute to the durability of the dwelling: *"An important advantage of these foundations is also that the Trek-In has an optimum venting*

*underneath. Good venting benefits the service life of timber. If a standard concrete foundation would be used, ventilation is not possible. This is why existing cabins often have problems with decay where the wood touches the concrete"* [Moonen and Hermans, 2013, p. 14].



**Figure 17.** The building is a wooden bungalow with concrete footings made from demolition waste [Moonen and Hermans, 2013]. **Figure 18.** A crane is used to position the bungalow over its foundation.



## 2.2. Why are not the foundations of dwellings prefabricated?

There may be many advantages of using prefabricated foundations, but unfortunately they are not often used. Foundations tend to be constructed in a traditional way. In 1972, Viswanath Krishna Kumar wrote the following in a report entitled *Industrialized foundations for low-rise light-weight buildings* [Krishna, 1972]: "The last decade has seen many changes in building technology towards industrialization and mass production. These changes have been a natural out-growth of your efforts to rationalize the building process. Striving for the highest quality building, utilizing minimal resources, the building industry is employing anything from improved nails to better management techniques. (...) These mass produced houses continue to be placed on conventional built foundations just the conventional built houses. In other words, industrialization of building has so far been applied to the superstructure of the house and rarely to the foundation."

He said that several factors decrease interest in prefabricated foundations. First, "bound by tradition, the builders have taken for granted that the foundation has to be an in-place operation even though the rest of the building may be industrialized. It also seems that builders do not trust industrialization to the extent of prefabricating the foundation, on the reliability of which the rest of the structure depends."

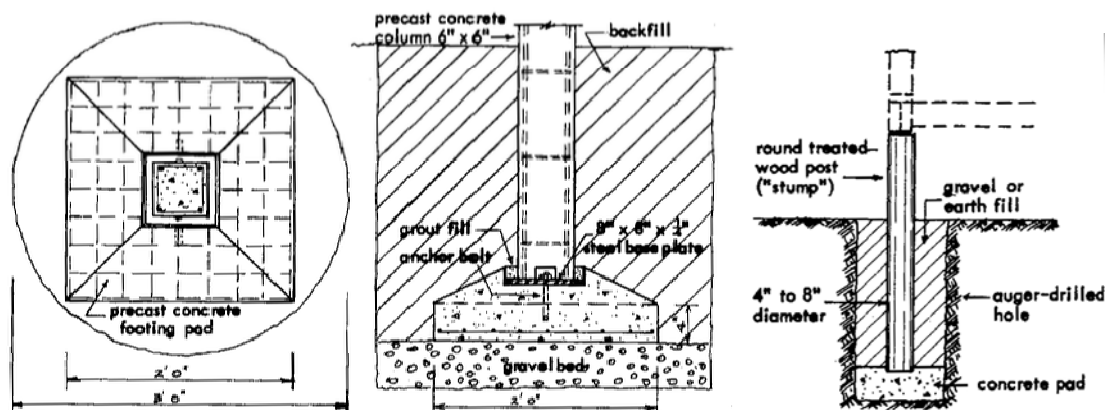


Figure 19. "Precast concrete column and footing details (...) They have been used extensively for commercial, industrial, institutional, and other buildings all over the world. (...) they make up an effective and economical foundation system" [Krishna, 1972, p. 15 & 17]. Figure 20. "Treated-wood posts in drilled holes or 'stump foundations' (...) have been used very commonly in Australia and New Zealand as house foundations" [Krishna, 1972, p. 13 & 15].

Another factor is that "industrialization cannot eliminate on-site operations completely. The work involving clearing the site, laying utility lines, grading, and landscaping cannot possibility

be transferred to the factory. However, foundation walls, columns, beams, and slabs can be mass-produced in the factory and assembled at the building site."

According to Viswanath, it is not always economically feasible to prefabricate the foundation: "For tall and heavy buildings, prefabricating the foundation components may not be economical due to the high loads involved. Foundations for such buildings can best be placed by pouring concrete in-place, except for those instances where driving of piles is required." He also stated: "Contrary to the popular myth, industrialized building does not always lead to significant reduction cost. This is due to the high overhead expenses, lack of experience, and lack of guaranteed volume."

He continued: "foundations are the most important part of any structure. However, a house providing a certain amount of accommodations and having elaborate and costly foundations, has no higher value to its owner or occupant than a similar one with less expensive foundation."

Furthermore, "foundation costs contribute only a small part to the total cost of the house (5% to 15%). Any savings in foundation costs represent only a very small percentage of the initial costs. (...) While the codes are somewhat constraining, it should be pointed out that they allow deviations where technical substantiation can be provided to defend novel solutions".

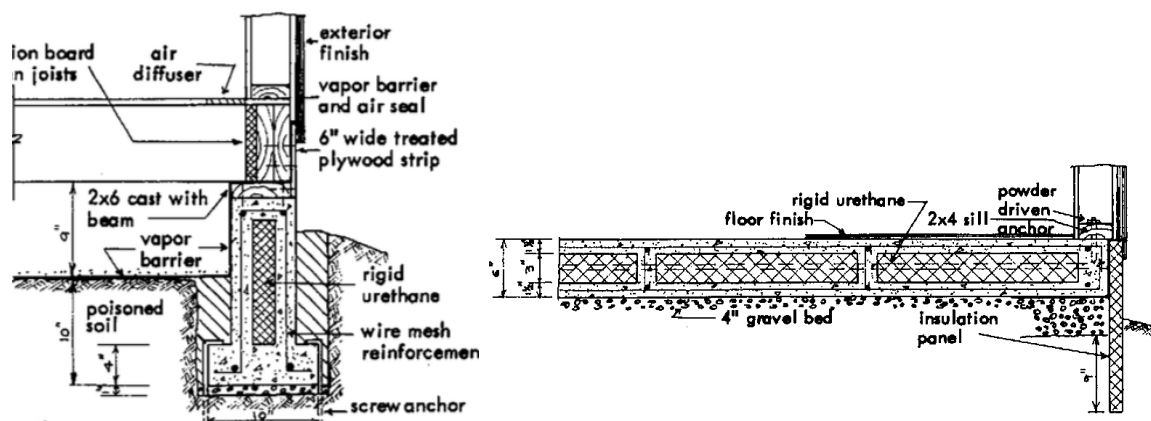


Figure 21. "Precast concrete grade-beam system" [Krishna, 1972, p. 21]. Figure 22. "Concrete slab foundation system. (...) A precast concrete slab foundation system is proposed which eliminates most of the problems encountered with conventional slab-on-grade foundations, while maintaining their advantages" [Krishna, 1972, p. 22].

Faas Moonen [Moonen, 2001] designed an accurate foundation to avoid potential problems with dimensional tolerance between foundations and industrialized dwellings. He found that one

factor was more important than price and functionality: acceptance. He stated that *"the construction sector is very conservative and all of the people that are involved in this sector contribute to it continuing in the same way."*

For example, Faas stated that clients are conservative *"because they see a building as a long-term investment, and do not want to experiment. If new materials or construction solutions are used, it is because they have been found to work well. Durability and the relatively high cost of construction hinder innovation. Many years must pass before we can show that a specific solution works well."*

*Companies are conservative because they pay for any problems that may arise. Therefore, they do not opt for new solutions. Solutions to problems do not just involve replacing a product, but repairing all of the damage that it could have caused. In addition, the profit margin is small. Therefore, companies tend to use known, tested solutions, and do not invest in changing their organizational structure with subcontracts.*

*Designers are also conservative due to the high number of parts involved. Constructing a precast foundation involves changing the organizational structure and may lead to error. In addition, the pressure of management schedules does not help in the implementation of a new solution. Although architects and consultant engineers may initially agree, generally precast foundations are not constructed because agreement between all stakeholders is not reached.*



**Figures 23, 24 and 25. Faas Moonen designed an accurate foundation to avoid potential dimensional tolerance problems between the foundation and the industrialized dwelling [Moonen, 2001, p. 3.34 & 3.45].**



*The government also promotes conservatism, because all the regulations have been designed for known solutions. A new product faces conditions that are difficult to meet. Therefore, many innovations are frustrated by current regulations, particularly those that refer to buildings."*

Faas Moonen considers that "two external factors could change the organization of the construction sector: environmental regulations and a lack of skilled workers."

Subsequently, in 2003, professor Bujang B. K. Huat also mentioned that "Cost is usually the most important factor affecting the choice of a foundation system and the nature of construction, but where rapid construction and quality assurance of construction are sufficiently important, these may be the factors which tip scales in favour of precast foundation system (...) A question that must be asked is, why shell foundations are not attempted even when they are known to be economical. The answer to this question does not lie in technology, but perhaps in the human psyche, which resists change even when the change is known to be to one's advantage" [Huat, 2003, p. 1 & 2].

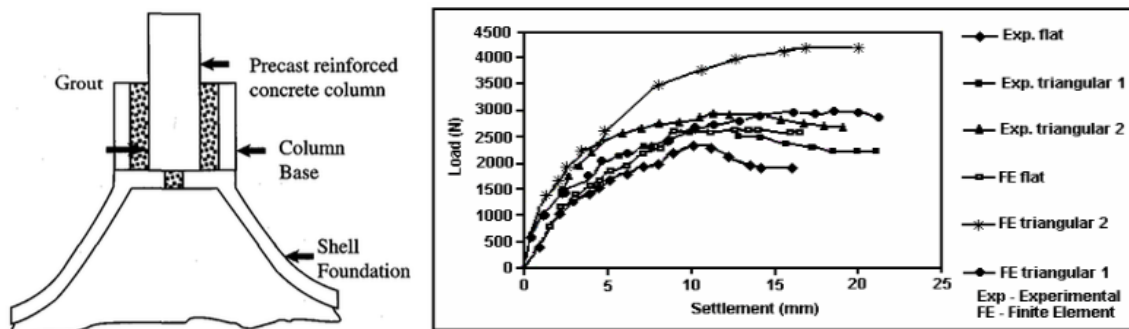


Figure 26. "Precast foundation shell with reinforced concrete column [Huat, 2003, p. 2] <http://hrc.eng.upm.edu.my/newsletter/nlv5i1.pdf>. Figure 27. "The shell footing is found to have a better load carrying capacity compared with the conventional slab/flat footing of similar cross sectional area" [Huat, 2006, p. 104 & 106]. <http://docsdrive.com/pdfs/sciencepublications/jcssp/2006/104-108.pdf>

Augusto Márquez [Márquez, 2006, p. 26 & 27] wrote that "Precast foundations face a series of difficult circumstances that have largely prevented them from being used widely either in formal construction or in self-building and housing self-management. These limits are due to the following factors:

*Specificity: usually, precast foundations are designed for specific structural or construction systems. The calculations are made for specific design conditions (pre-established coefficients, loads and*

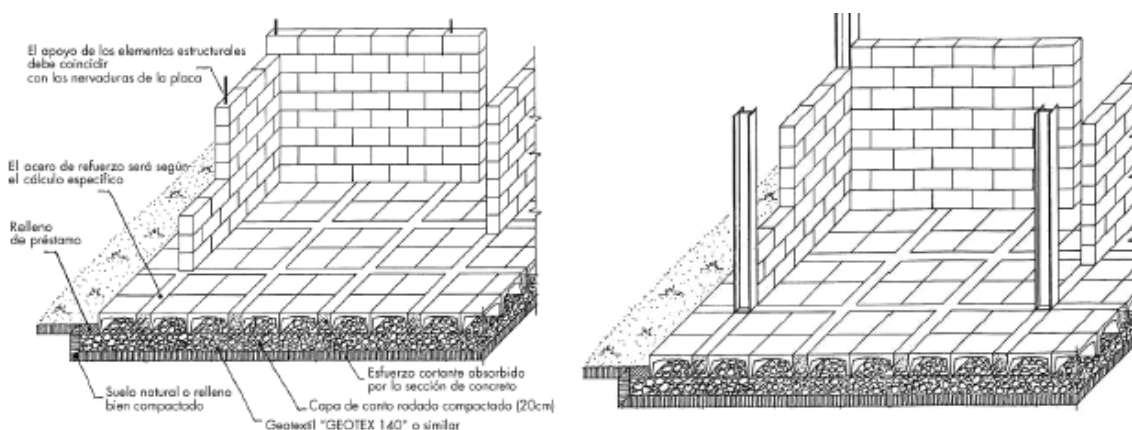
minimum soil resistance). These factors mean that certain precast foundations cannot be used in other constructions or other contextual circumstances.

*Structural correspondence:* the requirements of joining the foundations to the superstructure according to the support system (load-bearing frame, plane of resistance or a combination), as well as their relative location in the base plan (corner, edge or centre), often leads to the creation of an extensive series of specific components for each situation. This tends to decrease the efficiency of the estimation and control of quantities in the construction work and the inventories of components, and affects performance, due to the diversity and number of operations that need to be executed.

*Dimensional coordination:* as in the previous point, differences in the magnitude of structural spans between supports often result in dimensional variety in prefabricated components for foundations, so that the requirements can be suitably met. This may decrease efficiency, as explained above.

*Weight:* the common use of reinforced concrete as an essential material in foundations, which means that the specific weights of concrete ( $2,400 \text{ kg/m}^3$ ) and structural steel ( $7,800 \text{ kg/m}^3$ ) are combined, makes it difficult to handle and transport precast components without the use of machinery.

*Monolithic behaviour:* in general, precast foundations are addressed using a system of parts that need to be assembled. Joints are the most critical point, as they ensure suitable monolithic behaviour of the entire structure, particularly when exposed to dynamic loads (earthquakes, vibrations, different movements of the ground and others). This may limit or prevent their use in certain circumstances (areas with a seismic, geotechnical or other risk)."



**Figures 28 & 29. Márquez proposed "an open system of a shallow foundation that should be semi-prefabricated with reinforcement, and with the creation of ribs. This is compatible with superstructures of walls and load-bearing frames and adapts to the specifications of each design in particular, and to the structural regulations" [Márquez, 2006, p. 27].**

### 3. Case studies

#### 3.1. Modular construction systems

*"Modular construction systems are closed systems in which the elements are prefabricated by the manufacturers independent of a particular building. For a modular construction system, a particular number of elements are pre-determined which can be organized into complete entities by combining them in a number of different ways. The organization and assembly of these elements must be carried out according to geometric and constructional rules. Room module building systems can be developed for entire buildings, for example ready-built houses, or, equally for complex constructions like industrial sheds with large spans" [Staib, 2008, p. 43].*

#### 3.2. Room module buildings

Room module buildings are comprised of room modules (or boxes). The unit of construction is the room module or box. The modules are produced in a factory, transported on a lorry, and put in place using a crane.



**Figure 30. Habitat '67, a room module designed by Moshe Safdie and built for Expo 67 in Canada. The modules were put in place using a crane. <https://s-media-cache-ak0.pinimg.com/236x/b4/1c/64/b41c64707e719e56c09351c40552ae7b.jpg> Figure 31. Construction of a module in the factory. <http://cac.mcgill.ca/safdie/habitat/constructionPhoto.php?stage=1>**

In most of the cases studied, the modules were almost complete when they left the factory: toilets, windows and lining had already been added. On-site, joints were sealed, the plumbing and electricity were connected and, in some cases, the roof was constructed and/or cladding was assembled.

Prefabrication and improvisation are not highly compatible. Modules must be well-defined before they are produced in a factory. Prefabricated construction tends to lead to fewer errors than on-site construction. However, when problems occur, they are normally more difficult to solve.



**Figure 32. Room modules in a factory (A1-23). Figure 33. Positioning of modules over basement walls. Cladding and the roof then need to be added (A1-23).**

The degree of customization depends on the manufacturer. Some companies adapt their system to the client's design. Other companies have a catalogue from which the client has to select a model.

Modules are normally constructed from concrete, steel, wood or a combination of these materials. One advantage is speed of construction. Time is saved because a building can be produced in the factory at the same time as the land is prepared and the foundations are laid on-site. It is also very quick to assemble room module buildings on-site. Another advantage is the final quality of the building, as it is produced in a controlled, optimized environment, with specialized staff, and without the disruption of bad weather.

Modules can be dismantled, which means that they can be reused, relocated and replaced. At the end of their useful life, the materials can be recycled.

Modules are as valid for permanent buildings as for temporary buildings. And their dimensions “*are determined by the methods of transport available*” [Staib, 2008, p. 160]. “*The authorised dimensions for a load carried by an articulated lorry are approximately 2.5 x 3.2 x 12.0 m. In special cases oversize loads are allowed when transportation large building elements, but a special permit must be obtained*” [Staib, 2008, p. 46].

### 3.3. The room module buildings that were studied

Below is a description of the room module buildings that were studied. Appendix 1 contains a data sheet for each one of them (which can be searched for using the specific code for each building).

	Types	Code	Year of completion	Module weight (kg)	Area (m <sup>2</sup> )	Module weight (kg/m <sup>2</sup> ) <sup>1</sup>	Module weight (kN/m <sup>2</sup> ) <sup>2</sup>	Roof weight (kN/m <sup>2</sup> )
1	Concrete Panels	A1-9	2010	30000.00	28.44	1055.00	10.34	2.50
		A1-10	2010	45000.00	52.02	865.00	8.48	2.50
		A1-15	2011	40000.00	46.05	869.00	8.52	2.50
		A1-16	2011	43000.00	56.00	768.00	7.53	2.50
		A1-17	2011	43000.00	56.00	768.00	7.53	2.50
		A1-24	2012	33500.00	41.12	815.00	7.99	2.50
		A1-30	2014	24000.00	17.01	1410.93	11.11	2.50
2	Steel frames	A1-11	2010	11700.00	58.50	200.00	1.96	0.39
		A1-12	2010	13650.00	39.00	350.00	3.43	0.42
3	Steel panels	A1-1	2008	2500.00	14.76	169.38	1.66	0.00
		A1-3	2009	2500.00	13.87	180.22	1.77	0.14
		A1-18	2011	3740.00	28.30	332.16	3.26	2.00
		A1-26	2013	8351.10	30.00	278.37	2.73	2.00
4	Timber frames	A1-4	2009	8500.00	23.35	363.97	3.57	0.00
		A1-5	2009	10850.00	31.00	350.00	3.43	0.42
		A1-19	2011	6300.00	18.00	350.00	3.43	0.42
5	Timber panels	A1-6	2009	20700.00	52.23	364.00	3.57	0.14
6	Concrete-steel frames and panels	A1-7	2009	5000.00	15.19	329.16	3.23	0.00
		A1-14	2010	23967.00	53.26	450.00	4.41	1.47
		A1-13	2010	9000.00	20.00	450.00	4.41	1.47
		A1-20	2011	9000.00	24.15	372.67	3.65	0.00
		A1-23	2012	25000.00	27.00	925.93	9.07	2.50
7	Steel-timber frames	A1-2	2008	10000.00	40.00	250.00	2.45	0.39
		A1-8	2009	10000.00	40.00	250.00	2.45	0.39
		A1-27	2013	4000.00	15.00	266.67	2.61	0.39
8	Steel-timber frames and panels	A1-21	2011	5000.00	25.00	200.00	1.96	0.39
		A1-22	2011	4464.00	22.32	200.00	1.96	0.39
		A1-25	2012	4466.00	22.33	200.00	1.96	0.39
		A1-28	2013	6086.08	30.43	200.00	1.96	0.39
		A1-29	2014	4000.00	37.76	105.93	1.04	0.00

Table 2. The room module buildings that were studied.

<sup>1</sup> kg/m<sup>2</sup> floor surface

<sup>2</sup> kN/m<sup>2</sup> floor surface

### 3.4. Types

The thirty cases studied were organized into eight types. The material used for the module's structure (concrete, steel, timber, concrete-steel or steel-timber), and the structural elements of the module (frames, panels or frame and panels) were considered.

A representative module was selected for each type. A table was then created with the most relevant information, to illustrate the main differences between types. It should be considered that a design may include modules of different dimensions. Consequently, modules of the same type may have different weights depending on various factors, including the roof and cladding. Therefore, the selected modules were representative of their type and of the design.

It was observed that the structure of modules affects the type of foundation that is laid. Modules whose walls are made of panels transmit distributed loads to the foundations. In this case, strip footing or slabs are used [Jiménez, 2010]. However, some cases of concrete panel modules transmit point loads to the foundation. One example of this is the A1-16 case study, in which the modules were placed over precast concrete pads over the cast-in-place continuous footings (Figure 34).

Modules that have walls made of frames transmit point loads to the foundations. Isolated footings, micropiles [AENOR, 2006] or drilled shafts [DB SE-C, 2007, p. 43] were used in these cases. However, sometimes this type of module was fitted over beams, in which case the load on the foundations was distributed (Figure 35).

Deformability is also a factor to take into account. The module and foundations must have similar deformability to work well.



**Figure 34. Modules on connectors (A1-16). Figure 35. Modules on wooden beams (A1-4).**






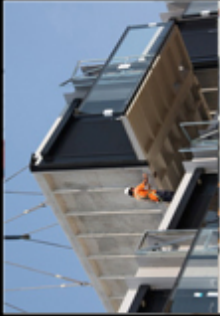





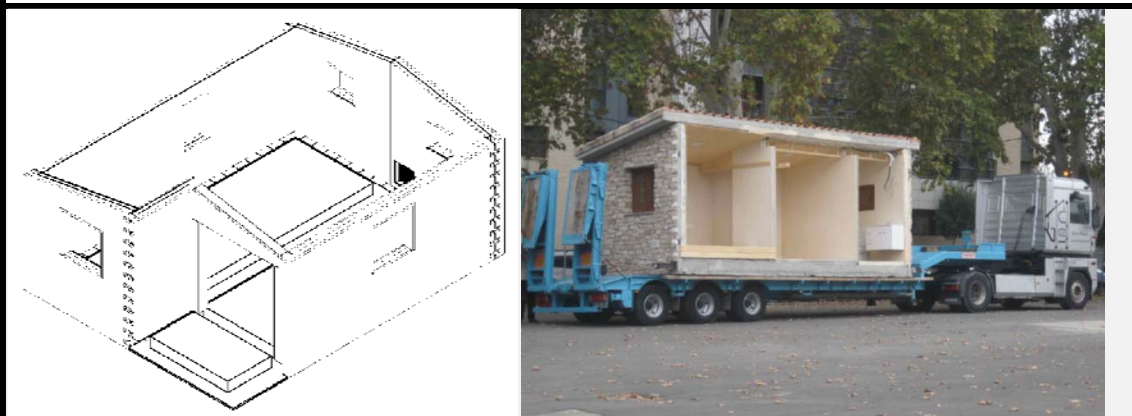
Types	Concrete	Steel	Timber	Concrete-steel	Steel-timber
Frames		 <p>2</p>	 <p>4</p>		 <p>7</p>
Panels	 <p>1</p>	 <p>3</p>	 <p>5</p>		
Frames and panels				 <p>6</p>	 <p>8</p>

Table 3. Type of room module buildings studied.

**Concrete panels** **1**

	Structure materials (C / S / T / C-S / S-T)	C
	Structural elements (F / P / F-P)	P
	Module weight (kN)	441.30
	Module weight (kN/m <sup>2</sup> floor surface)	8.48
	Maximum number of floors	8
	Type of transmitted loads (Point / Distributed)	Distributed
	Module deformability	T2
	Roof weight (kN/m <sup>2</sup> )	2.50

Modules in these systems can be produced using a cast or by fitting the walls together. In both cases, they work as a box or unit. The walls may be smooth or ribbed. They are manufactured in a controlled factory environment, and the result is a high quality product. The few, or complete absence of, joints in the module and the good quality of the prefabrication mean that the surfaces can be left on view both inside and outside the module.



**Figure 36.** This hut is made from two concrete modules. These were constructed by fitting their walls together, and they both work as a box or unit (A1 - 30). **Figure 37.** The image shows how one of the modules is transported to the site (A1-30).

This kind of module is normally very heavy, which makes them difficult to transport and handle. *"The modules weigh, according to type and dimensions, between 20 and 70 t.; thus heavy-duty hoisting equipment is necessary for assembly"* [Staub, 2008, p. 163]. Most of the concrete modules that were studied of this type required special transport, which affected the final cost of the construction work.



"The combination of concrete modules at the site automatically creates double-layered walling - this is advantageous for both fire and sound protection levels" [Staib, 2008, p. 163]. In some cases, the walls were covered with fire retardant foam to meet fire safety regulations [DB SI, 2010]. Due to the high strength of these modules, they can be used to build multi-family housing units.



Figure 38. The walls are impregnated with fire retardant foam (A1-16). Figure 39. The modules required special transport (A-16).

## Steel frames


2



Structure materials (C / S / T / C-S / S-T)	S
Structural elements (F / P / F-P)	F
Module weight (kN)	114.74
Module weight (kN/m <sup>2</sup> floor surface)	1.96
Maximum number of floors	3
Type of transmitted loads (Point / Distributed)	Point
Module deformability	T1
Roof weight (kN/m <sup>2</sup> )	0.39



Figure 40. This is a room module with steel frame walls. Figure 41. A house constructed using this system (A-20).

<b>Steel panels</b>	<b>3</b>	
	Structure materials (C / S / T / C-S / S-T)	S
	Structural elements (F / P / F-P)	P
	Module weight (kN)	81.90
	Module weight (kN/m <sup>2</sup> floor surface)	2.73
	Maximum number of floors	5
	Type of transmitted loads (Point / Distributed)	Point
	Module deformability	T2
	Roof weight (kN/m <sup>2</sup> )	2.00



**Figure 42. Various shipping containers have been adapted to make this house (A-26).  
Figure 43. The finished house whose structure is comprised of shipping containers (A-26).**

One of the best-known advantages of steel construction systems is that they are light. This makes them easy to transport and handle, and the foundations can be quite small. Once on-site, the modules are welded or screwed together so that all of the modules work together.

Two types of steel module can be distinguished. In the first type, the frames are load-bearing and the walls are not structurally necessary. The frame may be made of steel or stainless steel. Normally, the space between the frame is filled with insulating materials, but these are not essential to its stability.

In the second type, the walls are load-bearing. That is, although ribs or frames are present, they cannot bear the entire weight of the structure above them and therefore the walls are essential to the structure's stability. Buildings constructed from shipping containers would be within this group. In the designs studied, the shipping containers were used as a structure. Once on the site, the rest of the building was constructed.

Modular steel systems normally do not need maintenance, but they must be protected against fire. They are quick to build: in two or three weeks a two-storey building can be completed. They are also flexible, the layout and cladding can be selected and their use can be changed. They can be relocated and modules can be removed or added as desired.




Timber frames		4
	Structure materials (C / S / T / C-S / S-T)	T
	Structural elements (F / P / F-P)	F
	Module weight (kN)	61.78
	Module weight (kN/m <sup>2</sup> floor surface)	3.43
	Maximum number of floors	2
	Type of transmitted loads (Point / Distributed)	Point
	Module deformability	T1
	Roof weight (kN/m <sup>2</sup> )	0.42



Figure 44. This is a modular system of wood with walls constructed from frames (A-4). Figure 45. The module positioned on-site (A-4).


Timber panels		5
	Structure materials (C / S / T / C-S / S-T)	T
	Structural elements (F / P / F-P)	P
	Module weight (kN)	202.99
	Module weight (kN/m <sup>2</sup> floor surface)	3.57
	Maximum number of floors	10
	Type of transmitted loads (Point / Distributed)	Distributed
	Module deformability	T2
	Roof weight (kN/m <sup>2</sup> )	0.14



Figure 46. This is a modular system of wood with panel walls (A-6). <https://www.youtube.com/watch?v=npTcxWIDbsQ> Figure 47. The module positioned on-site (A-6).

Two types of wooden room module buildings can be identified: in the first, the wooden frame of the walls is structural, and therefore does not need any other layers to ensure its stability. Normally, the space between uprights is filled in with insulating boards, to meet thermal and acoustic needs. In the second case, the walls of the module are structural.

Wooden modules are ideal for small buildings and dwellings, because they are easy to customize in the factory using modern production techniques. They are normally finished in the factory, with lavatories, kitchens and bathrooms, flooring, electricity and plumbing. The panels or frames are made more rigid with joints made from wood or metal sections. The metal sections need to be treated to protect them from rusting.

Wooden modules are light. This makes them easier to transport, and they do not need large foundations. However, wooden modules are not normally as rigid as other types; they may come apart or be damaged during transport or handling. Nevertheless, it is also easier to improvise, as holes can quickly be made in the wood.



**Figure 48. Modules are complete when they leave the factory. This module includes the kitchen, bathroom, plumbing and wiring (A-6). Figure 49. The modules are light and easy to handle and transport. They can be packaged so that they do not get damaged (A-6).**

Wooden buildings normally have good acoustics and are good thermal insulators. In addition, wood is a renewable material with a low environmental impact. However, wood needs treatment and maintenance to prevent its deterioration.


Concrete-steel frames and panels		6
	Structure materials (C / S / T / C-S / S-T)	C-S
	Structural elements (F / P / F-P)	F-P
	Module weight (kN)	235.04
	Module weight (kN/m <sup>2</sup> floor surface)	4.41
	Maximum number of floors	
	Type of transmitted loads (Point / Distributed)	Point
	Module deformability	T1
Roof weight (kN/m <sup>2</sup> )	1.47	




Figure 50. Module system of frames and panels in the factory (A-14). Figure 51. Completed building that uses this system (A-14).

This kind of module normally weighs half that of a concrete module, at round 400 kg/m<sup>2</sup> (see Table 2). However, depending on what cladding is selected, they may end up equally heavy. They are stronger than wooden room module buildings, and therefore there is no danger of them coming apart when they are handled or transported. However, as their structure is made from metal, they must be protected from rusting and fire.

This system is flexible in various ways: they can be used to build multi-family housing. They can also be used in various kinds of structures, not just residential buildings. Building can be relocated, extended or changed, and the delivery deadlines are very short.



<b>Steel-timber frames</b>		<b>7</b>
	Structure materials (C / S / T / C-S / S-T)	S-T
	Structural elements (F / P / F-P)	F
	Module weight (kN)	39.23
	Module weight (kN/m <sup>2</sup> floor surface)	2.61
	Maximum number of floors	2
	Type of transmitted loads (Point / Distributed)	Point
	Module deformability	T1
	Roof weight (kN/m <sup>2</sup> )	0.39




**Figure 52. Construction of a module in the factory. It is comprised of frames made from a combination of steel and timber. Figure 53. The module positioned on-site. Windows and doors are sealed with shutters or with particle board to prevent damage in transport and handling (A-27).**

The base of this kind of module is comprised of a metal chassis. The roof could be flat or inclined and combine the metal structure with a wooden frame. The walls are formed from wooden frames.

These houses are light, which makes them easier to transport and handle. They are mainly made of wood and therefore benefit from many of the advantages of building from wood, such as thermal and acoustic insulation. However, wooden and metal elements must be protected. This system is flexible in its shape, use and cladding.

The modules that were studied of this type were complete when they arrived on-site, and even completely furnished. The tasks carried out on-site basically involved sealing joints and connecting plumbing and electricity.

**Steel-timber frames and panels** **8**

	Structure materials (C / S / T / C-S / S-T)	S-T
	Structural elements (F / P / F-P)	F-P
	Module weight (kN)	49.03
	Module weight (kN/m <sup>2</sup> floor surface)	1.96
	Maximum number of floors	2
	Type of transmitted loads (Point / Distributed)	Distributed
	Roof weight (kN/m <sup>2</sup> )	0.39

This system is similar to the one described above. The horizontal elements are comprised of a metallic frame. However, the walls are formed of panels and are structural.

This system is also very easy for the client to customize. The aesthetics can vary widely; from a modern house to a country house. These are low-level houses with one or two stories. They are normally designed for dwellings or bungalows. They can be constructed very quickly and installed in one or two days. Depending on the dimensions of the module, they may require special transport and a crane is needed to put them in place.

They are the lightest houses that were studied, at a weight of around 200 kg/m<sup>2</sup> (see Table 2). They have the advantages and disadvantages of building in wood, as explained above. The metal structure makes them more rigid than modular wooden systems.



Figure 54. The module is transported to the site on a lorry (A-28). Figure 55. The module is placed on the plot using a crane (A-28).

## 4. Foundations

### 4.1. Definitions

#### a) What is a prefabricated foundation?

A prefabricated foundation could be defined as one that has been produced from raw materials in a factory and is then assembled or mounted on-site. Sometimes, joints are also sealed and insulated. One example of this is a precast strip footing (See Figure 56).

#### b) What is a semi-prefabricated foundation?

A semi-prefabricated foundation could be defined as one that has been produced from raw materials in a factory that must be finished on-site. One example of this is a semi-prefabricated strip footing (Figure 57).



Figure 56. A precast strip footing is a prefabricated foundation. Once it is on-site, it must be assembled and the joints are sealed. Figure 57. A semi-prefabricated strip footing is a foundation that must be finished on-site. Once it is on-site, concrete must be added under the element.

### 4.2. Types

In the current market, we can find a variety of prefabricated and semi-prefabricated foundations. Some of these are shown in the table below:

Foundations	
Prefabricated foundations	(Micro) piles of wood, steel or concrete – Screw piles or helical piles – Composite piles – Group of micropiles – Steel sheet piling – Precast concrete isolated footings – Pads and piers – Precast concrete strip footings, continuous footings and ground beams – Concrete blocks – Grillages
Semi-prefabricated foundations	Semi-prefabricated foundations and formworks – (Micro) piles – Composite piles – Grillages

Table 4. Prefabricated and semi-prefabricated foundations. Further information can be found in Appendix 2 – Foundations. There is a descriptive table for each foundation.



**Precast concrete piles**

**1**

Precast concrete piles are suitable for most applications and grounds. They are a cost-effective solution, especially when soils have a low resistance. They are quick to install without producing spoil or generating material in the process, and provide a further saving on waste disposal costs. They can achieve great depths if they are spliced. Precast concrete piles are not suitable for soil deposits that contain a high number of boulders. In such cases, the pile may be equipped with a pile shoe, which protects the pile tip during hard driving. The tip may have a drill inside it, to survey some metres below the tip and to inject cement or mortar in order to fill holes or cavities. Sections of piles and caps are smaller than sections of cast-in-place concrete piles. In addition, the head of the pile must be broken in order to build a cap or a beam, which can be cast-in-place or precast. The most common problems of precast piles are vibrations and noise while they are installed, which can affect neighbouring buildings. However, this problem can be solved by using an hydraulic pile driver.

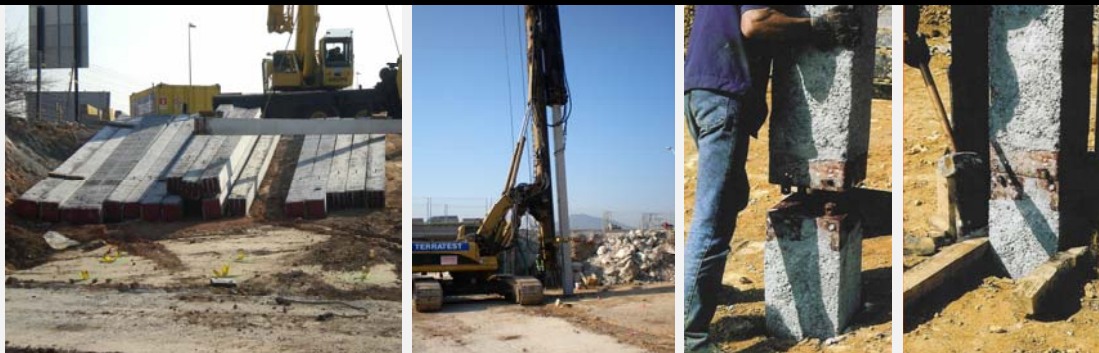


Figure 58. Precast concrete piles are stored horizontally. Figure 59. Pile driver. Figures 60 & 61. Placing the pile for joining. Introduction of pins. <http://www.terratest.es/docs/doc4ed5f12d132516.08695682.pdf>



Figure 62. Pile caps and the floor can be precast. <http://www.roger-bullivant.co.uk/images/photos/system1.jpg>  
 Figure 63. Precast concrete piles with precast ground beams. [http://charconcs.com/sites/default/files/editor/charconCS-FASTBEAM-main-section\\_01.jpg](http://charconcs.com/sites/default/files/editor/charconCS-FASTBEAM-main-section_01.jpg) Figure 64. Multifunctional hydraulic static pile driver. [http://img.isp.org.cn/nimg/04/95/1bd832dc4f9904aaef37f431ff6a-200x200-1/zyc900b\\_b\\_multifunctional\\_hydraulic\\_static\\_pile\\_driver.jpg](http://img.isp.org.cn/nimg/04/95/1bd832dc4f9904aaef37f431ff6a-200x200-1/zyc900b_b_multifunctional_hydraulic_static_pile_driver.jpg)

## Timber piling

2

*"It is the lowest cost deep foundation material and lasts for over 100 years, with a natural taper that increases friction capacity. It can be easily delivered, handled and installed using existing driving equipment at close spacing, minimizing expensive floor slab thickness and resisting attack from acidic soils. It is also unaffected by stray electrical currents and no corrosion protection is required, taking advantage of a plentiful, natural renewable resource."* [Llorens and Pujadas, 2014]. *"The main disadvantages of timber are the heterogenic characteristics of timber and also that it can be deteriorated if it is not completely submerged in water. For modest loads and piling lengths of about 12 m, timber piles are quite suitable, provided certain precautions are taken. They are available in diameters of up to 0.40 m. Usually, pile cross-sections are circular, although square sections can be used. Working loads are unlikely to exceed 500 kN, partly because of difficulties in driving piles to give sets appropriate to higher working loads. Also the cross-sections of timber piles and lower compressive strengths limit the load bearing capacity."* [<http://www.geoforum.com/info/pileinfo/view.asp?ID=56>, 2015] It is important to choose a suitable type of timber and treatment, to prevent or minimize its deterioration.



Figure 65. Storage of timber piles. <http://sachsen-anhalt-nebra.annoncen.org/export/handwerk-20120614121341.png> Figure 66. Timber pile driver. <http://www.myrickmarine.com/project/house-timber-pile-foundation/> Figure 67. Protective attachments at the pile tip and pile head can be used to prevent splitting and brooming of the pile. <https://www.pilebuckinternational.com/wp-content/uploads/2013/11/timberpts1a.jpg>

**Steel piles**

**3**

There are a variety of types of steel piles: they can be H-sections, box sections or tubular sections. Steel piles are normally not filled with concrete. They can withstand high loads and lateral forces. *"Compared by pile length, steel piles tend to be more costly than concrete piles, but they have high load-carrying capacity for a given weight of pile, which can reduce driving costs."* [<http://www.geoforum.com/info/pileinfo/view.asp?ID=49>, 2015]

H-sections are particularly suitable for soils where displacement or heave is a potential problem. However, they are not recommended for cohesive soils. Steel piles are easy to cut and splice, and the resulting parts can be reused or have value as waste. Protective attachments can be welded at the pile tip to protect it. Corrosion is not a big problem for steel piles when they are installed in uncontaminated grounds. In addition, effective treatments are available.



Figure 68. Pipe piles. [http://www.nssmc.com/en/product/construction/images/steel\\_pipe\\_pile\\_ph01.png](http://www.nssmc.com/en/product/construction/images/steel_pipe_pile_ph01.png) Figure 69. A pile point welded at the end of an H-pile to protect the pile tip. [http://www.14thstviaductreplacement.com/data/images2/steel\\_h-piles\\_for\\_new\\_foundations.jpg](http://www.14thstviaductreplacement.com/data/images2/steel_h-piles_for_new_foundations.jpg) Figure 70. An H-pile splicer. <https://www.pilebuckinternational.com/wp-content/uploads/2013/11/hpileattach.jpg>

**Screw piles or helical piles**

**4**

This is a steel pile that has none, one or more helices, and is screwed into the ground until the desired bearing capacity is achieved. The number of helices, their diameters and position on the pile shaft, as well as the steel plate thickness, are all determined by a combination of structure design load requirements, geotechnical parameters, environmental corrosion parameters, and the minimum design life of the structure being supported or restrained.

These piles are suitable for cramped and limited-access conditions, for retrofitting or repositioning. If they are in contact with water, they need to be protected against corrosion with a treatment or system. They can be spliced to achieve greater lengths. They can be used as geothermal piles to recover the geothermal energy stored in the soil.



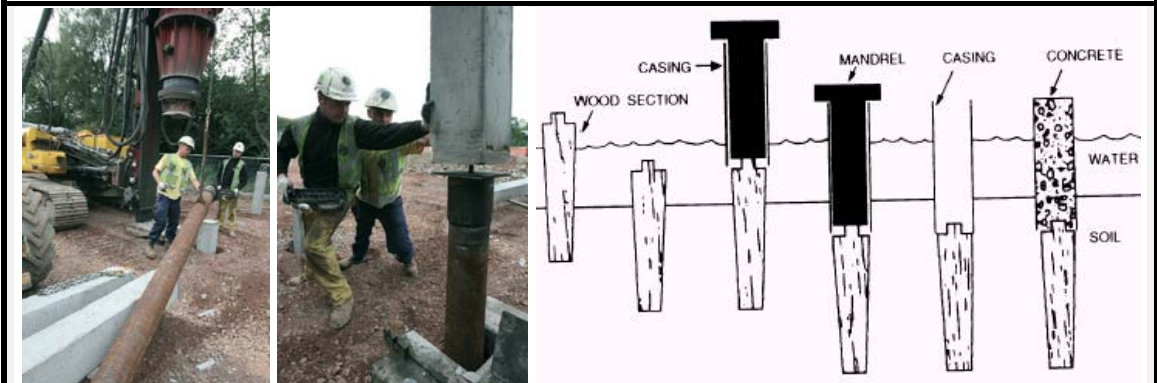
Figures 71 & 72. Screw piles or helical piles. [http://blog.business-model-innovation.com/wp-content/uploads/2009/03/358\\_bild-135x300.jpg](http://blog.business-model-innovation.com/wp-content/uploads/2009/03/358_bild-135x300.jpg) [http://postechnorthern.ca/wp-content/uploads/2014/07/pic\\_pile.jpg](http://postechnorthern.ca/wp-content/uploads/2014/07/pic_pile.jpg) Figure 73. This machinery could be suitable for cramped and limited-access conditions. Figure 74. Piles can be driven either vertically or at various angles of inclination to increase the support on lateral loads.

## Composite piles

5

A composite pile is composed of two different materials, and takes advantage of the qualities of both. Composite piles prove economical, as they combine one material's high corrosion resistance with the cheapness or strength of the other. One example is a composite pile made from a precast concrete pile and a timber pile. Timber piles are vulnerable when they are not completely submerged in water. For this reason, the concrete pile is used above ground level, whilst the timber pile is installed under the water table. It is important to assure a rigid union between these two elements. The concrete pile can also be cast-in-place. In addition, there are other types of composite piles that normally combine concrete piles, pipe piles, steel beams and timber piles.





Figures 75 & 76. A composite pile made of precast concrete and steel. <http://www.roger-bullivant.co.uk/index.cfm> This pile combines the strength of steel with the cost-effective benefits of precast. <http://www.roger-bullivant.co.uk/index.cfm> Figure 77. Phases in the construction of a composite pile made of timber and cast-in-place concrete. [http://www.tpub.com/eqopbas/12535\\_files/image996.jpg](http://www.tpub.com/eqopbas/12535_files/image996.jpg)

## Micropiles

6

This is a pile with a diameter no bigger than 300 mm [AENOR, 2006]. It is usually made of concrete, steel or a combination of these materials, and it can be completed with grout or mortar. It is very versatile. Not only it is able to transmit loads of compression, bending, shear and traction, but it is also compatible with most soils.

Micropile machines can be small, which makes them very flexible, and means that micropiles can be installed in inaccessible locations and also inside buildings. They produce low vibration and low noise. Some micropiles are reusable. But after the installation of injection micropiles, grout or mortar residues with soil must be removed from the ground.

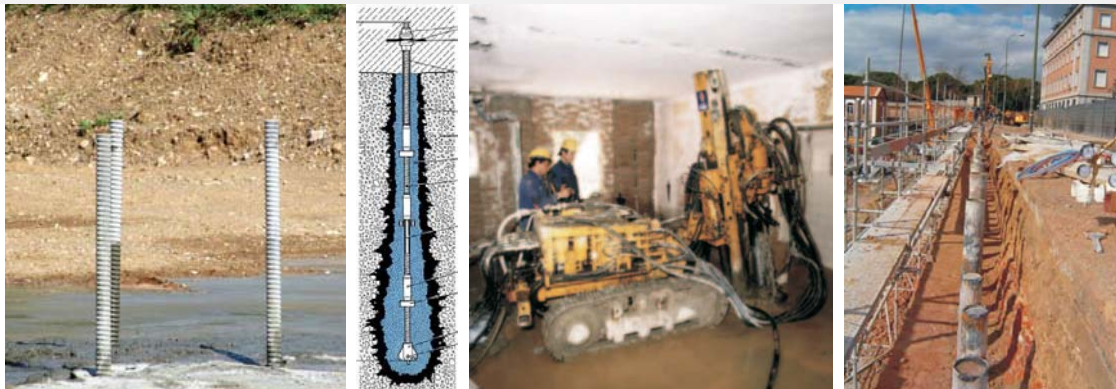


Figure 78. Grout and soil residues must be removed after installing injection micropiles. Figure 79. Injection micropile. <http://www.imeco.at/pro/dri/img/dri1101.jpg> Figure 80. Micropile machines can be small and can enter buildings. <http://www.keller-cimentaciones.com/micropilotes/> Figure 81. Steel micropiles installed. <http://www.keller-cimentaciones.com/micropilotes/>

## Group of micropiles

7

A group of micropiles consists of several micropiles or pipes connected to a cap. The cap can be made of steel or concrete. A group of micropiles has various advantages, including the following: they can be installed rapidly using light equipment, specialized workers are not always required, they can be repositioned or reused, and they minimize the footprint of the foundation. In addition, a group of micropiles can withstand a load just after installation. This is an ideal solution for light and temporary constructions.



Figure 82. A driving hammer is required to install this type of micropiles. <https://greentasreno.files.wordpress.com/2010/04/installing-mega-anchors-4.jpg> Figure 83. Caps can be made of steel or concrete <http://diamondpier.com/> Figure 84. Installing a room module over a group of micropile foundation. <http://diamondpier.com/>

## Steel sheet piling

8

*“This is a form of driven piling, using thin interlocking sheets of steel to obtain a continuous barrier in the ground. The main application of sheet piles is in retaining walls and cofferdams, but single or combined units may be employed as recoverable lightweight foundations. Vibrating hammers, hydraulic drivers and cranes are used to install them” [Llorens and Pujadas, 2014].*



Figure 85. Storage of sheet piles. [http://naavaay.com/wp-content/uploads/2012/10/Sheet\\_pile\\_New\\_Orleans-09-04-05.jpg](http://naavaay.com/wp-content/uploads/2012/10/Sheet_pile_New_Orleans-09-04-05.jpg) Figure 86. Installation of sheet piles. <http://www.imeco.at/pro/sho/img/sho0604.b.jpg> Figure 87. Removal of sheet piles. [https://upload.wikimedia.org/wikipedia/commons/7/7d/Etec\\_880\\_special\\_removing\\_Sheet\\_pile\\_walls\\_\(1\).jpg](https://upload.wikimedia.org/wikipedia/commons/7/7d/Etec_880_special_removing_Sheet_pile_walls_(1).jpg)

## Precast concrete isolated footings

9

A precast concrete isolated footing is a standardized element used to support low-medium building loads in ground with good bearing capacity and in small settlements. This solution is quite normal in industrial and agricultural buildings, but is rarely used in housing because it is expensive. After placing the footing on the site, the pillar is positioned inside the footing and the union is concreted with low shrinkage concrete. Tie beams can also be precast, depending on the footing model.

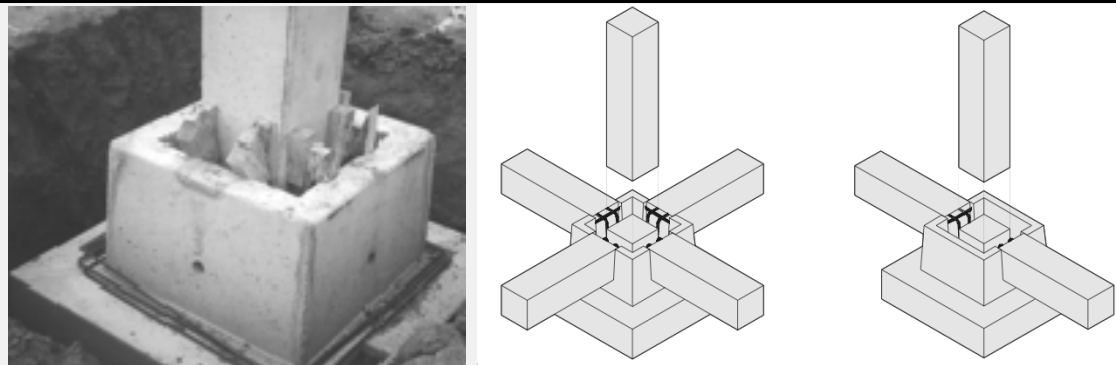


Figure 88. Precast concrete isolated footing. Figure 89. Tie beams can also be precast. <http://www.prefabricatsplanas.com/ca/documentacio>



**Pads and piers**

**10**

*"They are ideal for light buildings supported by almost all kind of soils, provided they have some resistance. Single-family, semi-detached and row houses, mobile and manufactured homes, prefabricated room modules, emergency shelters, temporary dwellings and the like do not usually need large amounts of poured concrete, keeping in mind however that hazardous conditions such as strong winds and earthquakes may require complementary anchors to prevent overturning and uplift. Even if this was the case, note that anchoring to the soil is much more efficient than relying on weight."* [Llorens and Pujadas, 2014]. They can be adjusted in height and may be reused and recycled.



Figure 90. Metal pier. Figure 91. Precast concrete pad. [https://www.swiftfoundations.co.uk/wp-content/uploads/2014/06/swift\\_plinth\\_image.jpg](https://www.swiftfoundations.co.uk/wp-content/uploads/2014/06/swift_plinth_image.jpg) Figure 92. They can support light structures. [http://4.bp.blogspot.com/--pg4orIWvb4/TbCfDPdSJ\\_I/AAAAAAAAANu4/EXv-W3uLtQg/s1600/swift.jpg](http://4.bp.blogspot.com/--pg4orIWvb4/TbCfDPdSJ_I/AAAAAAAAANu4/EXv-W3uLtQg/s1600/swift.jpg)

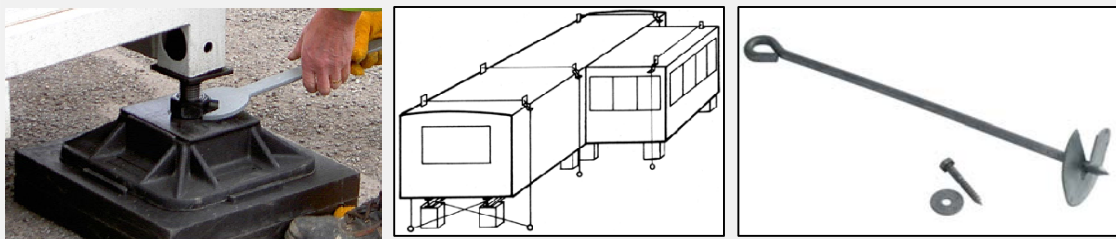


Figure 93. Plastic pad. [http://www.elliottuk.com/files/styles/700\\_slide/public/jack\\_pad.jpg?itok=rQY0Y1G](http://www.elliottuk.com/files/styles/700_slide/public/jack_pad.jpg?itok=rQY0Y1G) Figure 94. Complementary anchors to prevent overturning and uplift. <http://archive.nrc-cnrc.gc.ca/eng/ibp/irc/cbd/building-digest-188.html> Figure 95. Ground anchor. <http://www.ropesdirect.co.uk/images/uploads/Ground%20anchor%20screw.jpg>



**Precast ground beams, continuous footings and strip footings**

**11**

Precast ground beams, continuous footings and strip footings can have different sections, which are normally square or T-inverted shapes. Unions are normally sealed with mortar (Figure 96). They can have established characteristics, and enable rapid assembly of the foundation on-site. They may have piles. They can be post-tensioned and the sections tend to be smaller (Figure 98). Housing can be built upon them immediately, as there is no need to wait for concrete to reach the required resistance.

Some of them must be semi-prefabricated. They are monolithic and are positioned by crane. Once they are in the right position, they are completed with concrete below (Figures 99 & 100). They are easier to manipulate than completely precast beams, because they are lighter. And good contact with the ground is guaranteed.

Some strip footings are made up of parts that are assembled on-site. Sometimes joints are sealed, depending on the type. Some strip footings must also be completed with reinforcement and concrete. They are lighter than the above, and some can even be manipulated by hand (Figure 101).



Figure 96. A precast strip footing foundation. Joints must be sealed with mortar. Figure 97. They are put in place using a crane. Figure 98. They can be post-tensioned. <http://www.van-elle.co.uk/services/Smartfoot/>



Figure 99. Semi-prefabricated strip footing for a panel modular house. Figure 100. Semi-prefabricated precast ground beam with piles. Figure 101. Semi-prefabricated strip footing made up of parts.

**Concrete blocks**

**12**

Precast concrete blocks can be used as a foundation for temporary and light constructions. There are a variety of shapes and dimensions. They can be solid or hollow. They are usually buried. But when soils have a good resistance or bedrock is present, they can be placed on the surface to prevent or reduce excavation.



Figure 102. Block foundation for a studio. <http://www.settstudio.com/> Figure 103. Block foundation for a backyard shed. <http://www.finehomebuilding.com/how-to/articles/firm-foundation-backyard-shed.aspx> Figure 104. They can also prevent uplift [Kovacs and Yokel, 2014].

**Grillage**

**13**

This consists of a number of layers of beams usually arranged perpendicular to each other and used to disperse heavy point loads from the superstructure to an acceptable ground bearing pressure. A grillage is normally made of steel, timber or concrete. They can be recovered, which is ideal for temporary buildings (Figure 105). Timber grillages are ideal for water-logged areas where the bearing capacity of the soil is low. For durability, it is important to choose a suitable timber species or treatment (Figure 106). When steel grillages are underground, they must be protected with a concrete cover (Figure 107).

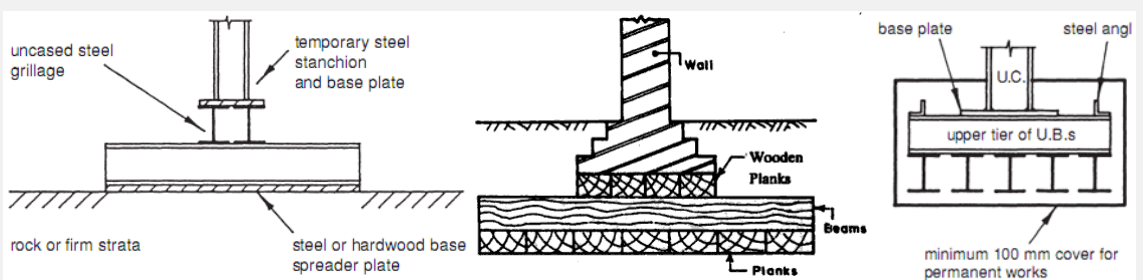


Figure 105. Steel grillage foundation for temporary works placed over rock or firm strata. <http://constructiontuts.com/wp-content/uploads/2015/06/Grillage-foundation-temporary-works.jpg>

Figure 106. Timber grillage foundation for a masonry wall. [http://3.bp.blogspot.com/-OzFITedXT\\_4UKPTGR3Umkl/AAAAAAAAA5w/2b4IDd52hO8/s1600/8.gif](http://3.bp.blogspot.com/-OzFITedXT_4UKPTGR3Umkl/AAAAAAAAA5w/2b4IDd52hO8/s1600/8.gif) Figure 107. Steel grillage foundation for a pillar. The grillage is protected with a concrete cover.

<http://constructiontuts.com/wp-content/uploads/2015/06/Grillage-foundation-Section-and-Plan.jpg>

## **5. The reasons given for not using prefabricated foundations in the case studies**

### **1. Initial cost**

This is the most common reason why foundations were not prefabricated. In general, the cheapest foundation in the short-term was selected, without considering the potential long-term consequences.

### **2. Comfort. *"It's always been done like this", "It's easy to do it this way"***

The second most common reason is that people build as they always have done, that is, in a traditional way or in the *"easiest"* way, which is normally the way that they already know.

### **3. Companies prefer to construct foundations using their own employees**

Construction companies have their own machinery and staff. Economically, they want to construct foundations in the way that they know so that they can amortize them. They are not interested in subcontracting items that they do not invoice themselves.

### **4. Insecurity *"A new foundation leads to new problems"***

It was found that in some constructions, the architects designed the foundations without knowing which company would construct them or what resources this company would have. For example, in the case of A1-20 (Appendix 1), the architect designed a ground slab cast-in-place because it was considered that most Spanish foundation construction companies have the means and the resources to build a ground slab and that it will have predictable errors.

### **5. They could not find a company that could precast the entire foundation**

The specialists in the case of A1-14 (Appendix 1) mentioned that they could not find a Spanish company that could prefabricate the entire foundation.

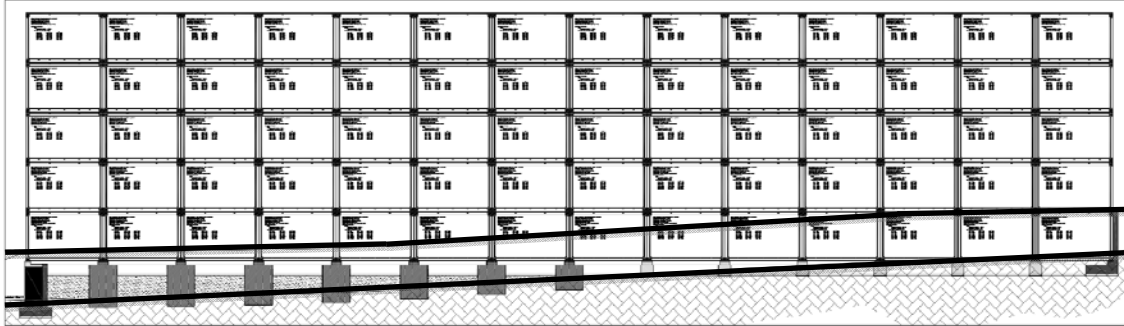
### **6. They do not know how to prefabricate the foundation**

The specialists in the case of A1-14 (Appendix 1) also stated that when they could not find a company to manufacture the entire foundation, they considered prefabricating it themselves. However, as they did not know how to do this, they finally constructed it on-site.

## 7. The characteristics of the land

### a) The slope of the land

In the case of A1-17, it was considered that the best way to adapt to the gradient of the land was through the use of drilled shafts constructed on-site.



**Figure 108.** As can be seen, the ground with suitable bearing capacity followed the original gradient of the land. Caissons constructed on-site enabled the depth of the foundations to be adjusted (A1-17) (Appendix 1).

### b) The ground was not homogenous

In A1-15 (Appendix 1), the layers of ground were not uniform. As the level of the soil with good bearing capacity varied, foundations were required that could be adapted to different depths. Semi-prefabricated beams and tie beams that were cast-in-place were used.



**Figures 109 and 110.** As shown in the images, the semi-prefabricated beams could be adapted to the different depths of the soil with good bearing capacity (A1-15) (Appendix 1).

### c) The upper layers of the ground were not consolidated

Drilled shafts constructed on-site were also used in this case (A1-23) (Appendix 1).



d) Water was present on the land

In the case of A1-10 (Appendix 1), the geotechnical study recommended constructing continuous flight auger piles, partly because water was present on the land. As shown in the following image, there is a small stream on the edge of the plot and the water table is 4.8 metres from the surface.

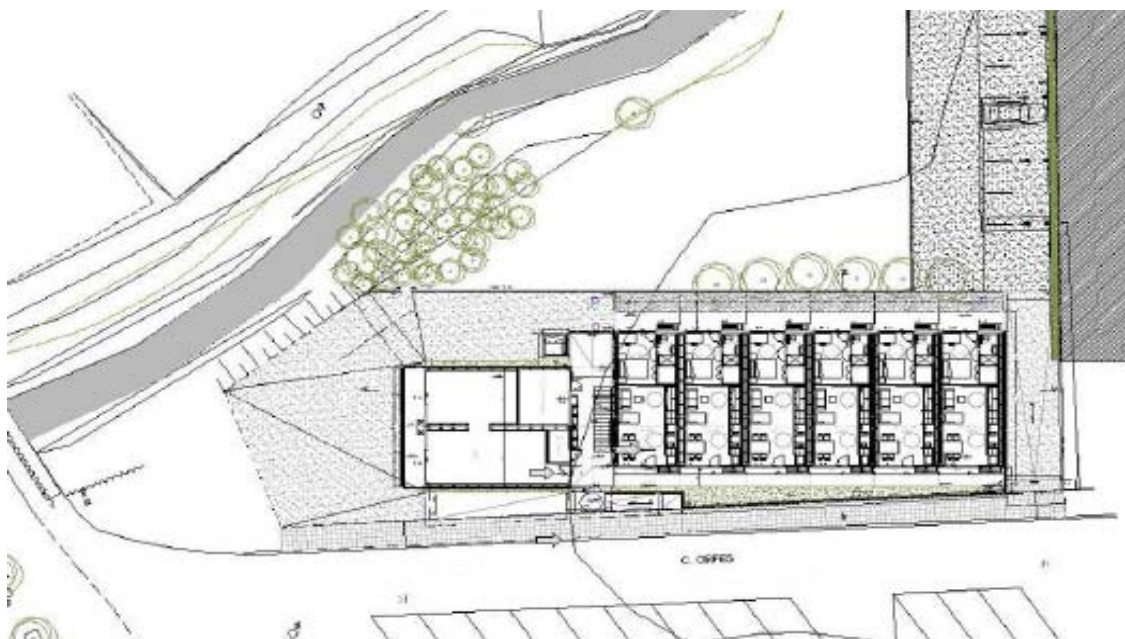


Figure 111. There is a small stream on the edge of the plot (A1-10) (Appendix 1).

e) The low consistency of the ground

In the case of A1-27 (Appendix 1), a ground slab foundation was cast-in-place because the consistency of the ground was low.

## 8. Initial constraints

a) The crane could not position the modules in one go

One of the factors that led to the use of cast-in-place foundations in A1-13 (Appendix 1) was that the positioning of the dwelling over the foundations had to take place in two steps. In the first step, the module was rested on the foundations. In the second step, it was placed in its exact position.

b) The ground floor had to be open plan

In A1-9 (Appendix 1), the ground floor had to be open plan to house the required access areas, a day centre, and the extension of the doctor's surgery. According to those involved, this made it difficult to use prefabricated foundations.



**Figures 112 and 113. In A1-13 (Appendix 1) the modules had to be placed over the foundations in two steps. In the first step, the module was rested on the foundations. In the second step, it was positioned in its exact place.**

c) The owner selected the construction company

In A1-24 (Appendix 1), the owner selected the construction company. Therefore, the design of the foundations had to take into account the construction company's resources. Cast-in-place ground beams were designed for the site, with some variations.

## **9. Recommendations**

In A1-10 (Appendix 1), the geotechnical study proposed the construction of continuous flight auger piles. The geologists were interviewed and stated that they had not considered the use of precast piles because piles were usually cast-in-place, the building was situated in a town, and there was water on the land.

## **10. Difficulties in transporting and handling precast foundations, due to their weight and size**

The construction company that built the foundations in A1-10, A1-15, A1-16, A1-17 and A1-24 (Appendix 1) mentioned that one of its reasons for selected semi-prefabricated or cast-in-place foundations was that the transport and handling of large, heavy precast elements was difficult.

## 6. Data

### 6.1. Comparison between the prefabricated foundation and the semi-prefabricated foundation in the A1-10 case study

#### 6.1.1. Description of the foundations

This is the foundation in the A1-10 case study. Only the part of the foundation inside the box will be analysed.

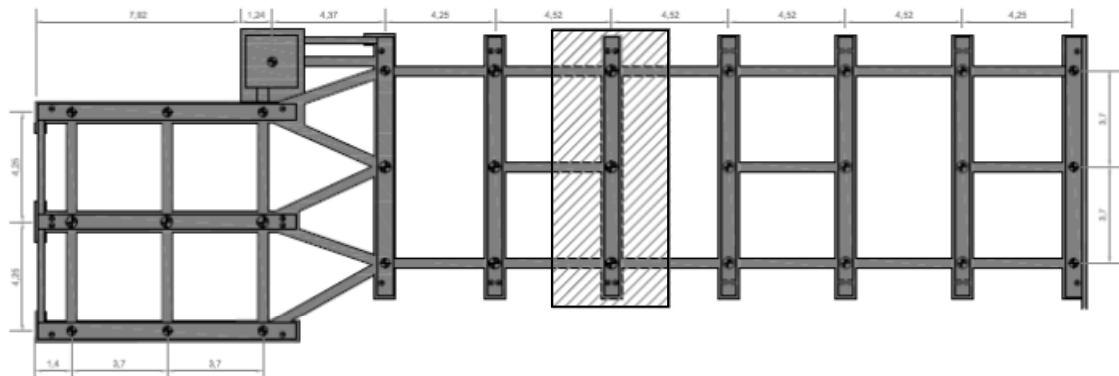


Figure 114. Foundation plan for the A1-10 case study. Only the part of the foundation inside the box will be analysed.

The part of the foundation that will be analysed consists of three continuous flight auger piles, a semi-prefabricated ground beam and cast-in-place tie beams.

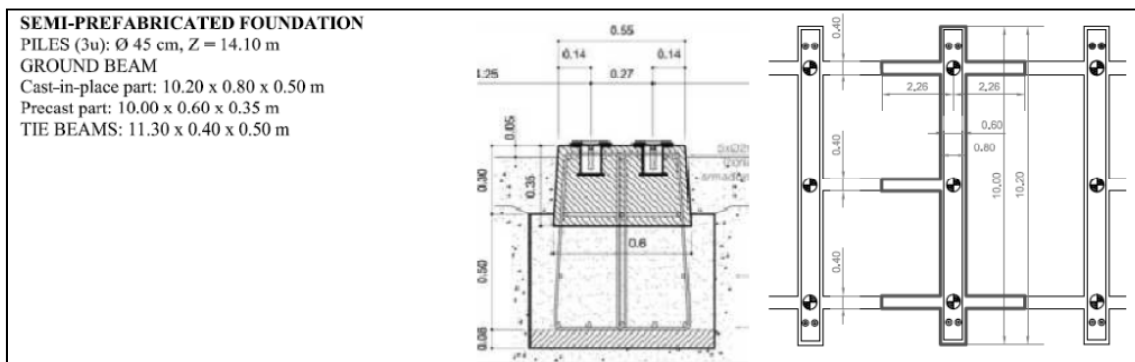


Figure 115. Semi-prefabricated foundation under analysis: dimensions, section of the semi-prefabricated ground beam and plan.

The ground beam is semi-prefabricated, to avoid problems of dimensional tolerances between the prefabricated building and the cast-in-place foundation. These prefabricated semi-beams have the connectors to the modules laid out with the factory error.

The executive project includes the cost of the precast ground beam delivery, but not its assembly. The assembly of these prefabricated semi-beams over the trenches seems to have been laborious. It is considered that the time and machinery required to assemble this precast semi-ground beam is equal to assembling a prefabricated beam, according to data from the BEDEC database. However, the assembly of the semi-ground beam would have required more time, machinery and workers. This has not been taken into account in the budgets, because of the lack of information [Pujadas et al., 2013]. The impact of the assembly of the semi-prefabricated ground beams is estimated in Section 6.1.5.



**Figure 116. Continuous flight auger piles. Pile heads were demolished and rebars were protected. Figure 117. Placing the semi-prefabricated ground beam over the piles with a crane. Figure 118. Placing reinforcing rebars of tie beams inside trenches.**



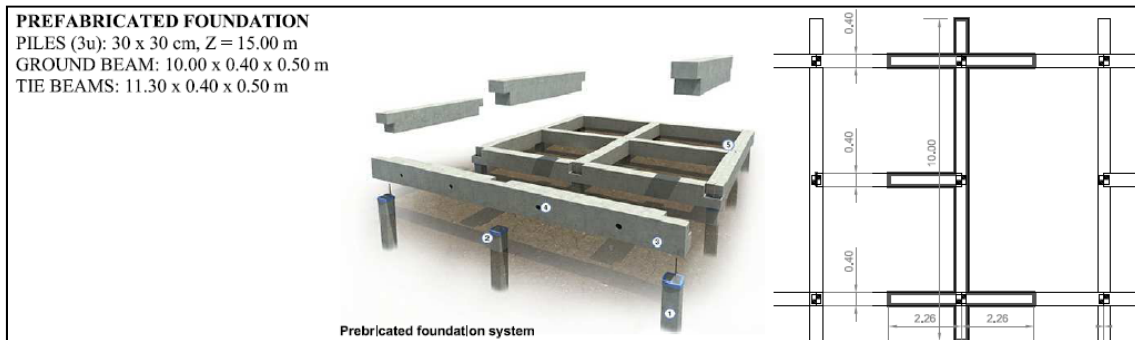
**Figure 119. Precast semi-beams laid out in plan and height. Figure 120. Tie beams and the lower parts of ground beams were concreted.**

The semi-prefabricated ground beams were oversized, and therefore the piles were also oversized because they had to support more load. The oversizing resulted in more concrete,



steel, earthworks, soil transport, and other factors. In addition, the semi-prefabricated ground beams need a base course.

The proposal was to build a prefabricated foundation composed of three precast piles, a precast ground beam and prefabricated tie beams.



**Figure 121. Prefabricated foundation under analysis: dimensions, foundation system image and plan.**

Cast-in-place tie beams must be at a lower level than prefabricated tie beams. This is because cast-in-place tie beams must be connected to the cast-in-place construction. In a prefabricated foundation system, this is not necessary: tie beams can be on the same level as the prefabricated ground beams. This results in less earthworks and less transport and disposal of earth.



**Figure 122. Cast-in-place tie beams are below the level of prefabricated semi-beams. Figure 123. In a prefabricated foundation system, the prefabricated tie beams can be at the same level as the precast ground beams.**

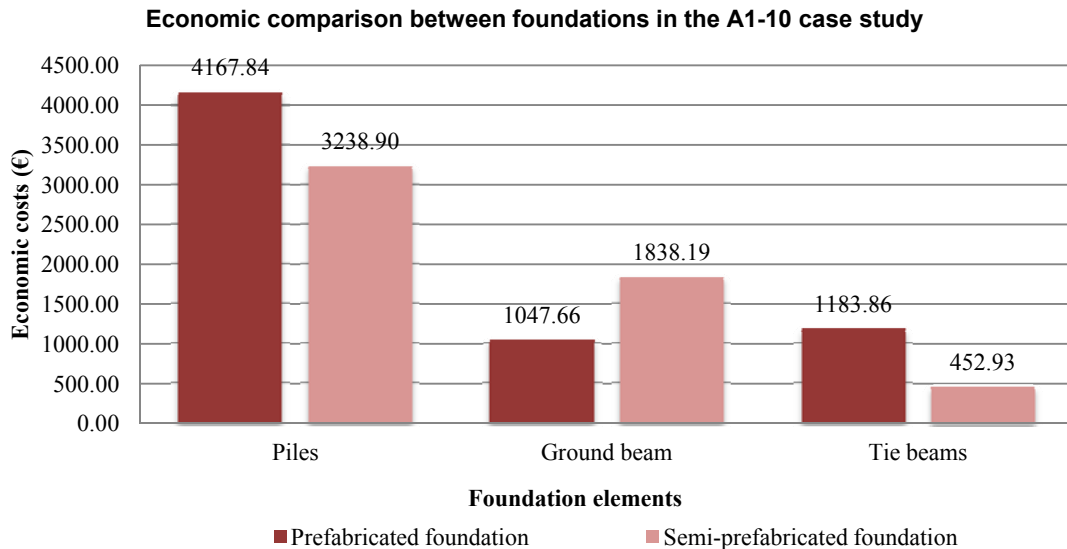
It was considered that excavated soil is transported to other works for reuse. Pile heads and dirty soil are transported to an authorized waste management facility.

**6.1.2. Economic comparison between the prefabricated foundation and the semi-prefabricated foundation in the A1-10 case study**

This prefabricated foundation is 16% more expensive than the semi-prefabricated foundation. Precast piles are 29% more expensive than cast-in-place piles. This is due to the fact that one meter of precast pile delivered on-site is much more expensive than one meter of pile built on-site. However, the prefabricated ground beam is 43% cheaper than the semi-prefabricated ground beam, because the semi-prefabricated ground beam was oversized, and also partly prefabricated. The price of the precast reinforced foundation is initially more expensive than the built on-site option, because it costs more money to manufacture it, and transport and assembly costs must be added. Prefabricated tie beams are more than one and a half times more expensive than those built on-site for the same reasons. The items of earthworks, pile breaking, and base course construction have little impact on the total budget.

Economic comparison between foundations in the A1-10 case study					
Foundation elements	Prefabricated foundation		Semi-prefabricated foundation		Difference
	€	%	€	%	
Piles	4167.84	65.13	3238.90	58.57	128.68
Ground beam	1047.66	16.37	1838.19	33.24	56.99
Tie beams	1183.86	18.50	452.93	8.19	261.38
<b>TOTAL</b>	<b>6399.36</b>	<b>100.00</b>	<b>5530.02</b>	<b>100.00</b>	<b>115.72</b>

**Table 5. Economic comparison between foundations in the A1-10 case study.**

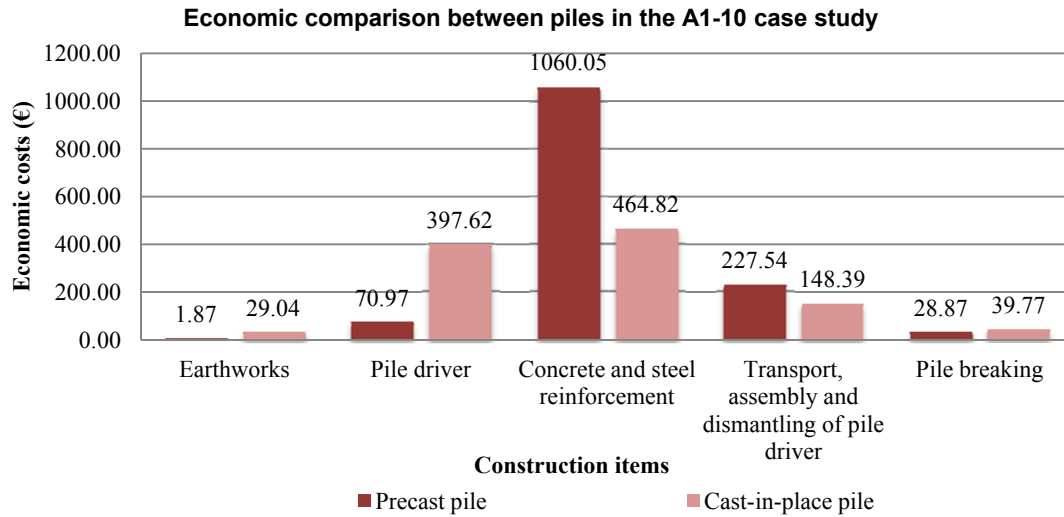


**Graph 1. Economic comparison between foundations in the A1-10 case study.**

a) Piles

Precast piles are 29% more expensive than cast-in-place piles, although precast piles are smaller (1.35 m<sup>3</sup>/pile – 2.24 m<sup>3</sup>/pile).

A pile of 30 x 30 cm and 15.00 m length was compared with a continuous flight auger pile of Ø45 cm and 14.10 m length.



**Graph 2. Economic comparison between piles in the A1-10 case study.**

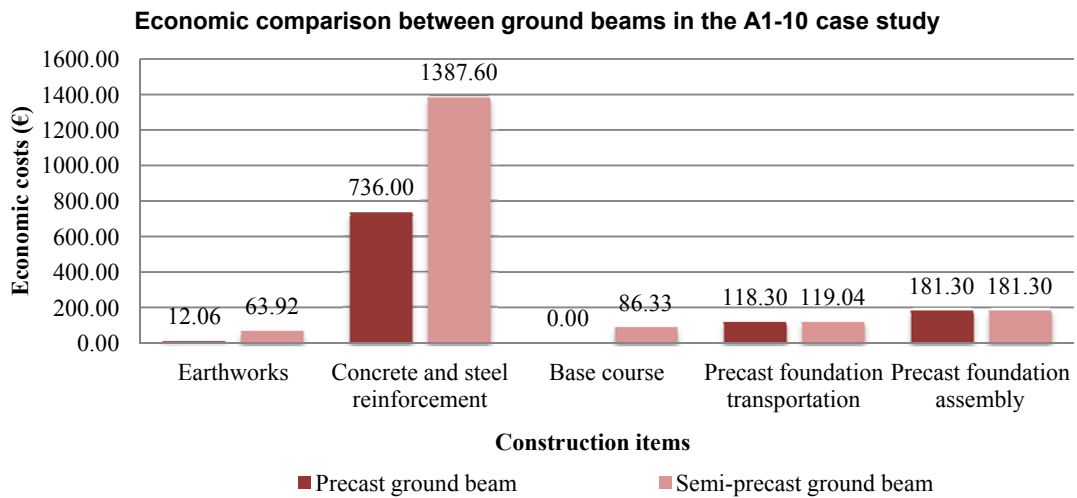
As can be seen, the item that has the greatest impact is the price of the pile (concrete and steel reinforcement). According to a leading precast company of piles, one meter of a precast pile of Ø 30 x 30 cm transported to the building site with an ABB joint is €75.40. In contrast, the price of one meter of a cast-in-place pile of Ø 45 cm is €32.97 (construction is not considered). Moreover, precast piles are longer (15.00 m - 14.10 m).

The price of the pile also varies depending on how it is built. According to the BEDEC database, driving a pile with a pile driver equipped with a free fall hammer costs €4.73 per linear meter. However, if the pile is built on-site, it is 5 times more expensive (€28.20). The transport, assembly and dismantling of a pile driver is 35% more expensive than the transport, assembly and dismantling of a rotary drilling rig (€7,053.64 – €4,600). Of course, this difference will be amortized, depending on the number of piles that are built on-site. (In this case, the amount was divided into the 31 piles in the design). The items of earthworks and breaking piles do not have a considerable impact on the total budget.

*b) Ground beam*

The semi-prefabricated ground beam is more three times larger than the prefabricated ground beam (2.00 m<sup>3</sup> – 6.09 m<sup>3</sup>), because it is oversized. The price of the linear foundation was considered to be 368 €/m<sup>3</sup>. This price is an average of the prices given by Spanish precast companies. (For more information, please see Appendix 3). In this budget, a semi-ground beam with these characteristics would cost €736.00 (2015) when it is delivered on-site. According to the executive project, the cost was €1,696.00 (2008). The assembly of the semi-prefabricated ground beam was considered in the same way as the assembly of a prefabricated ground beam (for more information, see Appendix 3). It appears that it was difficult to position the semi-beam, but there is not enough data to quantify this aspect.

The precast ground beam is 43% cheaper than the semi-prefabricated ground beam because it is made of less concrete. Both ground beams contain a similar amount of steel (316.69 kg – 348.64 kg). They have the same assembly costs because they are the same length, and this item is estimated in linear meters. And transportation costs are also similar because the weight is similar (5.00 t – 5.03 t). In addition, the precast ground beam has lower earthworks costs, and does not need a base course.

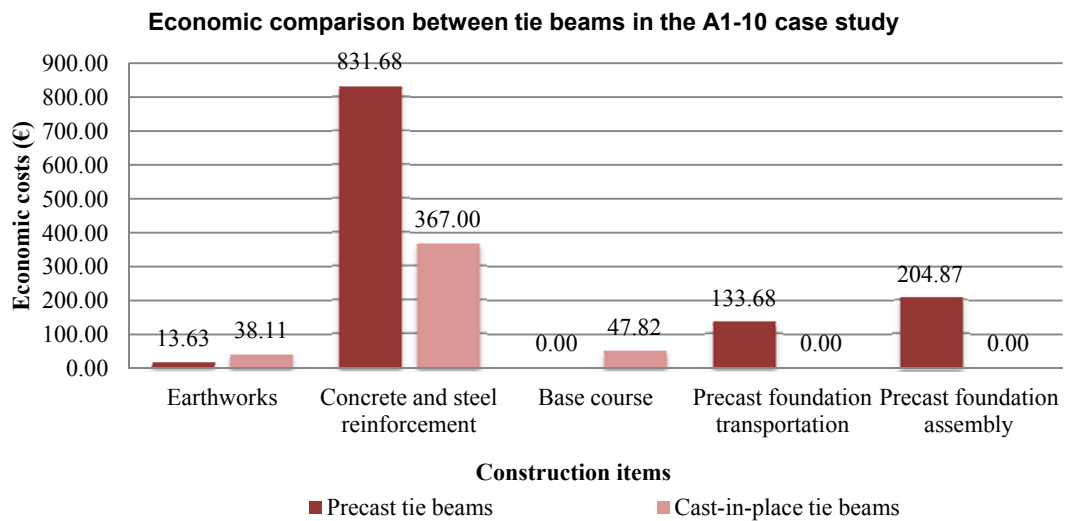


**Graph 3. Economic comparison between ground beams in the A1-10 case study.**

*c) Tie beams*

Precast tie beams are more than one and a half times more expensive than cast-in-place tie beams. The price of a precast tie beam was considered to be the same as that of a prefabricated ground beam (€368/m<sup>3</sup>). In reality, the price of a precast tie beam would be slightly lower than the price of a prefabricated ground beam. A tie beam has less steel reinforcement, but the amount of construction work, the amortization of the manufacturing plant, the molds and machinery would be similar.

As shown in the following graph, the material price of precast tie beams is more than twice as high as that of cast-in-place tie beams. Transportation and assembly costs must also be added.



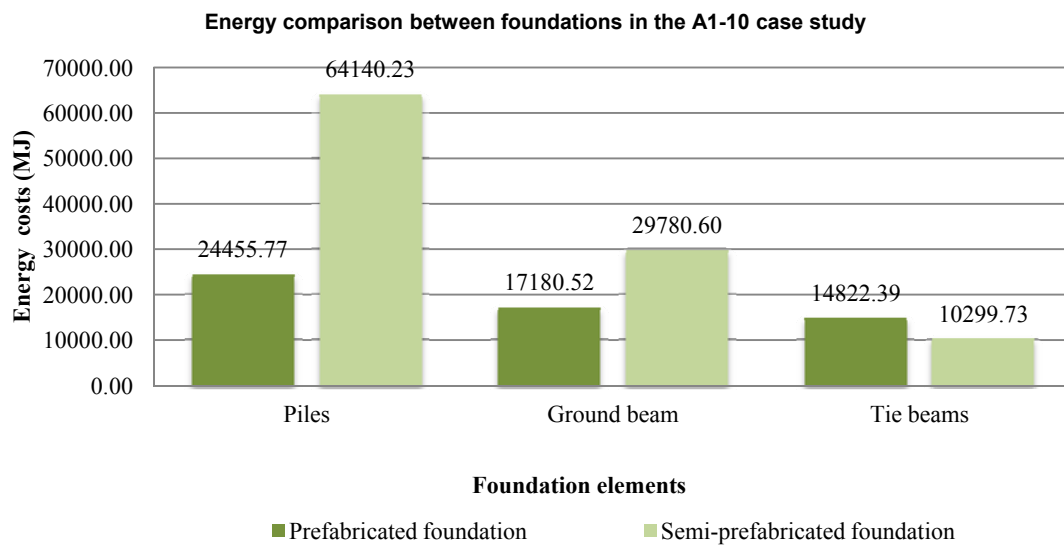
**Graph 4. Economic comparison between tie beams in the A1-10 case study.**

**6.1.3. The embodied energy in the prefabricated foundation and the semi-prefabricated foundation in the A1-10 case study**

Forty-six per cent less energy is required to prefabricate this foundation than to build it semi-prefabricated. To build a precast pile, 62% less energy is required than to build a cast-in-place pile. This is because less energy is required to drive a pile than to build it on-site (11.36 MJ/m – 667.72 MJ/m). In addition, the precast piles that were considered are smaller (1.35 m<sup>3</sup>/pile – 2.24 m<sup>3</sup>/pile). Forty-two per cent less energy is required to build a precast ground beam than to build a semi-prefabricated ground beam. This is because the semi-prefabricated ground beam was oversized, and part of it was prefabricated. And forty-four per cent more energy is required to build precast tie beams than to build it cast-in-place. This is because more energy is required to build a one cubic meter of a precast linear foundation than a cast-in-place one. Prefabricated concrete has more embodied energy (2770.12 MJ/m<sup>3</sup> – 2342.22 MJ/m<sup>3</sup>) because it contains more cement (400 kg/m<sup>3</sup> - 275 kg/m<sup>3</sup>). The energy consumed in the transportation and assembly of the prefabricated foundation must also be added.

Energy comparison between foundations in the A1-10 case study					
Foundation elements	Prefabricated foundation		Semi-prefabricated foundation		Difference
	MJ	%	MJ	%	
Piles	24455.77	43.32	64140.23	61.54	38.13
Ground beam	17180.52	30.43	29780.60	28.57	57.69
Tie beams	14822.39	26.25	10299.73	9.88	143.91
<b>TOTAL</b>	<b>56458.69</b>	<b>100.00</b>	<b>104220.57</b>	<b>100.00</b>	<b>54.17</b>

**Table 6. Energy comparison between foundations in the A1-10 case study.**

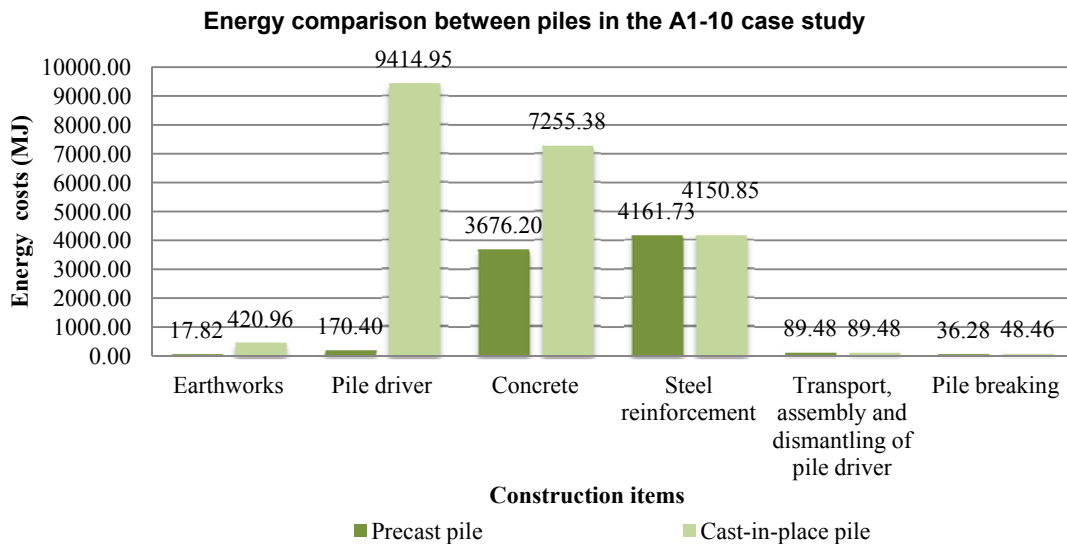


**Graph 5. Energy comparison between foundations in the A1-10 case study.**

a) Piles

Sixty-two per cent less energy is required to build a precast pile than a cast-in-place pile. The items that have greatest impact on energy consumption are those related to construction. Less energy is required to drive a precast pile than build it on-site. To drive one meter of 30 x 30 cm precast pile, 11.36 MJ/m is required. To build one linear meter of a Ø 45 cm pile, 58 times more energy is required (667.73 MJ/m). This comparison involves piles of different dimensions; but it is easy to see that more energy is required to build a pile on-site than to drive it on-site.

Materials also play an important role in this budget. The precast pile has smaller dimensions (1.35 m<sup>3</sup>/pile – 2.24 m<sup>3</sup>/pile), but more steel reinforcement (179.85 kg/pile – 179.38 kg/pile). Less earthworks are required because there is no extraction of soil. And precast piles compress the ground.



**Graph 6. Energy comparison between piles in the A1-10 case study.**

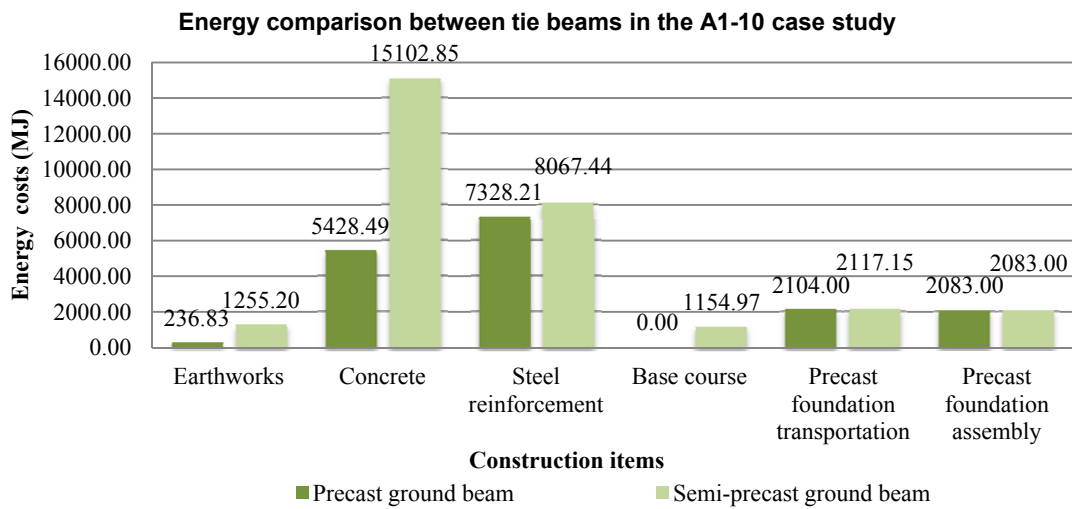


**Figure 124. Construction of continuous flight auger piles. Figure 125. Concrete pump and truck mixer.**



*b) Ground beam*

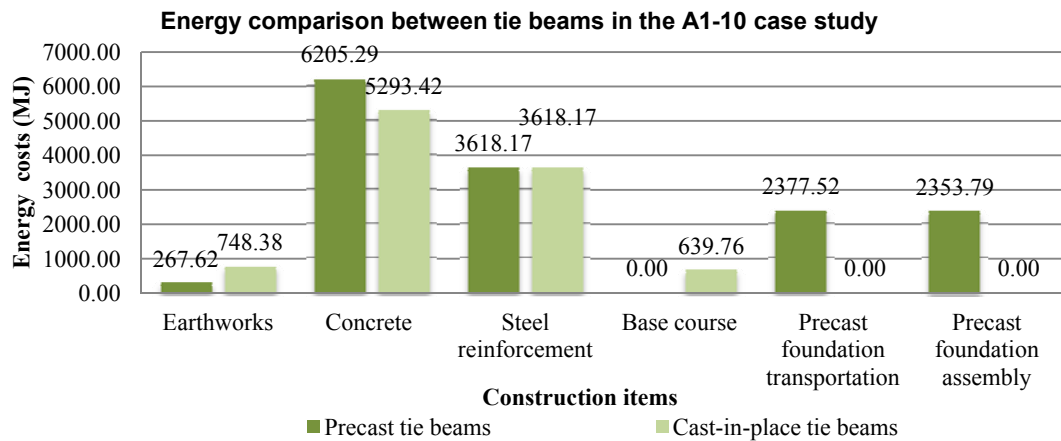
Forty-two per cent less energy is required to build the ground beam prefabricated than on-site. This is because the semi-prefabricated ground beam is oversized ( $2.00 \text{ m}^3 - 6.09 \text{ m}^3$ ). Both ground beams contain a similar amount of steel. Therefore, the amount of concrete is the factor that makes a difference in the embodied energy value. In addition, part of the semi-prefabricated ground beam is precast. Precast concrete has more embodied energy ( $2770.12 \text{ MJ/m}^3 - 2342.22 \text{ MJ/m}^3$ ). Furthermore, energy from the transportation and assembly of the prefabricated foundation must be added. The semi-prefabricated ground beam consumes more energy in earth movements and transport of soil, because it is oversized. It also requires a base course.



**Graph 7. Energy comparison between ground beams in the A1-10 case study.**

*c) Tie beams*

Precast tie beams and cast-in-place tie beams are the same size. However, forty-four per cent more energy is required to build precast tie beams. This is because precast concrete is more expensive energetically. The energy of transportation and assembly must also be added.



**Graph 8. Energy comparison between tie beams in the A1-10 case study.**

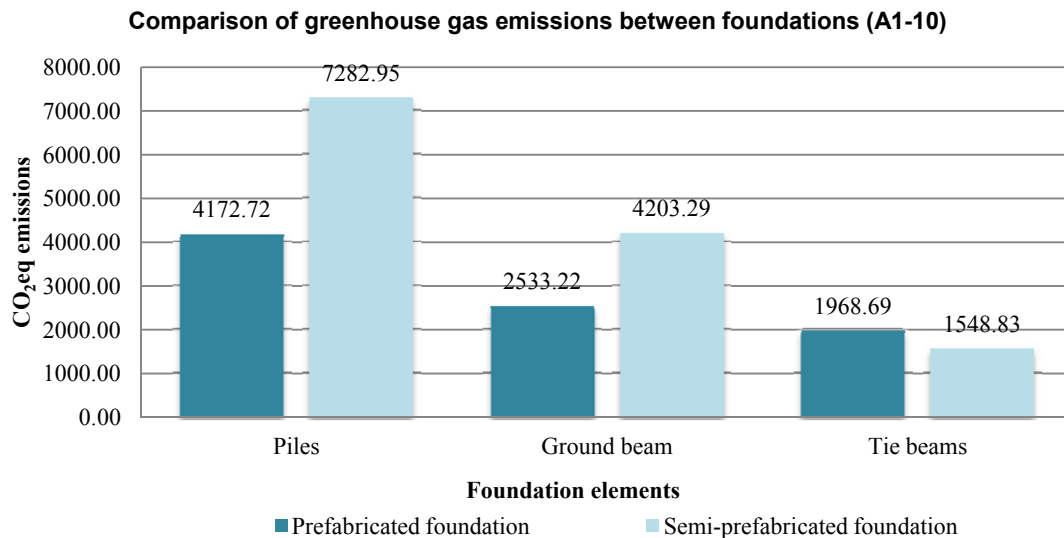


**6.1.4. Comparison of greenhouse gas emissions between the foundation and the semi-prefabricated foundation in the A1-10 case study**

The construction of the precast foundation releases 34% fewer kilogrammes of CO<sub>2</sub> equivalent than the semi-prefabricated foundation. The construction of prefabricated piles reduces the amount of greenhouse gas emissions by 43%, and the construction of precast ground beams reduces emissions by 40%. This is because ground beams and piles in the semi-prefabricated foundation are oversized, and consequently, they contain much more concrete. How a pile is built on-site is also relevant. The emissions produced in the construction of one linear meter of a Ø 45 cm cast-in-place pile are 58 times higher than for one meter of a 30 x 30 cm precast pile (0.74 kilogrammes of CO<sub>2</sub> equivalent/m – 43.55 kilogrammes of CO<sub>2</sub> equivalent/m). The construction of precast tie beams, which have the same dimensions as cast-in-place ground beams, releases 27% more emissions, because precast concrete contains more cement, and the emissions generated in transportation and assembly must be added.

Comparison of greenhouse gas emissions between foundations in the A1-10 case study					
Foundation elements	Prefabricated foundation		Semi-prefabricated foundation		Difference
	kg	%	kg	%	
Piles	4172.72	48.10	7282.95	55.87	57.29
Ground beam	2533.22	29.20	4203.29	32.25	60.27
Tie beams	1968.69	22.69	1548.83	11.88	127.11
<b>TOTAL</b>	<b>8674.62</b>	<b>100.00</b>	<b>13035.07</b>	<b>100.00</b>	<b>66.55</b>

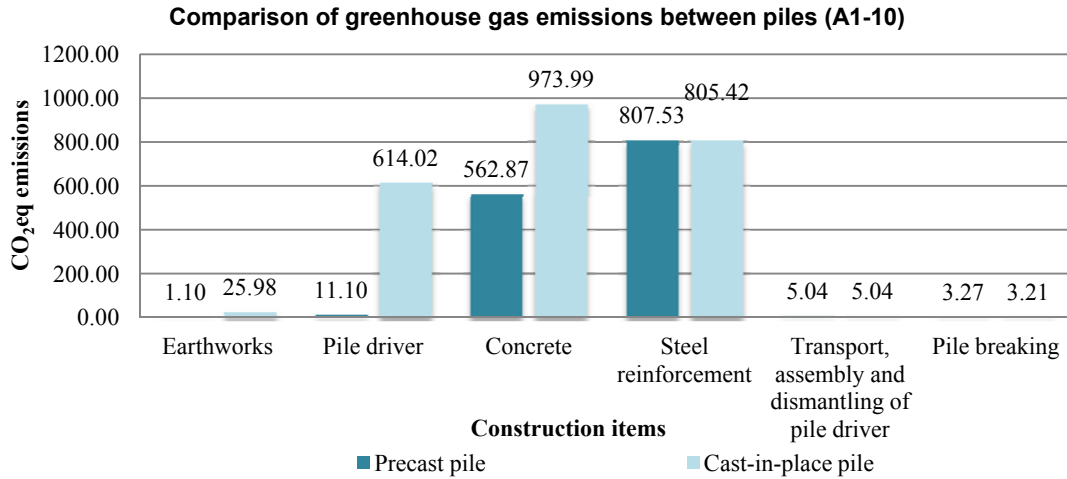
Table 7. Comparison of greenhouse gas emissions between foundations in the A1-10 case study.



Graph 9. Comparison of greenhouse gas emissions between foundations in the A1-10 case study.

a) Piles

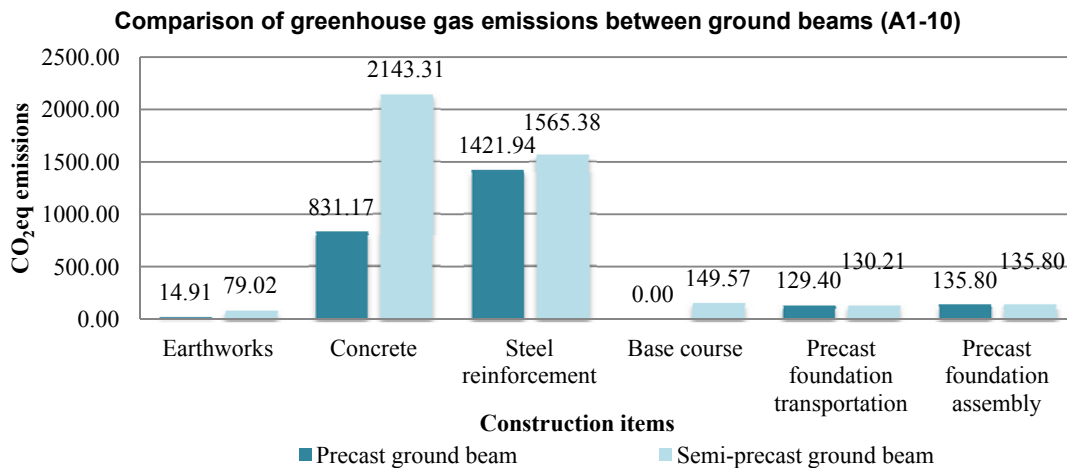
The construction of precast piles releases 43% less emissions of CO<sub>2</sub> equivalent than that of cast-in-place concrete piles. This is due to the fact that the precast piles considered here are smaller and consequently they contain less concrete. Moreover, driving a precast pile generates 58 times less emissions than building it cast-in-place (0.74 kilogrammes of CO<sub>2</sub> equivalent – 43.55 kilogrammes of CO<sub>2</sub> equivalent). Steel reinforcement has a considerable impact on both budgets.



Graph 10. Comparison of greenhouse gas emissions between piles in the A1-10 case study.

b) Ground beam

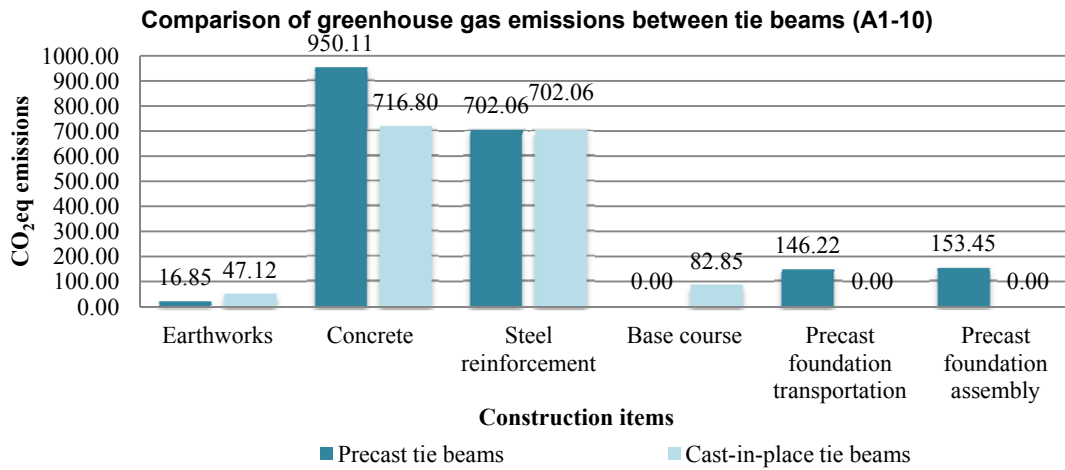
Greenhouse gas emissions are reduced by 40% when the ground beam is completely precast. Items related to materials are responsible for the release of more kilogrammes of CO<sub>2</sub> equivalent. Both foundations have similar emissions from reinforcing steel. However, the semi-prefabricated ground beam releases more emissions because it contains more concrete, and part of it is prefabricated.



Graph 11. Comparison of greenhouse gas emissions between ground beams in the A1-10 case study.

c) Tie beams

Prefabricated tie beams have same dimensions as cast-in-place tie beams. However, the construction of prefabricated tie beams generates 27% more kilogrammes of CO<sub>2</sub> equivalent. This is because precast concrete releases more greenhouse gases (424.14 kilogrammes of CO<sub>2</sub> equivalent/m<sup>3</sup> – 317.17 kilogrammes of CO<sub>2</sub> equivalent/m<sup>3</sup>). In addition, the kilogrammes of CO<sub>2</sub> equivalent generated in transportation and assembly must be added.



**Graph 12. Comparison of greenhouse gas emissions between tie beams in the A1-10 case study.**

**6.1.5. The impact of the assembly of the semi-prefabricated ground beams in relation to the foundation**

The impact of the assembly of semi-prefabricated ground beams was estimated. A working group comprised of a first officer, a labourer and a crane operator was considered, as well as a 12-tonne crane, according to the BEDEC database. The assembly of precast semi-beams was similar to the assembly of precast ground beams (for more information, please see Appendix 3).



**Figure 126 and 127. Placement of precast semi-beams over trenches. Figure 128. Layout of precast semi-beams in plan and height.**

The cost of the semi-prefabricated foundation exceeds the cost of the prefabricated foundation if one day and one hour of assembly are added. The embodied energy and emissions are already higher in the semi-prefabricated foundation.

<b>Economic impact of the assembly of the semi-prefabricated ground beams (A1-10)</b>						
	Prefabricated foundation			Semi-prefabricated foundation		
Ground beam	1047.66			1838.19		
<b>TOTAL</b>	<b>6399.36</b>			<b>5530.02</b>		
Semi-prefabricated foundation + assembly						
	+ 1 hour	+ 2 h	+ 4 h	+ 7 h	+ 1 day	+ 1 d + 1 h
	€	€	€	€	€	€
Ground beam	1936.44	2034.69	2231.20	2525.95	2624.21	2722.46
<b>TOTAL</b>	<b>5628.28</b>	<b>5726.53</b>	<b>5923.03</b>	<b>6217.79</b>	<b>6316.04</b>	<b>6414.29</b>

**Table 8. Economic impact of the assembly of the semi-prefabricated ground beams (A1-10).**

<b>Energy impact of the assembly of the semi-prefabricated ground beams on the A1-10 foundation</b>						
	Prefabricated foundation			Semi-prefabricated foundation		
Ground beam	17180.52			29780.60		
<b>TOTAL</b>	<b>56458.69</b>			<b>104220.57</b>		
Semi-prefabricated foundation + assembly						
	+ 1 h	+ 2 h	+ 4 h	+ 1 day	+ 1 d + 4 h	+ 2 d
	MJ	MJ	MJ	MJ	MJ	MJ
Ground beam	30822.08	31863.55	33946.49	38112.38	42278.27	46444.16
<b>TOTAL</b>	<b>105262.04</b>	<b>106303.51</b>	<b>108386.46</b>	<b>112552.34</b>	<b>116718.23</b>	<b>120884.12</b>

**Table 9. Energy impact of the assembly of the semi-prefabricated ground beams (A1-10).**

<b>CO<sub>2</sub>eq emissions impact of the assembly of the semi-prefabricated ground beams (A1-10)</b>						
	Prefabricated foundation			Semi-prefabricated foundation		
Ground beam	2533.22			4203.29		
<b>TOTAL</b>	<b>8674.62</b>			<b>13035.07</b>		
Semi-prefabricated foundation + assembly						
	+ 1 hour	+ 2 h	+ 4 h	+ 1 day	+ 1 d + 4 h	+ 2 d
	Kilogrammes CO <sub>2</sub> equivalent	Kilogrammes CO <sub>2</sub> equivalent	Kilogrammes CO <sub>2</sub> equivalent	Kilogrammes CO <sub>2</sub> equivalent	Kilogrammes CO <sub>2</sub> equivalent	Kilogrammes CO <sub>2</sub> equivalent
Ground beam	4271.21	4339.13	4474.98	4746.66	5018.35	5290.04
<b>TOTAL</b>	<b>13102.99</b>	<b>13170.91</b>	<b>13306.76</b>	<b>13578.44</b>	<b>13850.13</b>	<b>14121.82</b>

**Table 10. CO<sub>2</sub>eq emissions impact of the assembly of semi-prefabricated ground beams (A1-10).**

## 6.2. Comparison between the precast foundation and the cast-in-place foundation in the A1-16 case study

### 6.2.1. Description of the foundations

This is the foundation in the A1-16 case study. Only the part of the foundation inside the box will be analysed.

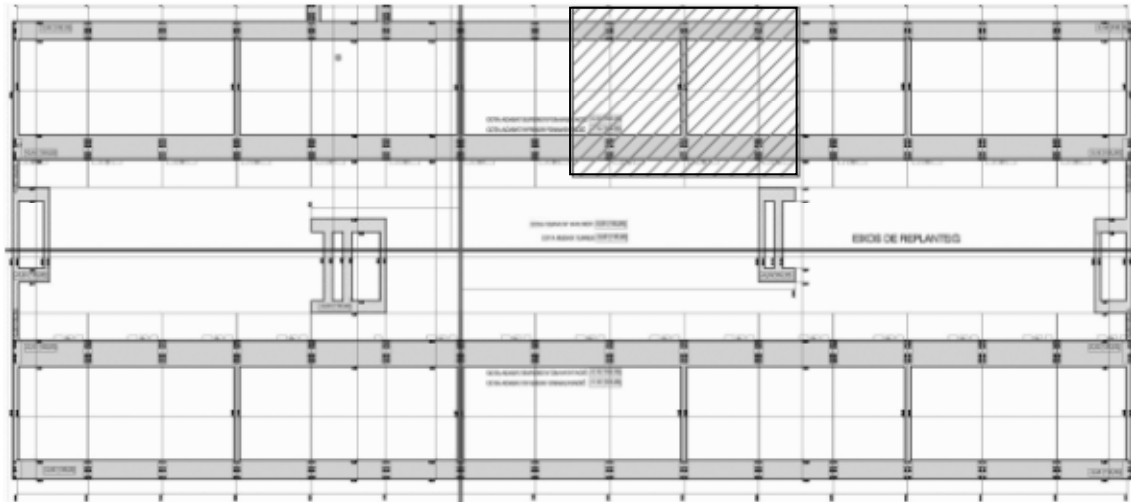


Figure 129. Foundation plan for the A1-16 case study. Only the part of the foundation inside the box will be analysed.

The foundation under analysis consists of two cast-in-place ground beams (A and B) and a tie beam built on-site. Each ground beam has three precast pads that have the connectors in the required position for the modules.

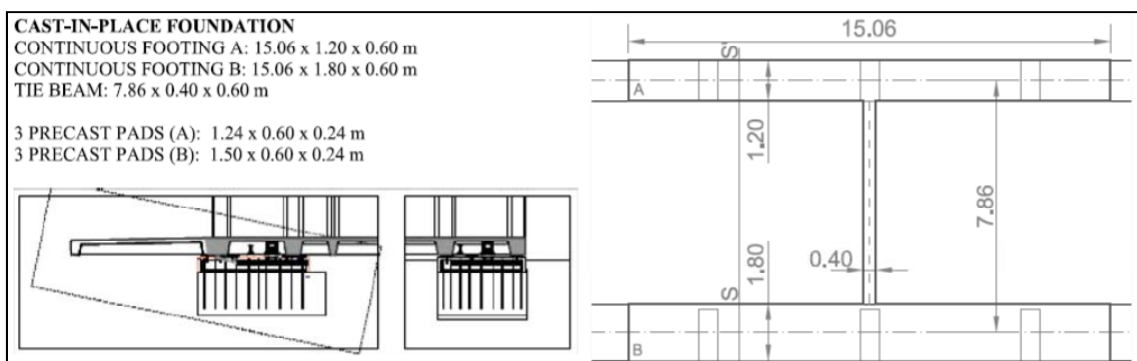


Figure 130. Cast-in-place foundation under analysis: dimensions, cast-in-place ground beam section and plan.



**Figure 131. Precast pads, mechanisms for laying out precast pads, and ground beam trench with steel reinforcement inside. Figure 132. Precast pads and cast-in-place ground beam.**

In the A1-16 case study, the intention was to save precast concrete. Rather than building a precast ground beam, precast pads were manufactured. Each module was placed over four precast pads. Each pad contained the connectors to the modules, which had been positioned in the factory. However, it was more laborious to install these precast pads than to install the precast semi-beams in the A1-10 case study. The pads were set out along the ground beam, in diagonal and in height, as can be seen in the following images [Pujadas et al., 2013].



**Figures 133, 134 & 135. It was laborious to position precast pads in the A1-16 case study. They were set out along the ground beam, in diagonal and in height.**

The laborious setting out of the pads involved extra items that were not included in the initial budget of the executive project. This delay affected not only the company that built the foundation, but also the module manufacturing company that had to place the modules over the foundations. Due to a lack of data, these items have not been taken into account in the budgets. However, it would be interesting to have all this data for a more complete analysis of the impact. An estimate of the assembly of prefabricated pads is given in Section 6.2.5.



The proposed prefabricated foundation has same dimensions as the cast-in-place foundation. However, the cast-in-place foundation has precast pads with the connectors set out in the factory.

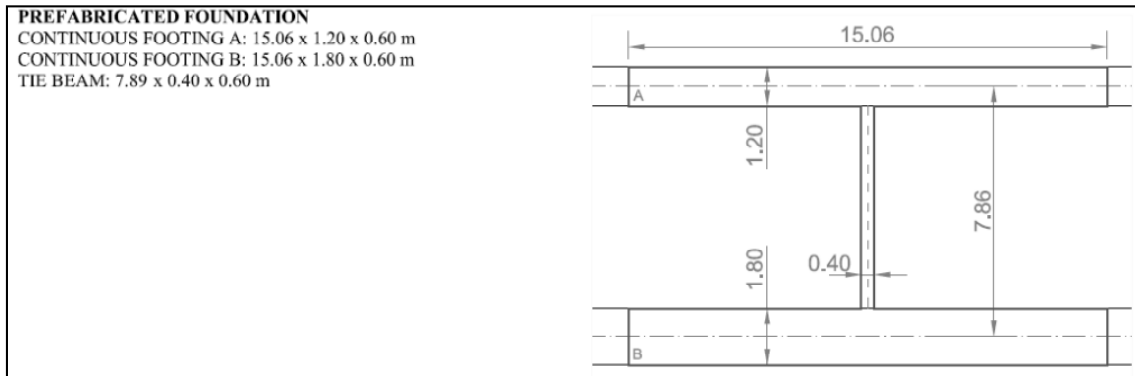


Figure 136. Precast foundation under analysis: dimensions and plan.

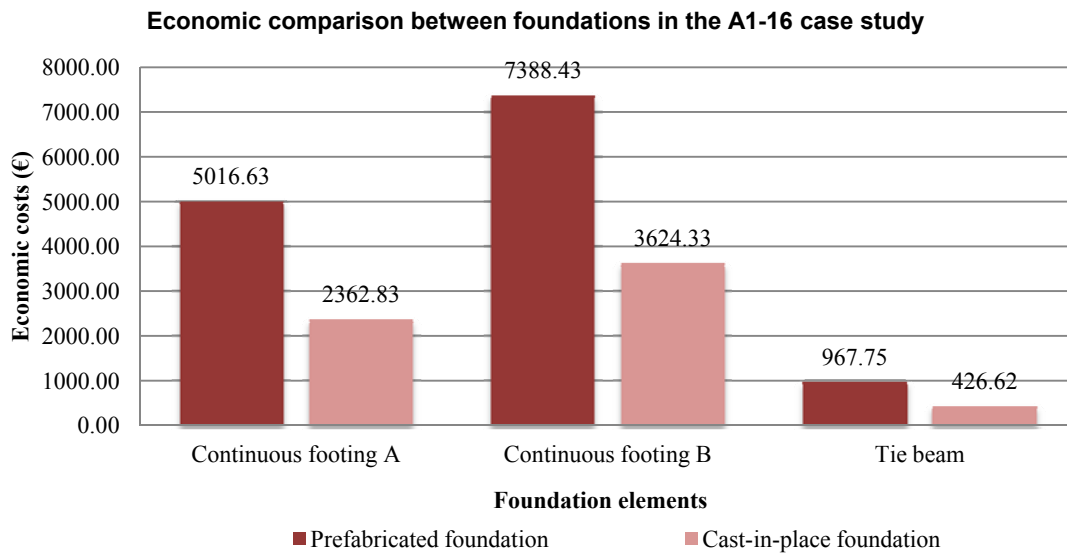
Therefore, these two foundations contain a similar amount of steel and concrete. The prefabricated pads need to be transported and installed. The built on-site foundation requires a base course, which affects the items of earthworks and building a base course. Excavated earth is transported to other works for reuse.

**6.2.2. Economic comparison between the precast foundation and the cast-in-place foundation in the A1-16 case study**

The prefabricated foundation is more than twice as expensive as the cast-in-place foundation. The same situation was found for all foundation elements. Both foundations are the same size, except the cast-in-place ground beams that incorporate prefabricated pads. The biggest difference in costs is due to the reinforced concrete. Precast reinforced concrete is much more expensive than concrete produced on-site. This is because it is more expensive to produce in a factory, and the costs of transport and assembly must be added. Cast-in-place ground beams and tie beam require a base course, and the items of earthworks and transport of soil have higher costs. However, these items are not important in the total budget.

Economic comparison between foundations in the A1-16 case study					
Foundation elements	Prefabricated foundation		Cast-in-place foundation		Difference
	€	%	€	%	%
Continuous footing A	5016.63	37.51	2362.83	36.84	212.31
Continuous footing B	7388.43	55.25	3624.33	56.51	203.86
Tie beam	967.75	7.24	426.62	6.65	226.84
<b>TOTAL</b>	<b>13372.81</b>	<b>100.00</b>	<b>6413.77</b>	<b>100.00</b>	<b>208.50</b>

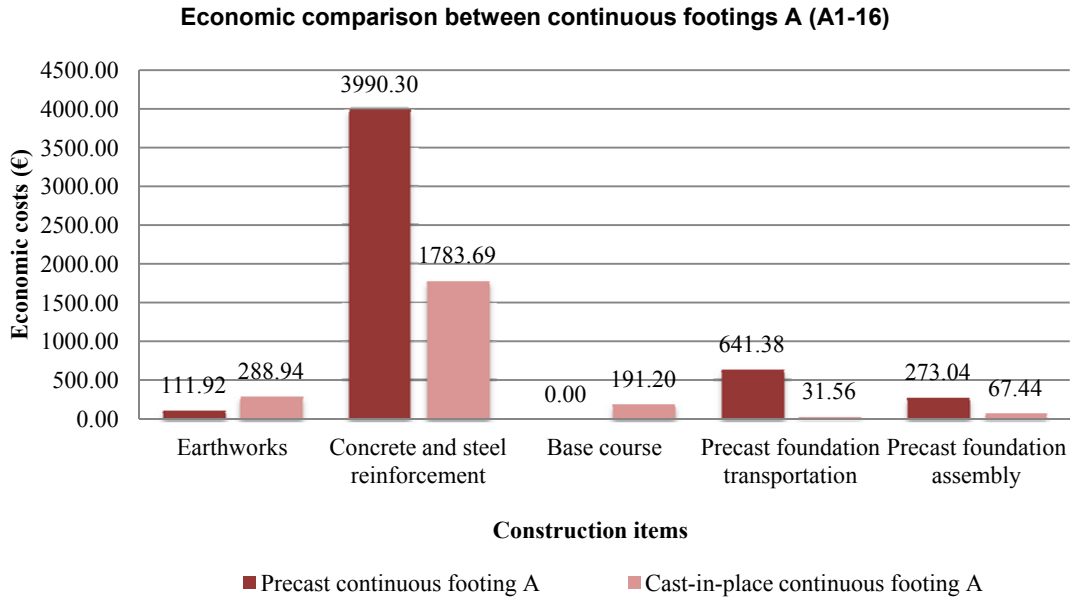
**Table 11. Economic comparison between foundations in the A1-16 case study.**



**Graph 13. Economic comparison between foundations in the A1-16 case study.**

*a) Continuous footing A*

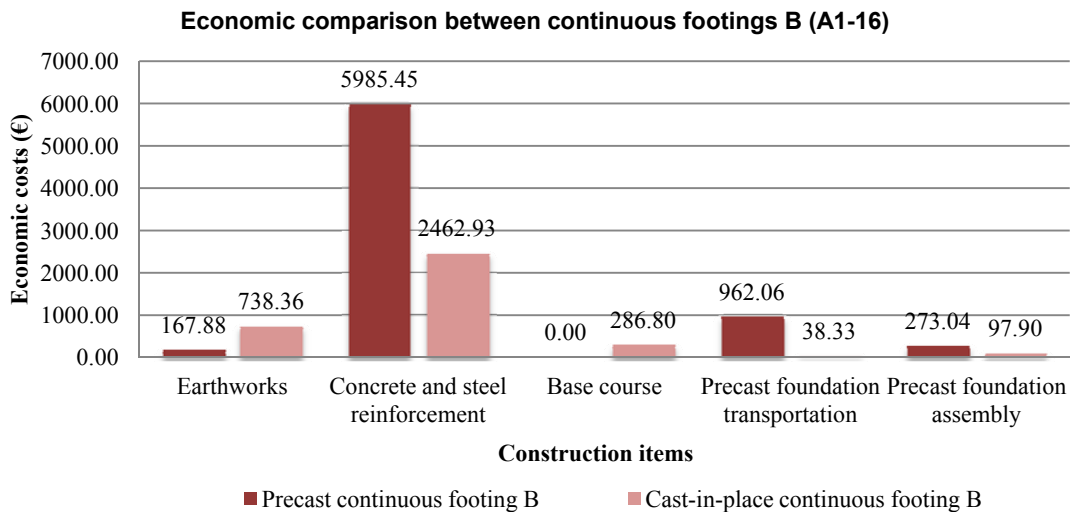
The prefabricated continuous footing is more than twice as expensive as the cast-in-place continuous footing. Both continuous footings have the same dimensions. But the cast-in-place one has three precast concrete pads. The biggest difference between the two footings is due to the price of precast concrete. The precast continuous footing costs €3,990.30, whereas the cast-in-place continuous footing costs €1,587.35, not counting the precast pads. In addition, the precast continuous footing has higher transportation and assembly costs.



**Graph 14. Economic comparison between continuous footings A in the A1-16 case study.**

*b) Continuous footing B*

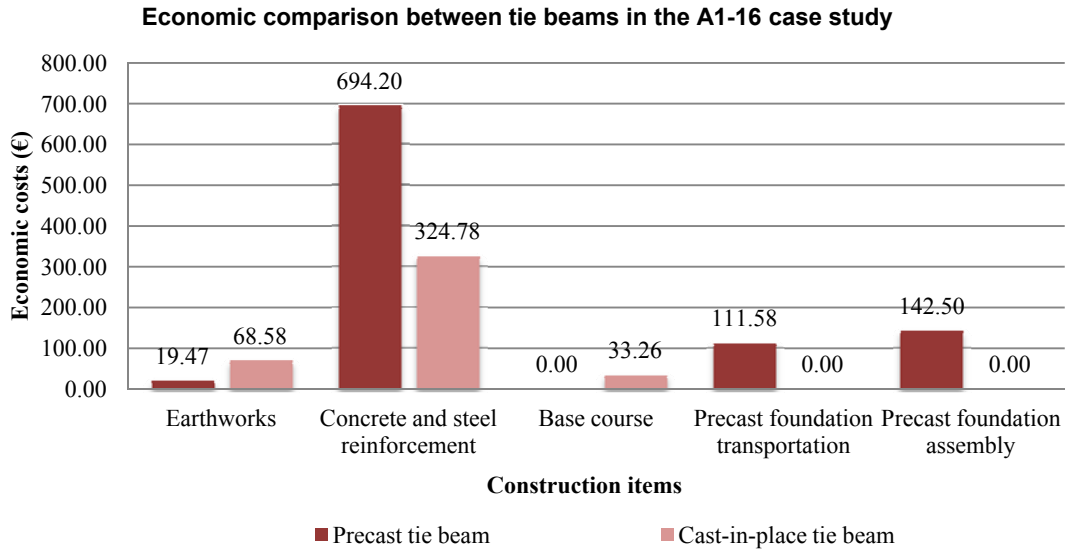
The precast continuous footing B is more than twice as expensive as the cast-in-place continuous footing B. The reasons are the same as for precast continuous footing A.



**Graph 15. Economic comparison between continuous footings B in the A1-16 case study.**

*c) Tie beam*

Prefabricated tie beam is more than twice as expensive than cast-in-place tie beam. The dimensions of the precast tie beam is the same as the cast-in-place tie beam. As shown in the graph below, the concrete in precast tie beams is twice as expensive as that in beams constructed in place. Transport and assembly costs must also be added.



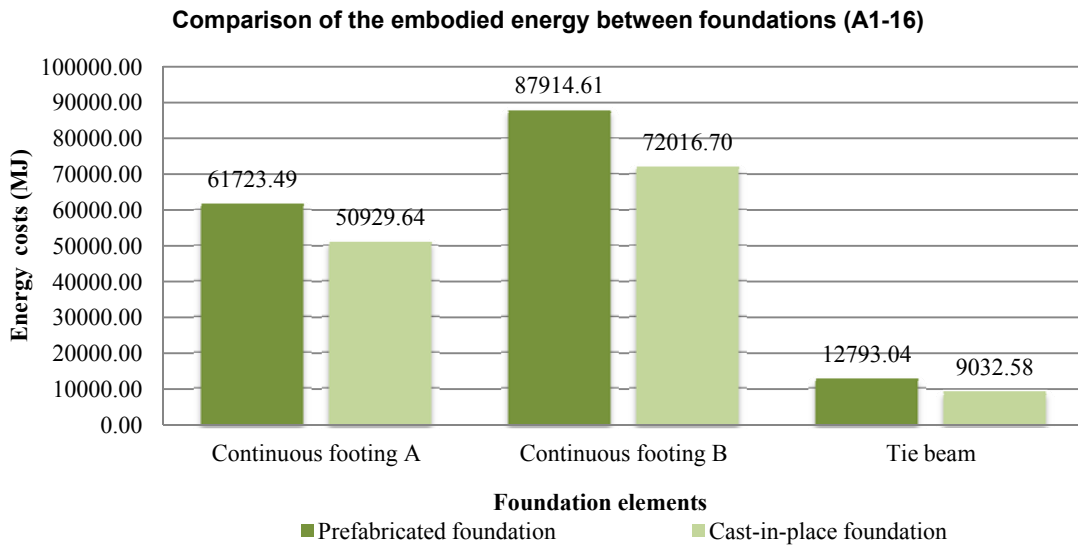
**Graph 16. Economic comparison between tie beams in the A1-16 case study.**

**6.2.3. Comparison of embodied energy between the precast foundation and the cast-in-place foundation in the case study A1-16**

The prefabricated foundation has similar dimensions to the cast-in-place foundation. To build this prefabricated foundation, 23% more energy is required. This is largely due to the fact that precast concrete is more expensive energetically ( $2770.12\text{MJ/m}^3 - 2342.22\text{ MJ/m}^3$ ), because it contains more cement ( $400\text{ kg/m}^3 - 275\text{ kg/m}^3$ ). Moreover, the prefabricated foundation also consumes more energy in transport and assembly than the cast-in-place foundation. Nevertheless, the cast-in-place foundation needs a base course and more earthworks. However, these items are of little relevance in the total budget.

Comparison of the embodied energy between foundations in the A1-16 case study					
Foundation elements	Prefabricated foundation		Cast-in-place foundation		Difference
	MJ	%	MJ	%	
Continuous footing A	61723.49	38.00	50929.64	38.59	121.19
Continuous footing B	87914.61	54.12	72016.70	54.57	122.08
Tie beam	12793.04	7.88	9032.58	6.84	141.63
<b>TOTAL</b>	<b>162431.13</b>	<b>100.00</b>	<b>131978.92</b>	<b>100.00</b>	<b>123.07</b>

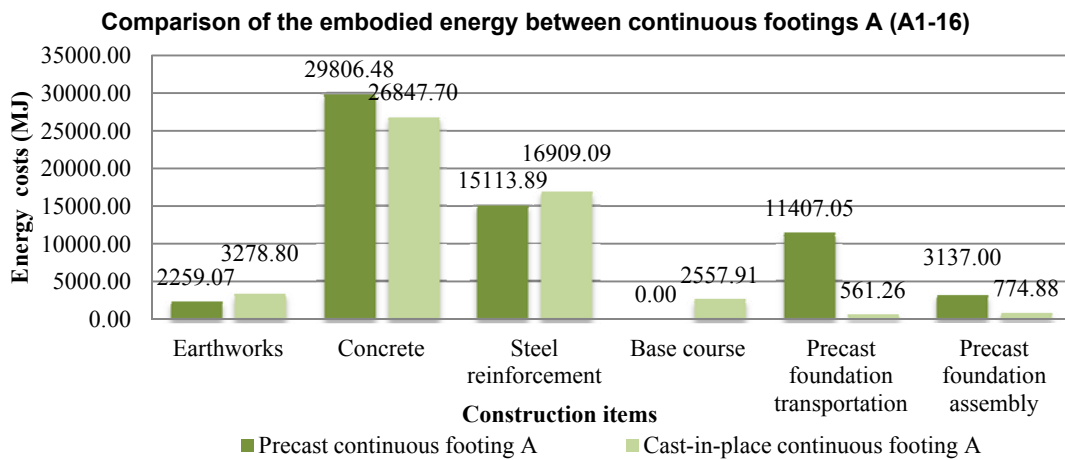
**Table 12. Comparison of the embodied energy between foundations in the A1-16 case study.**



**Graph 17. Comparison of the embodied energy between foundations in the A1-16 case study.**

*a) Continuous footing A*

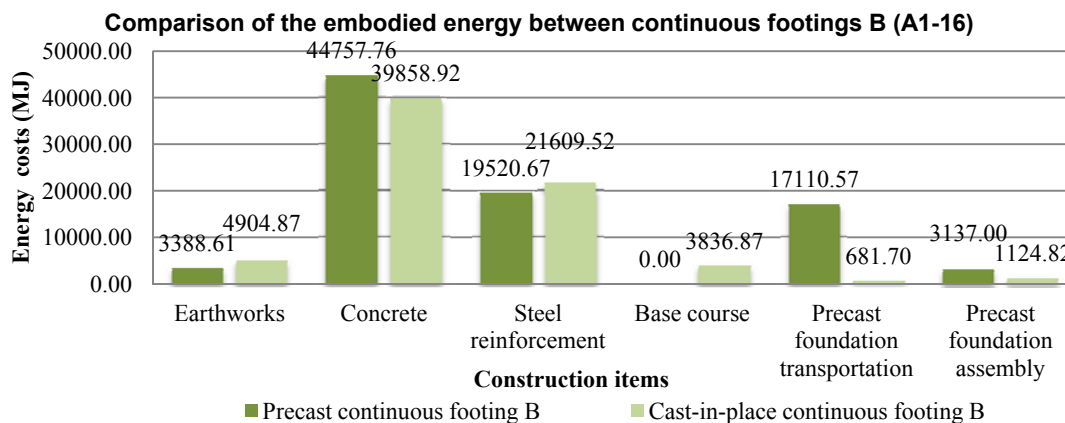
To build precast continuous footing A, 21% more energy is required than to build the cast-in-place continuous footing A. Cast-in-place continuous footing A has more concrete and steel reinforcement, because of the precast pads. More energy is consumed in the earthworks and steel reinforcement. It also needs a base course. However, although precast continuous footing A contains less concrete, it has more embodied energy because precast concrete is more expensive in energy terms. Moreover, prefabricated continuous footing A involves the transportation of more tonnes, and the assembly of more linear meters, than cast-in-place continuous footing A.



**Graph 18. Comparison of the embodied energy between continuous footings A (A1-16).**

*b) Continuous footing B*

To build precast continuous footing B, 22% more energy is required than to build the cast-in-place continuous footing. Like continuous footing A, this is due to the energy difference between concretes and the fact that the prefabricated foundation has to be transported and assembled.

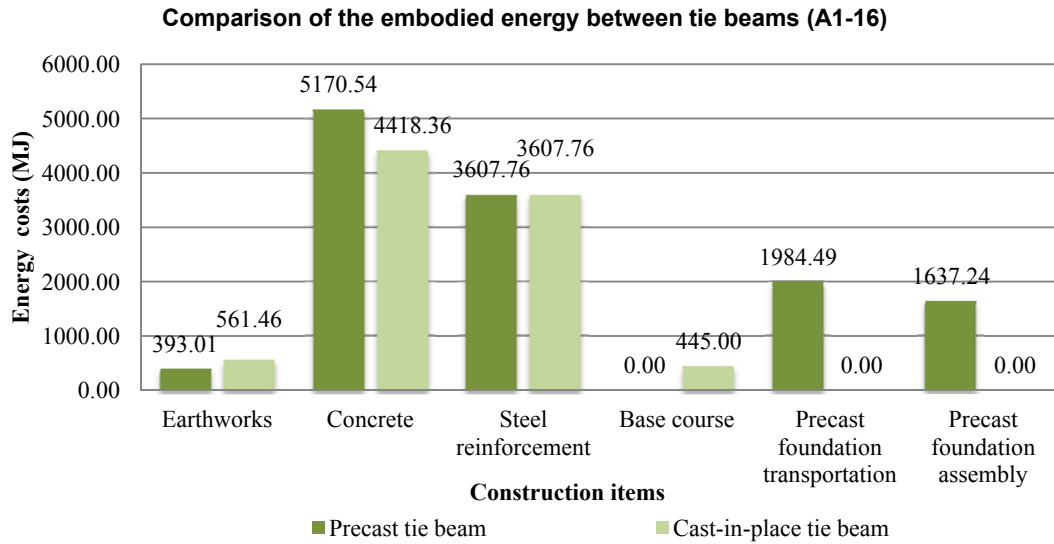


**Graph 19. Comparison of the embodied energy between continuous footings B (A1-16).**



c) Tie beam

Tie beams have the same dimensions and the same amount of steel, because they do not have precast pads. However, 42% more energy is required to build the precast tie beam than if it is cast-in-place. This is due to the same reasons as explained previously.



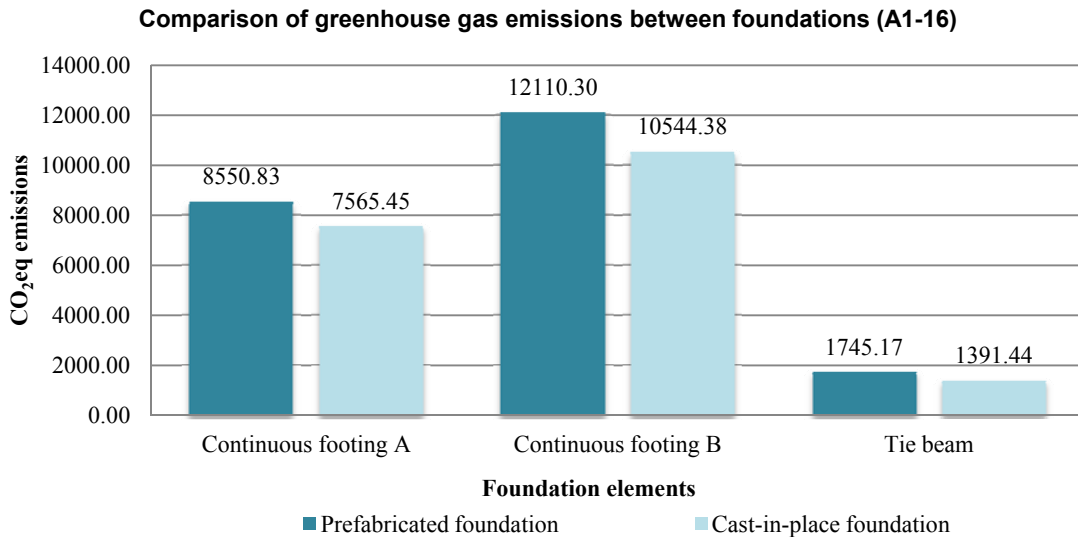
**Graph 20. Comparison of the embodied energy between tie beams in the A1-16 case study.**

**6.2.4. Comparison of greenhouse gas emissions between the precast foundation and the cast-in-place foundation in the case A1-16**

The precast foundation releases 15% more greenhouse gas emissions than the cast-in-place foundation. This is because precast concrete produces more CO<sub>2</sub> equivalent emissions than cast-in-place concrete, as it contains more cement (424.14 kilogrammes of CO<sub>2</sub>eq/m<sup>3</sup> – 317.17 kilogrammes of CO<sub>2</sub>eq/m<sup>3</sup>). Moreover, the prefabricated foundation produces more emissions due to transport and assembly. Steel reinforcement emissions are important in this budget, but they are similar between foundations. The cast-in-place foundation contains a little more steel and concrete, because it has embedded precast pads. The other budget items, such as the base course or earth movements, are of little relevance to the entire budget.

Comparison of greenhouse gas emissions between foundations in the A1-16 case study					
Foundation elements	Prefabricated foundation		Cast-in-place foundation		Difference
	kg	%	kg	%	
Continuous footing A	8550.83	38.16	7565.45	38.79	113.02
Continuous footing B	12110.30	54.05	10544.38	54.07	114.85
Tie beam	1745.17	7.79	1391.44	7.14	125.42
<b>TOTAL</b>	<b>22406.30</b>	<b>100.00</b>	<b>19501.28</b>	<b>100.00</b>	<b>114.90</b>

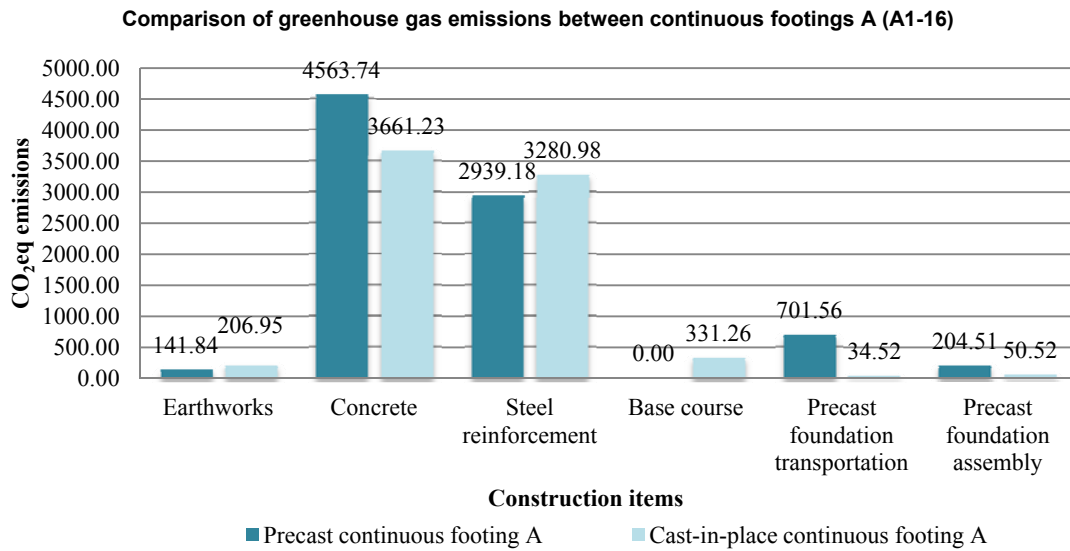
Table 13. Comparison of greenhouse gas emissions between foundations in the A1-16 case study.



Graph 21. Comparison of greenhouse gas emissions between foundations in the A1-16 case study.

a) *Continuous footing A*

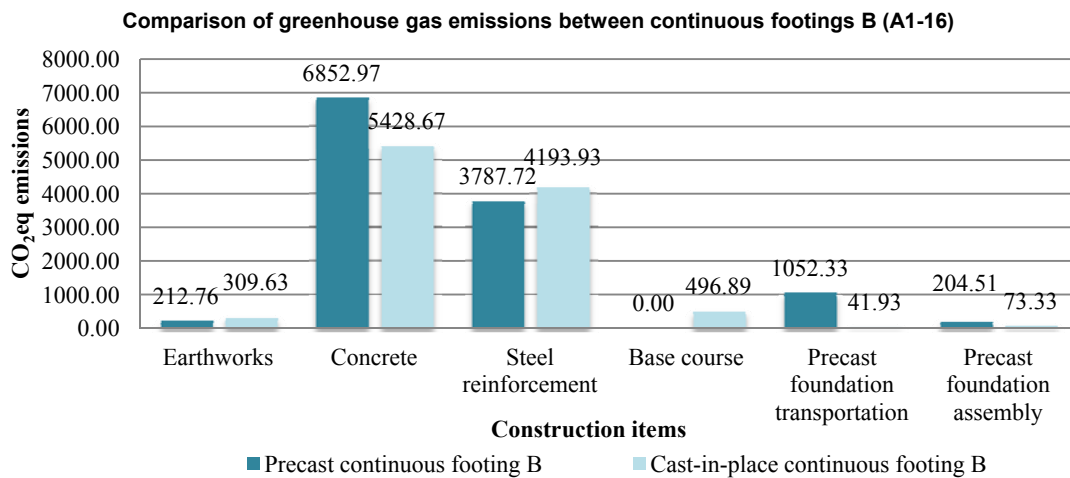
Building precast continuous footing A generates 13% more greenhouse gas emissions. Prefabricated concrete generates higher greenhouse gas emissions (424.14 kilogrammes of CO<sub>2</sub> eq/m<sup>3</sup> – 317.17 kilogrammes of CO<sub>2</sub> eq/m<sup>3</sup>), because it contains more cement. Moreover, precast continuous footing A produces more emissions in transport and assembly. The cast-in-place continuous footing contains more steel reinforcement, because of the precast pads. Although the cast-in-place continuous footing requires a base course and more earthworks, these items are not decisive in this budget.



**Graph 22. Comparison of greenhouse gas emissions between continuous footings A (A1-16).**

b) *Continuous footing B*

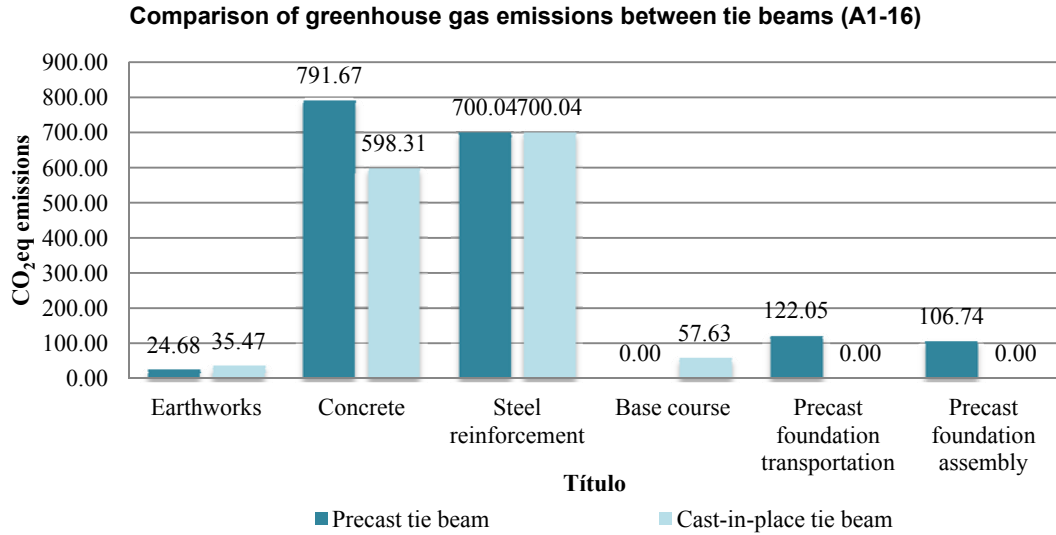
Building precast continuous footing B generates 15% more greenhouse gas emissions than building the cast-in-place continuous footing, for the reasons explained in the previous section.



**Graph 23. Comparison of greenhouse gas emissions between continuous footings B (A1-16).**

c) Tie beam

Building the precast tie beam generates 26% more emissions than building the cast-in-place tie beam. This is because of the precast concrete, and the transport and assembly emissions.



Graph 24. Comparison of greenhouse gas emissions between tie beams in the A1-16 case study.

**6.2.5. The impact of the assembly of precast pads in relation to the foundation**

The impact of the assembly of precast pads has been estimated. A working group comprised of a first officer, a laborer and a crane operator was considered, as well as a 12-tonne crane, according to the BEDEC database.



Figure 137. Placing of precast pads. Figure 138. Crane to place precast pads.

Cast-in-place budgets are higher than precast budgets if eight days and seven hours of precast foundation assembly are added to the economic budget; three days and six hours is added to the energy budget; and five days and three hours to the emissions budget.

<b>Economic impact of the assembly of prefabricated pads on the A1-16 foundation</b>						
	Prefabricated foundation			Cast-in-place foundation		
Continuous footing A	5016.63			2362.83		
<b>TOTAL</b>	<b>13372.81</b>			<b>6413.77</b>		
Cast-in-place foundation + assembly						
	+ 1 hour	+ 2 h	+ 4 h	+ 1 day	+ 1 d + 4 h	+ 8 d + 7 h
	€	€	€	€	€	€
Continuous footing A	2461.08	2559.33	2755.83	3148.84	3541.85	9338.72
<b>TOTAL</b>	<b>6512.03</b>	<b>6610.28</b>	<b>6806.78</b>	<b>7199.79</b>	<b>7592.80</b>	<b>13389.67</b>

**Table 14. Economic impact of the assembly of prefabricated pads on the A1-16 foundation.**

<b>Energy impact of the assembly of prefabricated pads on the A1-16 foundation</b>						
	Prefabricated foundation			Cast-in-place foundation		
Continuous footing A	61723.49			50929.64		
<b>TOTAL</b>	<b>162431.13</b>			<b>131978.92</b>		
Cast-in-place foundation + assembly						
	+ 1 hour	+ 2 h	+ 4 h	+ 1 day	+ 1 d + 4 h	+ 3 d + 6 h
	MJ	MJ	MJ	MJ	MJ	MJ
Continuous footing A	51971.12	53012.59	55095.53	59261.42	63427.31	82173.81
<b>TOTAL</b>	<b>133020.40</b>	<b>134061.87</b>	<b>136144.81</b>	<b>140310.70</b>	<b>144476.59</b>	<b>163223.09</b>

**Table 15. Energy impact of the assembly of prefabricated pads on the A1-16 foundation.**

<b>CO<sub>2</sub> eq emissions impact of the assembly of prefabricated pads on the A1-16 foundation</b>						
	Prefabricated foundation			Cast-in-place foundation		
Continuous footing A	8550.83			7565.45		
<b>TOTAL</b>	<b>22406.30</b>			<b>19501.28</b>		
Cast-in-place foundation + assembly						
	+ 1 hour	+ 2 h	+ 4 h	+ 1 day	+ 1 d + 4 h	+ 5 d + 3 h
	kilogrammes CO <sub>2</sub> equivalent	kilogrammes CO <sub>2</sub> equivalent	kilogrammes CO <sub>2</sub> equivalent	kilogrammes CO <sub>2</sub> equivalent	kilogrammes CO <sub>2</sub> equivalent	kilogrammes CO <sub>2</sub> equivalent
Continuous footing A	7633.38	7701.30	7837.14	8108.83	8380.52	10486.10
<b>TOTAL</b>	<b>19569.20</b>	<b>19637.12</b>	<b>19772.97</b>	<b>20044.65</b>	<b>20316.34</b>	<b>22421.93</b>

**Table 16. CO<sub>2</sub> eq emissions impact of the assembly of prefabricated pads on the A1-16 foundation.**

### 6.3. Comparison between the prefabricated foundation and the cast-in-place foundation in the A1-14 case study

#### 6.3.1. Description of the foundations

This is the foundation in the A1-14 case study. Only the part of the foundation inside the box will be analysed.

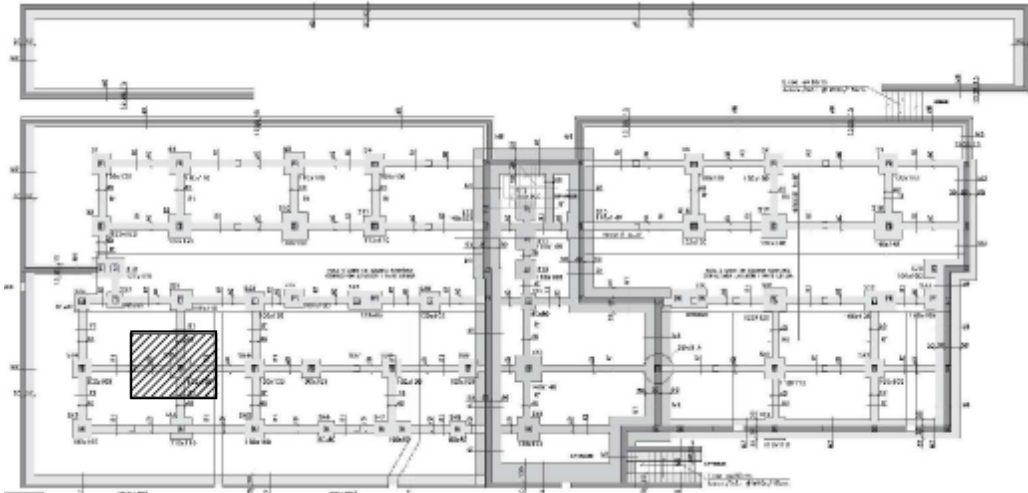


Figure 139. Foundation plan of the A1-14 case study. Only the part of the foundation inside the box will be analysed.

The part of the foundation that will be analysed consists of a cast-in-place isolated footing and tie beams. Footings and tie beams are built with formwork, as can be seen in the image below.

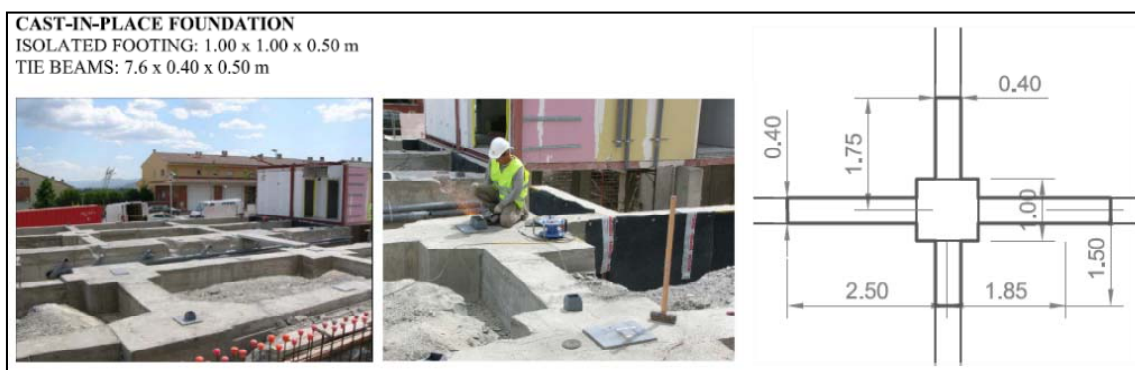


Figure 140. Cast-in-place foundation under analysis: dimensions, pictures and plan.



The proposal was to build a prefabricated foundation composed of a prefabricated footing without tie beams footings, for the reasons explained below.



**Figure 141. Precast foundation under analysis: dimensions and plan.**

The cast-in-place foundation is oversized for the following reasons. First, the cast-in-place foundation was designed based on a particular interpretation of regulations that underestimate the strength of the rock. The geotechnical study of the project stated that the resistance of the soil was from 77.63 kg/cm<sup>2</sup> to 143.78 kg/cm<sup>2</sup>. However, in the conclusions of the same geotechnical study, the construction of shallow foundations with an admissible load of 5 kg/cm<sup>2</sup> was recommended. This reduction in the resistance of the rock oversized the foundation. The original isolated footing is 100x100x50 cm, while an isolated footing of 40x40x40 cm would be big enough. This means a reduction of 87% of the volume of the footing. This has a huge impact on economic costs, energy consumption and greenhouse gas emissions.

The ground was very hard and special machinery was needed to dig it: cat excavators, boring machine and the use of expansive mortar.



**Figure 142. Cat excavator digging a trench. Figure 143. Boring machine boring holes in the ground to inject expansive mortar to break up the rock. Figure 144. Bore holes with the remains of expansive mortar.**

The second reason is that tie beams are not necessary. According to the *Norma de construcción sismorresistente: parte general y edificación* (Earthquake-resistant construction standard, general and building section) [NCSE, 2009, p. 43-44]: *“Each foundation element that transmits significant vertical loads to the ground should be connected to adjacent elements in two directions, using anchoring devices situated at the level of the footings, the pile caps or equivalent that can resist an axial force of traction or compression that is the same as the horizontal seismic load transmitted by each support.”*

In addition, *“When seismic acceleration is  $< 0.16 g$ , the ground slab could be considered the bracing element, if it is situated at the level of the footings or supported on their upper face, continues around the column in all directions, is at least 15 cm thick and there is a span of at least 1/50 between columns, and the slab can resist the force stated in the first paragraph of this section.”*

In this case study, seismic acceleration is  $0.08g < 0.16g$  [NCSE, 2009, p. 14]. Therefore tie beams are not necessary and the concrete ground slab is the bracing element. The slab rests over the foundations, and the modules are bolted to each other and give continuity to the slab. In addition, the slab is 15 cm thick, and there is a span of no less than 1/50 between columns.

It was difficult to find a precast isolated footing with these characteristics. There were no Spanish companies with similar foundations in their catalogues. Consequently, a Spanish prefabricated company was asked to estimate the budget for the isolated footing in this design. A purpose-built mold was not considered for so few units, because of the costs. In addition, pillar molds were adapted to build these precast isolated footings.

In other countries of the European Union, this type of foundation can be found in online catalogues. Prices are slightly lower, because the elements are not built for a specific design, and costs are studied and optimized. In addition, isolated footings may have anchors laid out in the factory, which would solve problems derived from different dimensional tolerances.



Figure 145. Isolated footing of 40x40x40, €55.94 (excl. VAT). Figure 146. Isolated footing of 45x45x50, €41.28 (excl. VAT). <https://www.sierbetononline.nl/betonpoeren/> Figure 147. Isolated footing of 36x36x30, €15.84 (excl. VAT). Figure 148. Isolated footing of 40x40x40, €58.43 (excl. VAT). <http://www.betondingen.nl/betonpoeren/>

In this case study, there were problems with different dimensional tolerances between the cast-in-place foundations and the prefabricated building. The foundation was constructed on-site. On top of it, some metal plates were placed and connectors were welded over them. However, when the modules arrived at the site, they did not fit into the connectors. This was because the connectors had not been placed in exactly the right position or with the error of prefabricated buildings. So it was decided to cut the connectors with an angle grinder, and the technical office was set to work to find solutions for the different connectors in order to meet regulations [Pujadas et al., 2013].



Figure 149. Cutting diverted connectors with an angle grinder. Figure 150. Placement of modules over connectors. Figure 151. Provisionally, the modules were welded over the connectors.

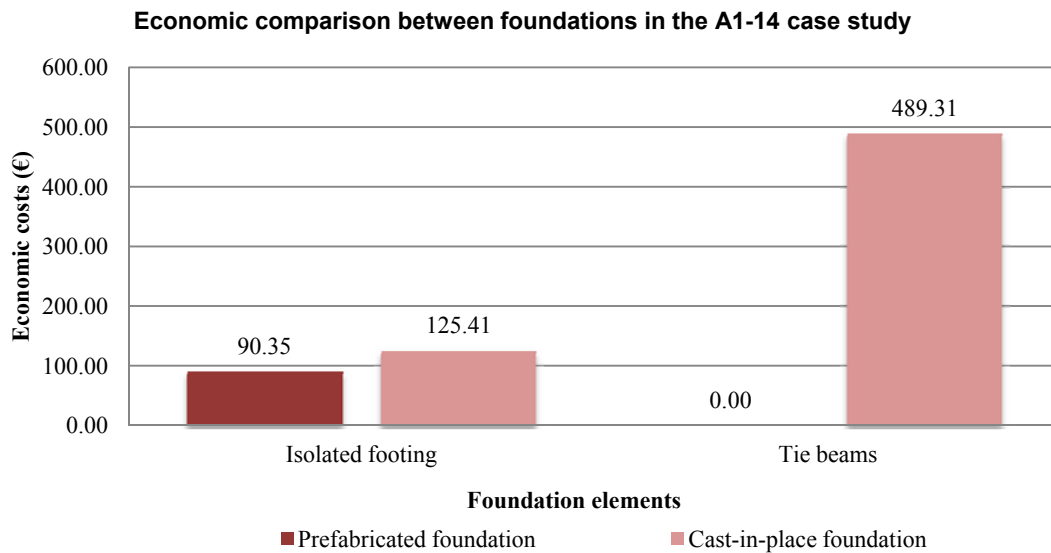
Delaying building work is expensive. It involves extra items that are not included in the initial budget, and it affects the final cost of the construction, due to the extra hours of work, more hours of machinery hire, and other factors. There are no data available on these extra items, so they cannot be considered in the budgets.

**6.3.2. Economic comparison between the precast foundation and the cast-in-place foundation in the A1-14 case study**

This precast foundation is 85% cheaper than the cast-in-place foundation. The cast-in-place foundation is oversized for the reasons explained previously. However, building one cubic meter of prefabricated foundation is much more expensive than building one cubic meter on-site. In addition, costs of transport and assembly must be added.

Economic comparison between foundations in the A1-14 case study					
Foundation elements	Prefabricated foundation		Cast-in-place foundation		Difference
	€	%	€	%	
Isolated footing	90.35	100.00	125.41	20.40	72.04
Tie beams	0.00	0.00	489.31	79.60	0.00
<b>TOTAL</b>	<b>90.35</b>	<b>100.00</b>	<b>614.72</b>	<b>100.00</b>	<b>14.70</b>

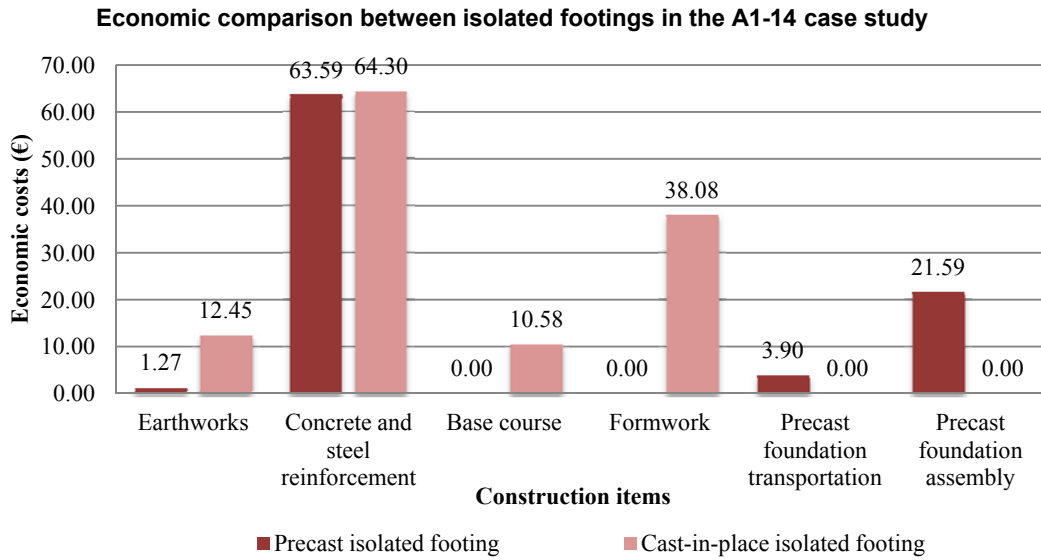
Table 17. Economic comparison between foundations in the A1-14 case study.



Graph 25. Economic comparison between foundations in the A1-14 case study.

*a) Isolated footing*

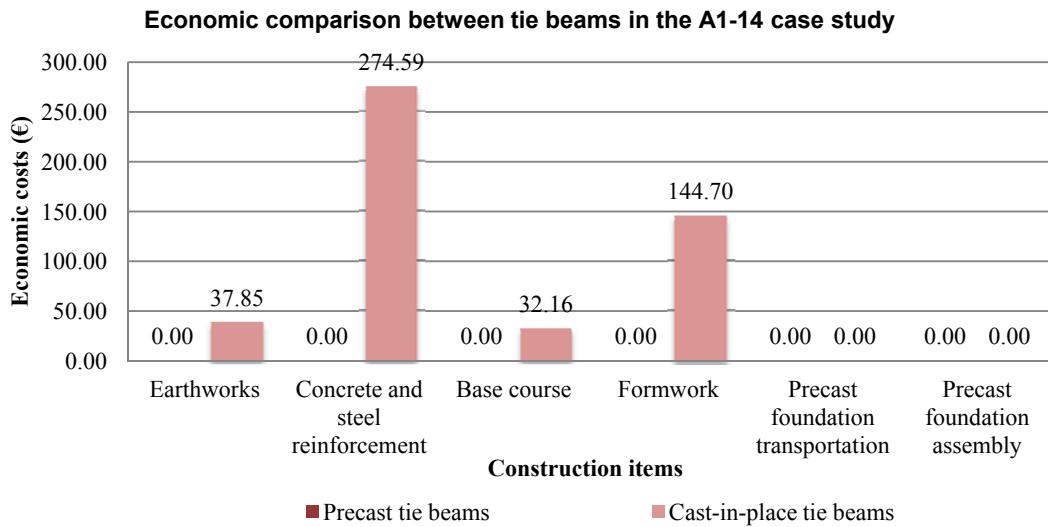
The prefabricated isolated footing is 28% cheaper than that built on-site. This is due to the fact that the precast isolated footing is around seven times smaller ( $0.064 \text{ m}^3 - 0.50 \text{ m}^3$ ). The costs of earthworks and transport of soil are much lower. It is not necessary to build a base course or formwork. However, transportation and assembly costs of the foundation must be added.



**Graph 26. Economic comparison between isolated footings in the A1-14 case study.**

*b) Tie beams*

This foundation does not need tie beams, as explained in Section 6.3.1. The cost of tie beams represents 80% of the cost of the foundation. Therefore, their construction has a major impact.



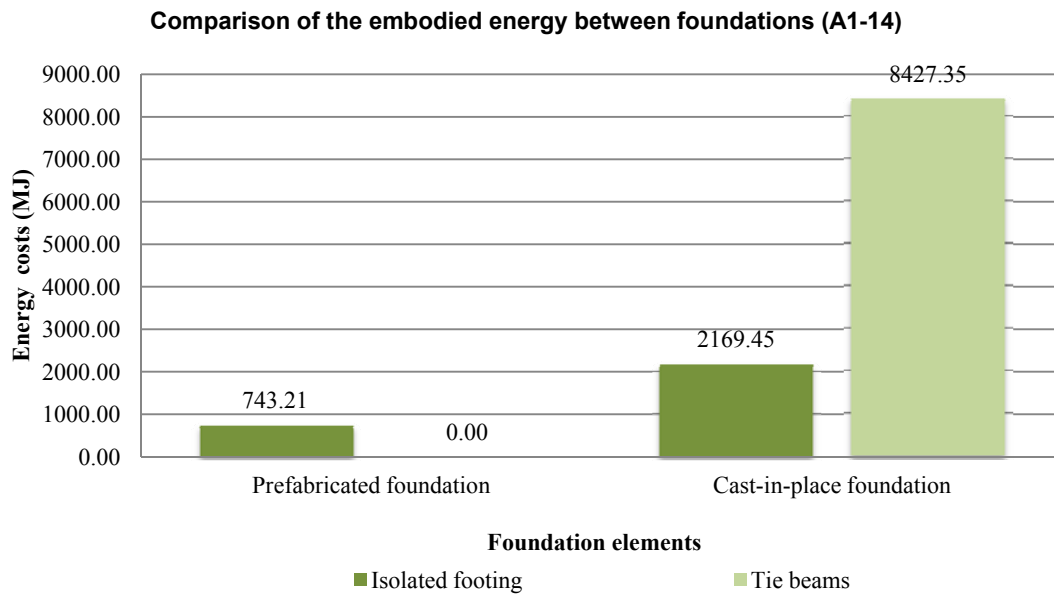
**Graph 27. Economic comparison between tie beams in the A1-14 case study.**

### 6.3.3. Comparison of the embodied energy between the precast foundation and the cast-in-place foundation in the A1-14 case study

It requires 93% more energy to build this foundation precast than on-site. This is because the cast-in-place foundation is very oversized. However, building one cubic meter of precast foundation requires more energy than building it on-site. Precast concrete requires more energy to be built ( $2770 \text{ MJ/m}^3 - 2041.74 \text{ MJ/m}^3$ ), because it contains more cement ( $400 \text{ kg/m}^3 - 275 \text{ kg/m}^3$ ) and cement is the component that has the biggest impact on concrete. In addition, the energy consumed in the transportation and assembly of the precast foundation must be added.

Comparison of the embodied energy between foundations in the A1-14 case study					
Foundation elements	Prefabricated foundation		Cast-in-place foundation		Difference
	MJ	%	MJ	%	%
Isolated footing	743.21	100.00	2169.45	20.47	34.26
Tie beams	0.00	0.00	8427.35	79.53	0.00
<b>TOTAL</b>	<b>743.21</b>	<b>100.00</b>	<b>10596.80</b>	<b>100.00</b>	<b>7.01</b>

Table 18. Comparison of the embodied energy between foundations in the A1-14 case study.

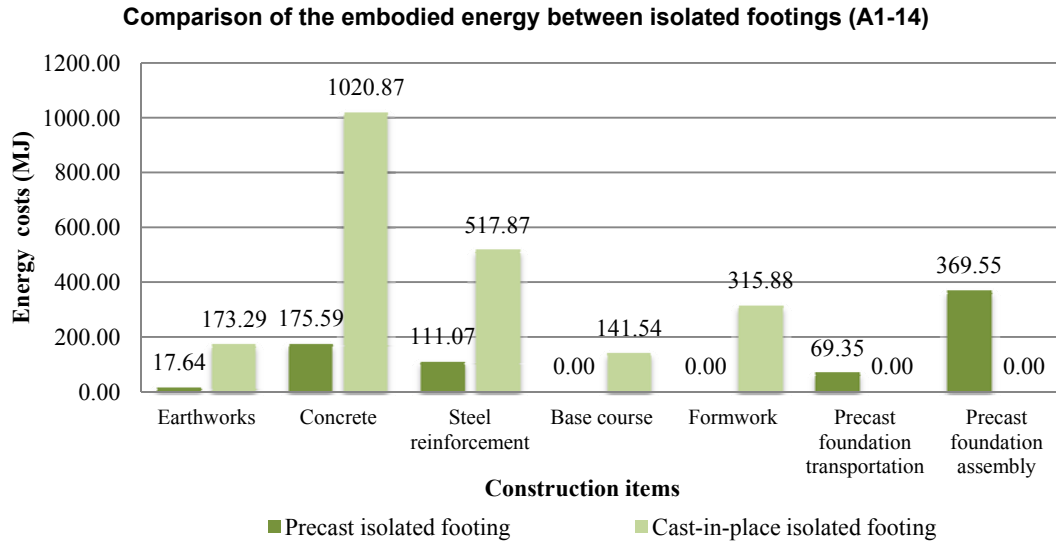


Graph 28. Comparison of the embodied energy between foundations in the A1-14 case study.



*a) Isolated footing*

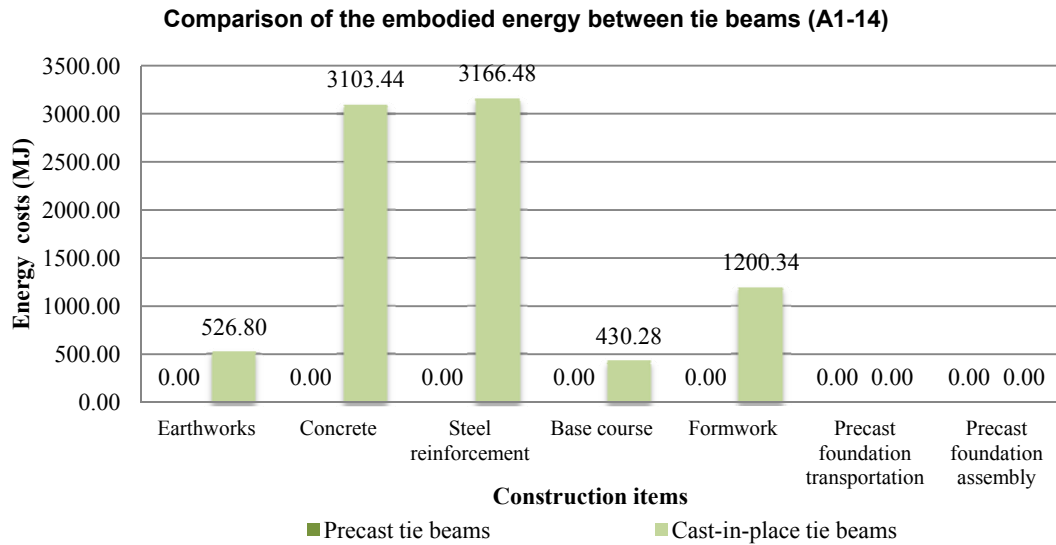
Sixty-six per cent more energy is required to build this foundation precast than on-site. This is due to the fact that the cast-in-place foundation is very oversized. The precast footing requires less energy for earthworks, concrete, steel reinforcing, the base course and formwork. However, it requires energy for the transportation and assembly of the precast footing.



**Graph 29. Comparison of the embodied energy between isolated footings in the A1-14 case study.**

*b) Tie beams*

Tie beams are not required, as explained previously. This represents a substantial energy saving. Tie beams represent 80% of the energy consumed to build the cast-in-place foundation.



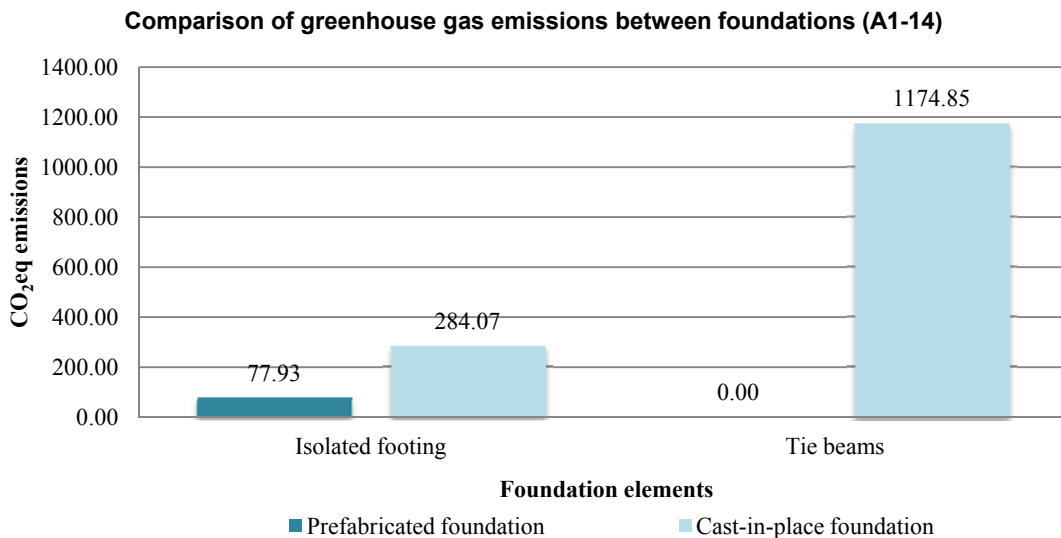
**Graph 30. Comparison of the embodied energy between tie beams in the A1-14 case study.**

**6.3.4. Comparison of greenhouse gas emissions between the precast foundation and the cast-in-place foundation in the A1-14 case**

Greenhouse gas emissions are 95% lower when this foundation is precast. This is due to the fact that the cast-in-place foundation is very oversized. However, one cubic meter of precast foundation releases more emissions than one cubic meter of cast-in-place foundation. Precast concrete gives off more emissions (424.14 kilogrammes of CO<sub>2</sub> equivalent – 302.20 kilogrammes of CO<sub>2</sub> equivalent) because it has more cement (400 kg/m<sup>3</sup> - 275 kg/m<sup>3</sup>). Emissions from the transportation and assembly of the precast foundation must also be added.

Comparison of greenhouse gas emissions between foundations in the A1-14 case study					
Foundation elements	Prefabricated foundation		Cast-in-place foundation		Difference
	kg	%	kg	%	
Isolated footing	77.93	100.00	284.07	19.47	27.43
Tie beams	0.00	0.00	1174.85	80.53	0.00
<b>TOTAL</b>	<b>77.93</b>	<b>100.00</b>	<b>1458.91</b>	<b>100.00</b>	<b>5.34</b>

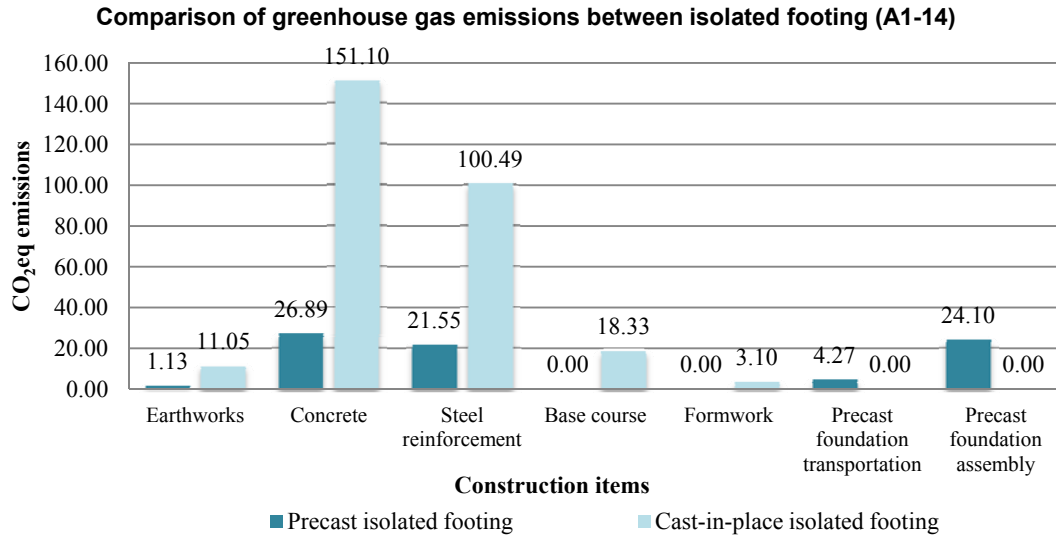
**Table 19. Comparison of greenhouse gas emissions between foundations in the A1-14 case study.**



**Graph 31. Comparison of greenhouse gas emissions between foundations in the A1-14 case study.**

*a) Isolated footing*

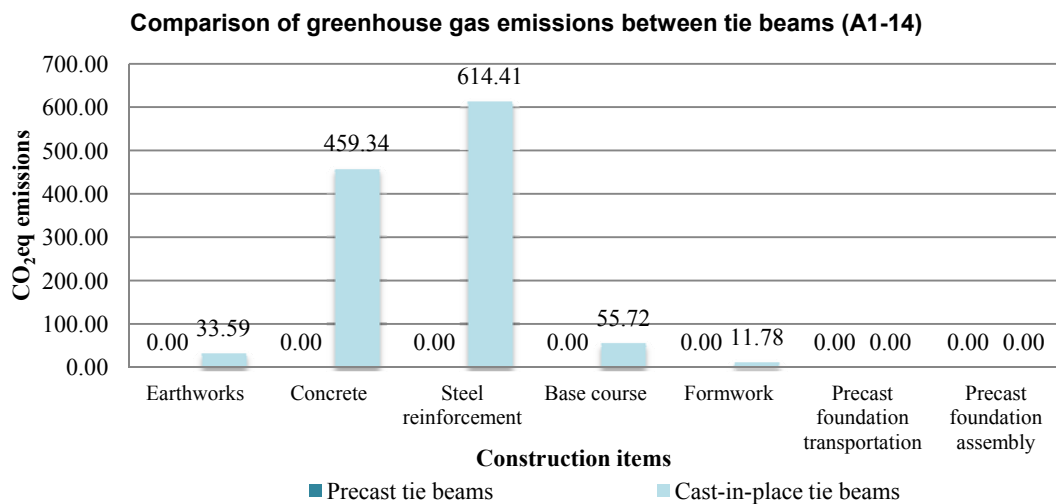
It requires 73% less energy to build this foundation precast than on-site. This is because the cast-in-place foundation is oversized. The considered precast foundation reduces the emissions of earthworks, concrete, steel reinforcement, base course and formwork. However, the precast foundation is associated with higher emissions related to transportation and assembly.



**Graph 32. Comparison of greenhouse gas emissions between isolated footing (A1-14).**

*b) Tie beams*

The foundation does not require tie beams, as explained above. This represents a big saving in greenhouse gas emissions. The construction of tie beams represents 81% of the emissions from the cast-in-place foundation.



**Graph 33. Comparison of greenhouse gas emissions between tie beams in the A1-14 case study.**

## 7. Discussion of the results

Factors that favour the use of precast foundations are:

1. **Low buildings.** Low buildings were not analysed in this study.
2. **The volume.** As shown, it is important to produce a high enough volume of precast foundations, so that the impact of the investment on each unit is as small as possible.
3. **The speed.** Precast foundations are produced in a factory and assembled on-site. They can be manufactured quickly and they can bear a load immediately after installation. They are ideal for buildings that have to be constructed rapidly.
4. **The cost.** In this point, it is important to state that precast foundations have a fixed cost. In the three foundations analysed that were cast-in-place, the initial budget was not the same as the final cost.
5. **The quality.** A precast footing and beam manufacturer was visited, and various works to construct precast micropiles, piles and continuous footings were monitored. At the sites that were visited, the staff were specialized and there were no incidental factors that affected quality, costs or timing. Precast foundations avoid problems due to different dimensional tolerances.
6. **The human factor.** It was found that precast processes are monitored and a safety protocol is applied. Fewer groups are involved in the works.
7. **The transport.** Transport has an impact when a precast foundation is produced. It is generally agreed that: *"the value of a building element and the costs of transporting it determine the economical transport radius."* [Staib, 2008, p. 46 & 47]. This book also considers that it is feasible to transport a precast reinforced concrete element up to a distance of 100 km, approximately. In the analysis of the three cases, it was considered that the precast foundations are transported a distance of 155 km [QPA, 2008]. The impact of transport accounted for around 4% to 13% of the total cost of the assembled foundation.
8. **Sustainability.** Resources and waste were found to be controlled in building works that use precast foundations, and in factories making precast foundations. It was also found that the works in general were cleaner. In addition, precast foundations can be relocated, reused and recycled, which can extend the useful life of the foundation. On this point, precast foundation systems could reduce CO<sub>2</sub> emissions by 75% [Wren, 2012]. Most of the systems considered are comprised of foundations and the floor.

In this thesis, comparisons with a reinforced concrete foundation with the same characteristics revealed that more energy is consumed and more greenhouse gases are emitted in the production of a precast foundation. However, if the volume of the foundations that are compared is different, the above factors will also differ. In addition, incidental costs may also play a role.

Authors state that precast foundations are not usually used in dwellings because:

1. *"Cost is usually the most important factor affecting the choice of a foundation system and the nature of construction (...)" [Huat, 2003].*
2. *"It also seems that builders do not trust industrialization to the extent of prefabricating the foundation, on the reliability of which the rest of the structure depends." [Krishna, 1972].*
3. *"Bound by tradition, the builders have taken for granted that the foundation has to be an in-place operation even though the rest of the building may be industrialized." [Krishna, 1972]*
4. *"The construction sector is very conservative and all of the people that are involved in this sector contribute to it continuing in the same way." "Companies are conservative because they pay for any problems that may arise." [Moonen, 2001]*
5. *"In addition, the profit margin is small. Therefore, companies tend to use known, tested solutions, and do not invest in changing their organizational structure with subcontracts." [Moonen, 2001]*
6. *"The answer to this question does not lie in technology, but perhaps in the human psyche, which resists change even when the change is known to be to one's advantage" [Huat, 2003].*
7. *"However, a house providing a certain amount of accommodations and having elaborate and costly foundations, has no higher value to its owner or occupant than a similar one with less expensive foundation." [Krishna, 1972]*
8. *"Industrialization cannot eliminate on-site operations completely. The work involving clearing the site, laying utility lines, grading, and landscaping cannot possibility be transferred to the factory." [Krishna, 1972]*
9. *"Foundation costs contribute only a small part to the total cost of the house (5% to 15%)." [Krishna, 1972]*
10. *"The government also promotes conservatism, because all the regulations have been designed for known solutions. A new product faces conditions that are difficult to meet.*

*Therefore, many innovations are frustrated by current regulations, particularly those that refer to buildings." [Moonen, 2001]*

11. According to the author, the following factors make prefabrication difficult [Màrquez, 2006]: specificity, structural correspondence, structural coordination, dimensional coordination, the weight and the monolithic behaviour. These are all points to take into account when designing a precast foundation, but are not limiting factors. The following statement is not considered to be true: *"Usually, precast foundations are designed for specific structural or construction systems. The calculations are made for specific design conditions (pre-established coefficients, loads and minimum soil resistance). These factors mean that certain precast foundations cannot be used in other constructions or other contextual circumstances."* Many precast foundations are not built for a specific design and could be reused. This is the case of some micropiles, piles, supports and small footings, among others.

Room module buildings are those that are transported and assembled like a box. The unit of construction is the room module. Different types and the thirty cases that were studied are described. A data sheet on each of them can be found in Appendix 1.

The precast and semi-prefabricated foundations that are on the market at the current time and are suitable for prefabricated dwellings are described in Appendix 2.

In most of the case studies, the reasons why precast foundations were not used are as follows:

1. Initial cost. This is the most common reason why foundations were not precast. In general, the cheapest foundation in the short-term was selected, without considering the potential long-term consequences.
2. Comfort. *"It's always been done like this", "It's easy to do it this way"* is the second most common reason. In other words, people build in a traditional way, either because no other option is considered or because the *"easy"* option is taken; the one that is known.
3. Companies may prefer to construct foundations using their own employees.
4. Lack of security. *"New foundations lead to new problems."* There is no reason why they should if they are executed well.
5. A precast company could not be found that could make all of the foundation. It is difficult to find companies that make precast foundations in Spain that will take



responsibility for the entire process. This is even more difficult in the case of shallow foundations. In other northern European countries, there are more options to choose from.

6. A lack of knowledge about how to precast foundations. Most architects and engineers do not know how to precast foundations. They do not know, for example, how molds are made, the kind of joints used in precast or the economic impact of each choice. As observed, not all precast companies help in the design of a precast foundation and often, once a precast foundation has been considered, it is not feasible to produce it because of the small number of units that are required. Some companies are specialized in foundations. They know their product well, have considered all the details and potential problems, and optimized all the processes and resources. Consequently, the impact of the investment on each unit is lower, because it is amortized over many projects, not just one. Such companies may take charge of the entire process: from the design of the foundations to their assembly. This makes it easier to precast the foundation: the architect or engineer is not involved in the design of the product and only has to focus on selecting the most appropriate foundation or system of foundations and implementing it correctly in the design of the building.
7. The characteristics of the land
  - a. The slope
  - b. Non-homogenous land
  - c. Unconsolidated upper layers of soil
  - d. Presence of water
  - e. Low consistency



**Figure 152. Screw micropiles can be a good solution when there is a slope. Figure 153. Or when they are in contact with water.** <http://www.archiexpo.es/prod/techno-pieux-inc/product-61493-992253.html>

None of these land characteristics prevent the use of precast foundations. However, the right kind of precast foundation must be selected. If the soil has low bearing capacity, micropiles or piles can be constructed in the upper layers to penetrate a more resistant deeper layer. If water is present, wood is a good solution as long as it is completely submerged, steel can be used to protect it, and additives can be put in the concrete.

8. Initial constraints

- a. The crane could not position the modules in one go
- b. The ground floor must be open plan
- c. The owner selects the construction company

The fact that modules should be positioned over the foundations in one step or that the ground floor is open plan, and therefore the loads are more concentrated, does not mean that precast foundations cannot be used. In this case, what is important is to select the right kind of foundation.

9. Recommendations. Many professionals recommend the use of cast-in-place foundations automatically. However, they may not be familiar with, or may not have used, prefabricated foundations. The advice of experts is useful, but it is also important to cultivate a critical approach.

10. Difficulties in transporting and handling precast foundations due to their weight and dimensions. Some northern European companies construct precast beams or footings, and transport and handling are not an obstacle. This is also true of structures such as bridges or prefabricated industrial buildings and warehouses.



Figure 154 and 155. Transport and positioning of precast continuous footings.

Regarding the economic and environmental feasibility of foundations, precast foundations have been found to be more expensive initially, consume more energy in their production, and emit

more greenhouse gases than cast-in-place foundations with the same characteristics. Only precast piles require less energy in their construction and generate less greenhouse gases.

However, precast foundations are cheaper, consume less energy and emit less greenhouse gases when cast-in-place or semi-prefabricated foundations have been oversized due to the design, the interpretation of regulations or an underestimation of the bearing capacity of the soil.

When a building is precast and the foundations are cast-in-place, problems could arise in relation to different dimensional tolerances. Therefore, in the design of A1-10 and A1-16 some precast intermediate elements were constructed to avoid these problems. However, they were difficult to fit. In the design of A1-14, no intermediate elements were constructed and problems arose when the modules were positioned. These delays led to a series of incidental items for which no data are available and that were not added to the budgets.

An estimation was made of the assembly of the precast semi-beams for A-10 case study and the repositioning of the pads in A1-16 case study. It was found that the assembly was costly, particularly in environmental terms. No other incidental items were considered, due to a lack of information. It would be interesting to have data on all the real assembly and incidental items, maintenance items and the durability of the foundation, so as to assess the long-term costs.

The price of reinforced concrete is crucial in the budget. In this thesis, the prices used for precast reinforced concrete were those provided by Spanish precast companies. In Spain, some companies are specialized in piles and micropiles, but there are hardly any companies dedicated to precast shallow foundations. A Catalan company builds precast footings for the industrial and agricultural buildings that it manufactures, but not for dwellings. European companies were found that have lower prices for precast elements. This is due to the fact that these companies are devoted to producing concrete foundations and have optimized the processes.

## 8. Conclusions

As shown by the case studies, the answer to the question of why aren't precast foundations used in prefabricated dwellings is complex. Initial costs play a key role in the selection of a precast foundation. As we have seen in this study, precast foundations have higher initial costs, because precast reinforced concrete is more expensive, and the costs of assembling and transporting prefabricated elements must be included. However, precast foundations do have a fixed price. In contrast, in the three cases of cast-in-place or semi-prefabricated foundations that were studied, various incidental costs arose that were not included in the initial budget and affected the final budget. A comparison of individual budget items is not the same as a comparison of the final budget for all the building work.

Another common reason why precast foundations are not used is the preference for constructing buildings in the traditional way, without considering other possibilities. The easiest construction method is generally selected, which tends to be the one that is already known: in other words, people build in a conventional way. Stakeholders tend to invest in tested solutions with predictable results.

In addition, construction companies try to invoice as many budget items as possible with the lowest investment. Therefore, they do not subcontract other companies to construct the foundations, and they use their own machinery and staff. Companies do not see a large enough profit margin to invest in building in a different way.

Another factor is that there is very little variability in precast foundations in Catalonia. Although some companies are specialized in piles and micropiles, it is difficult to find enterprises that are specialized in precast shallow foundations. Some companies may be interested in precasting a proposed foundation. However, the prefabrication of a small number of units is much more expensive, as the design costs, the costs of molds or adaptation of molds, and other costs must all be absorbed by just a few units. This reduces their competitiveness, especially if we consider that the initial cost has a considerable influence on the choice of foundation. In northern Europe, there are companies specialized in precast foundation systems that take responsibility for all tasks, from the calculations to assembly on-site. These companies have optimized all of the processes, and can offer a better price. In this case, the architect or engineer is not involved in the design of the foundation, and only has to focus on selecting an appropriate system and ensuring that it is implemented correctly in the design of the building.

Information about the types of precast foundations that are available, and the opportunities that they offer, is often misleading. When the land is sloped, water is present, the soil has poor bearing capacity, or the ground floor is to be open plan, it is considered that the foundations must be cast-in-place, because there are no suitable precast options. In many cases, the problem is a lack of knowledge about the available options. Furthermore, specialists generally recommended systems that they know, and solutions that have worked for them. It is important to listen to their views, but it is also essential to analyse them critically.

The answer to the question of whether precast foundations are more expensive than those that are cast-in-place in Spain would be *"It depends on the case"*. When two foundations with the same characteristics are compared, the costs of the precast foundation will be higher (considering the same amount of concrete and steel). Precast concrete is more expensive than concrete made on-site because it requires specialized staff, and the molds and facilities depreciate, among other factors. In addition, the costs of transport and assembly must be added. However, if the semi-prefabricated or cast-in-place foundation is larger than the precast foundation, the balance may change. In addition, when foundations are constructed on-site but the building is prefabricated, a series of incidental costs may emerge that was not in the initial budget and affects the final budget for the building work. These items could be avoided by using precast foundations, as precast foundations can include connectors positioned in the factory with the same error as in the prefabricated building. Note that in this study, the price of Spanish precast reinforced concrete was used. The price of precast piles was obtained from a Spanish piling company specialized in precast piles. But the price of linear elements and footings was obtained from Spanish precast companies that are not specialized in precast foundations, which means that the cost of prefabrication is higher.

The answer to the question of whether precast foundations are more environmentally friendly than those that are cast-in-place would also be *"It depends on the case"*. In this study, it was found that prefabricated foundations consume more energy and produce more greenhouse gas emissions than traditional foundations with the same characteristics (made with the same amount of steel and concrete). This is due to the fact that precast foundations tend to have higher resistance and therefore are made with more cement. Cement is the component that has the greatest impact on precast concrete. In addition, the energy consumption and emissions related to transport and assembly must be added. However, as in the economic costs, if the precast foundation is smaller than the cast-in-place foundation it may be more environmentally friendly. In addition, as precast foundations require less earth movements, transport of soil, and

transport and management of inert waste, as has been shown, these items have little impact on the whole.

Exceptionally, precast piles have a lower environmental impact than continuous flight auger piles. This is because driving a precast pile consumes less energy and produces less greenhouse gas emissions than a cast-in-place pile. In addition, for a precast pile, earth does not have to be removed and the load bearing capacity of the ground is improved. Furthermore, as we have seen, companies that are specialized in precast foundations control the resources and the waste.

It would be interesting to examine the incidental budget items for the building work, the maintenance and durability of the foundations, to evaluate them in the long-term.

Each precast foundation has an ideal framework of application. Below is a list of factors that would promote the use of precast foundations for precast dwellings in Spain:

First, a change of mentality would be required, so that the final cost is considered more important than the initial cost, and the guarantee of quality, costs and timing are valued.

Information should be disseminated on the kinds of foundations that exist, their qualities, advantages and limitations, so that stakeholders consider and use them. In addition, it is important to increase confidence in prefabricated elements, by highlighting completed works, providing guarantees, obtaining certificates or other methods.

A high enough volume of precast foundations must be manufactured to split the production, logistics and assembly costs as much as possible. All the stages in the construction of the foundation or system of foundations should be optimized so that the product is competitive in the market. Precast reinforced concrete is more costly in financial and environmental terms. Therefore, precast foundations should be designed that represent savings in terms of the amount of concrete used and/or when it is difficult to cast-in-place because of a lack of qualified staff or for other reasons (for example, T-sections or post-tensioned elements).

All of the details and processes of the foundation or system of foundations must be defined clearly, and potential errors must be monitored. Foundations could be considered as well-documented products in which the architect or engineer can trust. It is also important to take into account the characteristics of available precast foundations during the design of a building,



so that they are viable, and not oversized. An accurate geotechnical study is also important to avoid misinterpretations that could lead to errors or oversizing.

Future research could focus on the environmental feasibility of precast foundations, taking into account other indicators such as waste; the viability of using precast foundations in dwellings, taking into account their life cycle; the viability of precast foundations in other kinds of buildings; the viability of precast foundations for dwellings depending on the transport range of the precast elements; and improving environmental databases; analyse the economic and environmental impact of precast isolated footings and pads built in molds for isolated footings and pads.

## 9. Bibliography

1. A.A.V.V. *La construcción modular, una alternativa innovadora a la crisis de la vivienda*. Conference on 17 February 2009. Demarcación de Mataró del Colegio de Aparejadores de Cataluña, Mataró.
2. Águila y García, A. del *La industrialización de la edificación de viviendas*. Madrid: Mairera, 2006. ISBN 8493471135 (vol. 1). ISBN 8493471143 (vol. 2).
3. Arroyo, J.C. ... [et al.]. 2009. *Números gordos en el proyecto de estructuras*. Madrid: Cinter. ISBN 9788493227043.
4. Asociación Española de Normalización y Certificación. *Ejecución de trabajo geotécnicos especiales. Micropilotes. UNE-EN 14199*. Madrid: AENOR, 2006.
5. Avellaneda, J. ... [et al.]. La innovación tecnológica desde la promoción de vivienda pública: el Concurso de Innovación Técnica INCASOL. *Informes de la Construcción*, 2009, vol. 61, iss. 153, p. 87-100.
6. BEDEC [online]. Barcelona: Institut de Tecnologia de la Construcció de Catalunya [Accessed: 05/11/2015]. Available at: <<http://itec.cat/nouBedec.c/bedec.aspx>>
7. BEDEC (ITeC). *Continguts i criteris*. [online]. Barcelona: ITeC, 2015. [Accessed: 05/11/2015]. Available at: <<http://docs1.itec.cat/c/Guia.criteris.bedec.pdf>>
8. *Betondingen* [online] Lienden: Betondingen, 2015. [Accessed: 05/11/2015]. Available at: <<http://www.betondingen.nl>>
9. Burón, M. La durabilidad de las estructuras prefabricadas de hormigón. *Hormigón y acero*, 2000, iss. 218, p. 81-88.
10. *Buscador de fabricantes*. [online]. Madrid: ANDECE. *Asociación de la Industria del Prefabricado de hormigón*. [Accessed: 05/11/2015]. Available at: <<http://www.andece.org/index.php/buscatufabricante>>
11. Calavera, J. ... [et al.]. *Recomendaciones para el proyecto, ejecución y montaje de elementos prefabricados*. Madrid: Colegio de Ingenieros de Caminos, Canales y Puertos, 2004. Recomendaciones y manuales técnicos. Estructuras y edificación; E-10. ACHE, Asociación Científico-Técnica del Hormigón Estructural. ISBN 8438002730.
12. Calavera, J. *Cálculo de estructuras de cimentación*. 4ª ed. Madrid: INTEMAC, 2000. ISBN 848876409X.
13. Campos, J.L. 2008. *La Burbuja inmobiliaria española*. Barcelona: Marcial Pons. ISBN 9788497685344.

14. Day, Robert W. *Geotechnical and foundation engineering: design and construction*. Hightstown: McGraw-Hill, 1999. ISBN 0071341382.
15. Sanjuan-Delmás, D. ... [et al.]. Environmental and geometric optimisation of cylindrical drinking water storage tanks. *The International Journal of Life Cycle Assessment* [online]. 2015 [Accessed: 05/11/2015]. p. 1-13  
Available at: <<http://link.springer.com/article/10.1007/s11367-015-0963-y>>
16. Sanjuan-Delmás, D. ... [et al.]. Environmental assessment of different pipelines for drinking water transport and distribution network in small to medium cities: a case from Betanzos, Spain. *Journal of cleaner production*, 2014 vol. 66, p. 588-598.
17. Department for Communities and Local Government. *Innovative Construction Products and Techniques*. BD2503. London: DCLG, 2008.
18. EHE-08. *Instrucción de hormigón estructural / Con comentarios de los miembros de la Comisión Permanente del Hormigón*. 5ª ed. Madrid: Centro de Publicaciones, Secretaría General Técnica, Ministerio de Fomento, 2011.
19. Documento Básico SI Seguridad en caso de incendio. Con comentarios del Ministerio de Fomento. [online]. Madrid: Ministerio de Fomento, 2010. Comment: 2011 [Accessed: 05/11/2015]. Available at: <<http://www.coitir.org/Noticias/PDF/DB-SI-junio-2011-comentarios.pdf>>
20. *Documento Básico SE-AE. Seguridad Estructural. Acciones en la edificación*. [online]. Madrid: Ministerio de la Vivienda, 2009. [Accessed: 05/11/2015]. Available at: <http://www.fomento.gob.es/NR/rdonlyres/118EEE6C-BA87-4148-8B38-DF01CEAD8496/95704/4.pdf>
21. *Documento Básico SE. Seguridad estructural* [online]. Madrid: Ministerio de la Vivienda, 2009. [Accessed: 05/11/2015]. Available at: <http://www.codigotecnico.org/images/stories/pdf/seguridadEstructural/DBSE.pdf>
22. *Documento Básico SE-C Seguridad estructural. Cimientos*. [online]. Madrid: Ministerio de Vivienda, 2007. Corrección de errores 2008. [Accessed: 05/11/2015]. Available at: <http://www.fomento.gob.es/NR/rdonlyres/204AF31C-67E0-402A-BC8A-CB110C8E981F/95705/5.pdf>
23. Ecoinvent Key Materials Indicators. [online] *Granta material Intelligence*. [Accessed: 03/09/2015]. Available at: <<http://www.grantadesign.com/products/data/ecoinvent.htm>>  
*Ecoinvent v3* [database]. Zurich: Ecoinvent. [Accessed: 05/11/2015]. Available at: <<http://www.ecoinvent.org/database/ecoinvent-version-3/ecoinvent-version-3.html>>

24. EFCA Environmental Product Declarations, (EPD). [online] *European Federation of Concrete Admixtures Associations* [Accessed: 05/11/2015]. Available at: <http://efca.info/publications.html>
25. *Estructuras de edificación prefabricadas FIP-ATEP*. Madrid: ATEP, 1996. ISBN 8472922812.
26. Frank, R. ... [et al.]. *Designers' guide to EN 1997-1 Eurocode 7: geotechnical design - general rules*. London: Thomas Telford, 2004. ISBN 0727731548.
27. *Geoforum.com*. [online] Solna: Geo risk & vibration Scandinavia AB, 1998-2009. [Accessed: 05/11/2015]. Available at: <http://www.geoforum.com>
28. Gómez, P. *Estructures de formigó armat: predimensionament i càlcul de seccions*. Gómez, J.V. Primera Edició. Barcelona: Iniciativa Digital Politècnica, 2003. ISBN 9788483015865.
29. *Guía de aplicación de la instrucción de Hormigón Estructural (EHE-08)*. Madrid : Centro de Publicaciones, Secretaría General Técnica, Ministerio de Fomento, 2014. ISBN 9788449809781.
30. Guide to foundation and support systems for manufactured homes. Excellence in Design, Manufacturing and Installation series. *Manufactured Housing Research Alliance*: 2002. ISSN 15293424.
31. Hammond, G. *Inventory of Carbon & Energy (ICE)*. V2. Bath: University of Bath, 2011.
32. Hanna, A.; Zeliniski, Z. Prefabricated concrete foundations for housing. *International Journal for Housing Science*, 2003, vol. 27, iss. 1, p. 41-51.
33. Huat, B.B.K.; Mohammed, T.A. Finite Element Study Using FE Code (PLAXIS) on the Geotechnical Behavior of Shell Footings. *Journal of Computer Science*, 2006, p. 104-108.
34. Huat, B.B.K. An Overview of Precast Foundations for Housing. *Housing and Construction news: News magazine of the Housing research center, Universiti Putra Malaysia*, 2003, vol. 5, iss. 1, p. 1-2.
35. Institut Català del Sòl. *CIT : concurs d'innovació tècnica : concurs per a la redacció de projectes i la construcció d'edificis d'habitatges protegits amb incorporació de nous sistemes i tecnologies innovadores*. 2008. [online] Barcelona: INCASOL. [Accessed: 05/11/2015]. Available at: [http://incasol.gencat.cat/web/.content/home/1-incasol/5-premsa\\_i\\_comunicacio/publicacions/lilibre\\_cit\\_ok.pdf](http://incasol.gencat.cat/web/.content/home/1-incasol/5-premsa_i_comunicacio/publicacions/lilibre_cit_ok.pdf)
36. Jiménez, P. *Hormigón armado*. 15ª ed. basada en la EHE-2008, ajustada al código modelo y al Eurocódigo EC-2. Barcelona : Gili, 2010. ISBN 9788425223075
37. Kellenberger, D; Althaus, H. Relevance of simplifications in LCA of building components. *Building and Environment*, 2009, iss. 44, p. 818-825.

38. Kind-Barkauskas, F. *Concrete construction manual*. Basel; Boston; Berlin; Birkhäuser; Munich: Detail, 2002. ISBN 3764367245.
39. Kovacs,W.D.; Yokel,F.Y.; *Soil and rock anchors for mobile homes. A state of the art report*. U.S. Department of Commerce, National Bureau of Standards, 1979, iss. 107.
40. Krishna Kumar, V. *Industrialized Foundations for Low-rise Light-weight Buildings*. Blacksburg, VA: Virginia Polytechnic Institute and State University, 1972, iss. 109.
41. Llorens, J.; Pons, O. *El terreny i l'estudi geotècnic*. Universitat Politècnica de Catalunya. Iniciativa Digital Politècnica, 2015. ISBN 9788498805215
42. Llorens, J.; Pujadas, E. Lightweight Recoverable Foundations on Suitable Ground. [online] *Proceedings of World Sustainable building. Barcelona conference*, 28-30 October 2014, Barcelona, vol. 6, p. 16-22. [Accessed: 05/11/2015]. Available at: [http://www.gbce.es/archivos/ckfinderfiles/WSB14/CreatingNewResources\\_volume6.pdf](http://www.gbce.es/archivos/ckfinderfiles/WSB14/CreatingNewResources_volume6.pdf)
43. Llorens, J. ... [et al.]. *Creris de projecte de fonaments*. Construcció II. Escola Tècnica Superior d'Arquitectura (UPC), 2012.
44. Llorens, J.; Pujadas, E. Cimentaciones prefabricadas para módulos de vivienda 3D. [online] Abstract presented at the *5th Congreso de ACHE*, 25-27 October 2011, Barcelona. [Accessed: 05/11/2015]. Available at: [http://upcommons.upc.edu/bitstream/handle/2117/15494/pon125\\_2.pdf?sequence=1](http://upcommons.upc.edu/bitstream/handle/2117/15494/pon125_2.pdf?sequence=1)
45. Llorens, J. Apunts del curs Construcció IV. Escola Tècnica Superior d'Arquitectura (UPC).
46. Llorens, J. *Càlculs senzills per al projecte d'estructures i fonaments*. Col·legi d'Arquitectes de Catalunya i Demarcació de Barcelona. Àrea de cultura, formació i publicacions, 2006.
47. Llorens, J.; Soldevilla A., Alternativas tipológicas a la vivienda convencional. *Informes de la Construcción*, 1994, vol. 46, iss. 434, p. 5-25.
48. López, A. La construcción del futuro...¿y por qué no del presente? Soluciones industrializadas y sostenibles con elementos prefabricados de hormigón, *Cursos Avanzados del Instituto Eduardo Torroja*, Madrid, 2015.
49. Lozano, G.; Lozano, A. *Diseño, cálculo, construcción y patología de cimentaciones y recalces*. Consultores técnicos de construcción. Somio, Gijón: Consultores Técnicos de Construcción, 1998. ISBN 8492040122.
50. Manzano y Arroyo, E. 2010. Singularidades del proyecto de cimentaciones profundas con pilotes hincados. *Quaderns d'estructures*, iss. 39, p. 46-52.
51. Márquez, A. Componente modular prefabricado de concreto para placa de fundación superficial reticular alveolada. Una opción para la vivienda de bajo costo de desarrollo progresivo sobre suelo retro-expansivo. *Tecnología y construcción*. 2006, vol. 22-II, p. 23-3

52. Moonen, F. Rapidly building with lightweight modules and a dry assembled foundation: used in a mock-up for home units made out of reclaimed materials. N de Temmerman & C.A. Brebbia (Eds.), *Proceedings of the 4th International Conference on Mobile, Adaptable and Rapidly Assembled Structures (MARAS 2014)*, 11-13 June 2014, Ostend Belgium, p. 209-222.
53. Moonen, F. & Hermans, K. Building with materials from demolition projects. Shu-Ming, Che-Ming Chiang, Chun-Ta Tzeng, Kuang-Sheng Liu, Nien-Tsu Chen, Yi-Pin Lin & S. Emmitt (Eds.), *Proceedings of the 11th International Detail Design in Architecture (DDiA) Conference*, 21-22 October 2013, Kaohsiung, Taiwan, p. 9-16.
54. Moonen, F. *De geïndustrialiseerde foundering*. Thesis. Eindhoven: TU Eindhoven, 2001. ISBN 9068145592
55. *Norma de construcción sismorresistente: parte general y edificación (NCSE-02). Con comentarios de la subcomisión permanente de normas sismorresistentes*. Madrid: Centro de Publicaciones. Ministerio de Fomento Secretaría General Técnica, 2009.
56. Pons-Valladares, O.; Aguado, A. Integrated value model for sustainable assessment of school centers construction. World Sustainable Building Conference. *World Sustainable Building 2014*. Barcelona: 2014, p. 9-15.
57. Pons, O. Hacia sistemas y productos más arquitectónicos, constructivos e industriales. *CIC, Arquitectura y construcción*, 2012, vol. July-August 2012, iss. 498, p. 22-25.
58. Pons, O. *Prefabricated school buildings in Catalonia*. [on line] Thesis director: González, J.M. UPC, Departament de Construccions Arquitectòniques I, 2009 [Accessed: 05/11/15]. Available at: <http://www.tdx.cesca.es/handle/10803/6133>
59. *Off-site manufacture in Australia: Current state and future directions*. Brisbane: Cooperative Research Centre for Construction Innovation, 2007. ISBN 9780980426281.
60. Oliver-Solà, X. ... [et al.]. Environmental optimization of concrete sidewalks in urban areas. *The International Journal of Life Cycle Assessment*, 2009, iss. 14, p. 302-312.
61. Peraza, J. E. ... [et al.]. *Casas de madera. Sistemas constructivos a base de madera aplicados a viviendas unifamiliares*. Madrid: Asociación de Investigación Técnica de las Industrias de la Madera y Corcho (AITIM), 1995. ISBN 848738108.
62. Peraza, J.E. Pilotes de madera para cimentaciones. *Boletín de información técnica*, iss. 227, p.22-26.
63. *Permanent Wood Foundations. Wood text series*. Ottawa: Canadian Wood Council, 1992. ISBN 0921628196



64. *Pilotes Prefabricados y Pretensados TERRA*. [online] Van elle. Total foundation Solutions [Accessed: 05/11/2015]. Available at: <http://www.terratest.es/docs/doc4ed5f12d132516.08695682.pdf>
65. Prakash, S.; Sharma, H. D. *Pile foundations in engineering practice*. New York: Wiley, 1990. ISBN 0471616532.
66. Pujadas, E.; Llorens J.; Moonen, F. Prefabricated foundations for 3D modular housing. Oktay Ural, Emilio Pizzi and Sergi Croce (Eds.), *Proceedings of the 39th IAHS Congress. Changing Needs, Adaptive Buildings, Smart Cities*, Milan, Italy, p. 267-274.
67. Reynolds MSc, T. N. *Timber pile and foundations. Digest 479*. London: BRE (Building Research Establishment), 2003. ISBN 1860816614.
68. Salas, J. Después de ‘la burbuja del ladrillo’... ¿otra tecnología constructiva?. *Informes de la construcción*. [online], 2009, vol. 61, iss. 513 [Accessed: 05/11/2015]. Available at: <http://informesdelaconstruccion.revistas.csic.es/index.php/Informesdelaconstruccion>
69. Sastre, R. *WinEva*. V8. [software]. Sant Cugat del Vallès: Escola Tècnica Superior d'Arquitectura del Vallès, Universitat Politècnica de Catalunya. [Accessed: 05/11/2015]. Available at: <http://wineva.upc.edu>
70. Seminario de prefabricación. *Prefabricación: teoría y práctica*. Barcelona: Editores Técnicos Asociados, 1974. ISBN 8471461315.
71. *Sierbeton online* [online] Eindhoven: Sierbeton online, 2015 [Accessed: 05/11/2015]. Available at: <https://www.sierbetononline.nl>
72. *SimaPro LCA software*. V8. [Software] Amersfoort: Pré Consultants. [Accessed: 05/11/2015]. Available at: <http://www.pre-sustainability.com/simapro>
73. *Smartfoot® Pre-cast modular foundations*. [online] Van elle. Total foundation Solutions [Accessed: 05/11/2015]. Available at: <http://www.van-elle.co.uk/Downloads/Smartfoot%20Brochure.pdf>
74. Staib, G. 2008. *Components and systems: modular construction: design, structure, new technologies*. Dörrhöfer, A.; Rosenthal, M. München: Detail; Basel: Birkhäuser. ISBN 9783764386566.
75. *Sustainable Development Report 2008. QPA Providing Essential Materials* [online]. London: Quarry Products Association Limited, 2008. [Accessed: 05/11/2015]. Available at: [http://www.mineralproducts.org/documents/QPA%20\\_SD%20\\_08%20\\_Rep.pdf](http://www.mineralproducts.org/documents/QPA%20_SD%20_08%20_Rep.pdf)
76. *Tectónica: Monografías de Arquitectura, Tecnología y Construcción. Hormigón II*. 1997, iss 5.

77. Vaquero, JJ. ... [et al.]. 1996. *Edificación con prefabricados de hormigón: para usos industriales, comerciales, aparcamientos y servicios*. Madrid: Instituto Español del Cemento y sus Aplicaciones. ANDECE, Asociación Nacional de Prefabricados y Derivados del Cemento. ISBN 8489702020.
78. Wadel, G. *La sostenibilidad en la arquitectura industrializada: la construcción modular ligera aplicada a la vivienda* [on line] Thesis director: Avellaneda, J. UPC, Departament de Construccions Arquitectòniques I, 2009 [Accessed: 05/11/15]. Available at: <http://www.tdx.cesca.es/handle/10803/6136>
79. Wren, C. Modular foundations and retaining walls. Burland J. ... [et al.]. *ICE Manual of Geotechnical Engineering*. Institution of Civil Engineers, 2012, p. 1343-1350.
80. Yu, H. ... [et al.]. Sustainable precast concrete foundation system for residential construction. *Canadian Journal of Civil Engineering*, 2008, vol. 35, iss. 2, p. 190-199.

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