



MOBILITY HUBS AND THE CARBON FOOTPRINT OF PARKING SOLUTIONS

Prospects and possibilities of parking solutions

September 2026



Reykjavík

24550

No. of issue	Date	Prepared by	Reviewed by	Approved by
1	14.9.2026	BS/LSD	BS/LSD/GK	BS

Prepared by:

Bryndís Skúladóttir and Lilja S. Davíðsdóttir
VSO Consulting
Borgartún 20, 105 Reykjavík

www.vso.is

**Prepared for the City of Reykjavík, with support from the European Union
and NetZeroCities**



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1 Introduction – about the project

This report is one in a set of four reports and a memorandum that summarise the results of the project *Enabling City Transformations (ECT): Developing the Future of the Climate Neutral City*. The project was carried out in collaboration between the City of Reykjavík and VSÓ Consulting, with professional assistance from NetZeroCities and funded by the European Union through a grant to which the City of Reykjavík gained access on the basis of the city's Climate City Contract.

The ECT project is linked to the City of Reykjavík's goals for a carbon-neutral city and the transformation that needs to take place to achieve them. Transport and travel habits are an important factor in this development and are determined, among other things, by the city's planning, access to different modes of transport and incentives that influence the choice of travel mode. The project specifically looked at the role of parking in this context, considering how its availability, location and design can affect travel habits, land use, development and carbon footprint. The aim of the project was to increase knowledge of these connections, carry out analyses and submit proposals for tools that can be useful to the City of Reykjavík in its continued policy-making. The topic was examined from different perspectives, including from the experience and views of stakeholders, policy-making and governance tools of municipalities in the Nordic countries, and the environmental impact of different parking solutions. The project's components are interconnected and together form a basis for recommendations on continued policy-making in the field of travel habits and parking.

The project's output is summarised in four reports and a memorandum:

- *Policy formulation on changing travel habits – analysis of the City of Reykjavík's policy and comparison with Nordic cities:* A literature review of how different parking policies can be implemented in different ways and a review of the available data on their impact on travel habits. A case analysis of the City of Reykjavík's policy on changing travel habits and the role of parking policy in that context. The City of Reykjavík's policy is compared with the approach of two Nordic cities at a similar latitude, Trondheim in Norway and Umeå in Sweden.
- *Parking solutions of the future – community views:* An analysis of stakeholder views on parking solutions and changing travel habits, based on interviews with property developers, real estate agents, bank employees and residents in densification areas. The aim is to shed light on the experience and perspectives of different parties and how parking arrangements can affect development, housing and travel habits.
- *Mobility hubs and the carbon footprint of parking solutions: prospects and possibilities of parking solution.* The development of the use of multi-storey car parks is examined and how they have acquired a new role in neighbourhood planning as mobility hubs. The carbon footprint of a multi-storey car park and an underground car park were compared. Also, how circular building can affect the use of buildings as well as the challenges that often arise in the design of underground car parks.
- *The Travel Habits Game:* A memorandum and data explaining *The Travel Habits Game*, a simple workshop model that is set up and presented as a board game, where participants have to choose actions together to achieve the goal of changing travel habits. The aim of the game is both to steer discussions and investigate people's

attitudes towards actions, but it can also be used as part of education and awareness-raising.

- *Recommendations on policy-making for changing travel habits:* A summary of the main results of the project, which draws together recommendations based on research, analyses and other components of the ECT project. The recommendations are intended to be useful for the City of Reykjavík's continued policy-making on changing travel habits and parking issues.

2 Summary and main findings

We are most familiar with multistorey car parks at shopping and service centres. In Iceland, however, there is limited experience of centralised multistorey car parks in residential areas. Abroad, there is experience of reducing or removing parking spaces from residential streets and instead providing centralised neighbourhood parking in multistorey car parks.

In this part of the ECT project, the work was threefold:

- **Examine developments in the design and construction of multistorey car parks and their evolving role as mobility hub in neighbourhood planning.**
Examples were examined of buildings that serve a broader range of functions than simply providing car parking.
- **Assess the difference in the carbon footprint of parking spaces in underground and multistorey car parks,** based on both the carbon footprint per parking space and the carbon footprint per square metre.
- **Examine circular multistorey car parks designed for conversion to other uses** if demand for parking decreases in the future. The challenges faced by designers when designing underground car parks beneath buildings were also examined.

Since the turn of the century, neighbourhoods have been developed in Europe where parking is centralised rather than located next to residential buildings. Experience shows that moving parking away from residential streets can create greener, more vibrant neighbourhoods, with more space for open and communal areas. Social benefits can include stronger connections with neighbours and increased interaction. A multistorey car park that is also a mobility hub can create further opportunities for residents to meet and contribute to a stronger sense of community. Good access to public transport and the provision of services within the mobility hub that also allow residents to combine trips to the car park with other activities. There are also examples of older underground car parks in city centres that have been repurposed as hubs for service trips and transport by smaller vehicles.

The aim of the analysis is to compare the carbon footprints of underground car parks and multistorey car parks and determine whether there is a significant difference between them. Calculations were carried out for two types of structures: an underground car park beneath a residential building and a multistorey car park. The calculations showed that the carbon footprint per parking space is lower for the multistorey car park than for the underground car park. However, the carbon footprint per square metre is higher for the multistorey car park. This is because the multistorey car park is designed specifically for parking cars, allowing the available floor area to be used more efficiently. In an underground car park beneath a building, the building's load-bearing structure and other required spaces occupy part of the basement area.

The structures used in the calculations are relatively simple and offer limited flexibility. The results could change considerably if, on the one hand, the challenges designers often face when designing underground car parks are considered and, on the other hand, a multistorey car park is designed to allow conversion to other uses in the future. These factors can affect the carbon footprint, potentially increasing it for underground car parks and either increasing or decreasing it for multistorey car parks.

The main findings to consider when planning parking spaces and multistorey car parks are:

- **Requirements in local development plans for above-ground car parks**
Local development plans establish the framework for transport routes and parking within neighbourhoods and can therefore provide opportunities to consolidate parking in multistorey car parks. A holistic approach to neighbourhood planning is required, encompassing roads, pedestrian and cycle routes, and connections to public transport. At the same time, the planning framework should support a diverse range of transport modes.
- **Clear and accessible routes between the multistorey car park and homes**
Care should be taken to provide clear, accessible and attractive routes between the car park and residential buildings. Facilities for parking bicycles and e-scooters should be provided within the car park. It should also remain possible to drive up to residential buildings, even where permanent parking is not provided, for example when transporting large or heavy items. Providing electric cargo bikes for hire can make it easier for residents to transport goods between the multistorey car park and their homes, thereby helping to address the “last mile” challenge.
- **Benefits for residents from reducing parking spaces next to buildings**
By moving parking away from residential buildings, areas that would otherwise be occupied by parking can instead be used for the benefit of residents, for example as green spaces, playgrounds and recreational areas. This makes the benefits of the change more tangible and can improve the quality of life within the neighbourhood.
- **Multistorey car parks to mobility hubs**
Neighbourhoods should be planned so that multistorey car parks can function as mobility hubs, with good access to public transport and space for services. This allows residents to combine trips to the building with activities other than parking a car.
- **Ensure access to public transport**
Access to public transport should be in place when the first residents move into a new neighbourhood, helping to prevent car-dependent travel habits from becoming established from the outset. Residents in new neighbourhoods could also be offered discounted or free public transport for a trial period, giving them an opportunity to become familiar with using public transport before car-based travel habits become established.
- **Set aside an area for “showcase parking”**
Reducing the number of parking spaces can be challenging. There are examples of areas being set aside for “showcase parking”, where additional parking spaces can be provided if the initial parking provision proves insufficient to meet demand. Until such a need arises, the area can remain as publicly accessible green space. This approach retains the option of increasing parking provision in the future if required.
- **Circular building that can be converted for other uses**
Planning and development frameworks should make it easier for developers to construct circular buildings that can be converted to other uses if demand for parking decreases in the future.
- **Consider the carbon footprint of parking**
The results of the project showed that the carbon footprint per parking space is considerably lower for a multistorey car park, as such structures are designed

specifically to accommodate cars and therefore use space efficiently. The analysis considered a relatively simple underground car park; in many cases, however, basement design and construction are more complex, which can increase the carbon footprint per parking space in an underground car park.

3 **Multistorey car parks as mobility hubs**

Multistorey car parks are fundamentally simple buildings with a single primary purpose; to provide parking for cars. Their main advantage is that parking is provided on several levels, requiring less land than would be needed to accommodate the same number of parking spaces at ground level. In recent years, however, multistorey car parks have evolved to play a broader role in the planning and development of the neighbourhoods in which they are located (Stedenbouw, 2024; Car Parks, n.d.).

The trend in Europe is towards buildings that serve multiple purposes and function as mobility hubs, where users can transfer between different modes of transport. They provide parking for cars and bicycles and are well connected to public transport, such as buses, metro systems and trains. There are also several examples of mobility hubs incorporating retail and service facilities or providing space for community services, thereby giving the buildings a broader social function. As the term “multistorey car park” does not fully capture this broader role, the term “mobility hub” will be used here.

Access to a mobility hub can make it easier for residents to adopt a car-free or less car-dependent lifestyle while reducing the amount of land required for parking. Designers increasingly consider the possibility that demands for parking may decrease in the future. Buildings are therefore often designed from the outset to allow for full or partial conversion to other uses, for example through flexible layouts that allow walls or building components to be easily moved or removed.

Buildings of this type can form part of environmentally sustainable neighbourhoods, reflected, among other things, in the choice of building materials and an emphasis on green and diverse outdoor spaces. Such neighbourhoods may also incorporate local renewable energy generation and sustainable surface-water management. By reducing or eliminating parking requirements on individual plots, space can instead be allocated to other uses, such as recreational areas, green spaces, playgrounds and sports facilities. The roofs of multistorey car parks can also be used for purposes such as solar energy generation or recreational areas.

3.1 **Neighbourhood car parks and showcase parking**

The Vauban district in Freiburg, Germany, was developed around the turn of the millennium as an example of sustainable and environmentally friendly urban planning. Now, more than 25 years later, the experience gained from the development provides useful insights into the long-term outcomes of this approach (Szumilas, 2024) (Fraker, 2013).

A combination of measures is used to encourage sustainable modes of transport and discourage the use of private cars. The development process was strongly influenced by a residents' association, which played an active role in overcoming various obstacles, including legal requirements concerning minimum parking provision. Instead of providing parking spaces next to residential buildings, two neighbourhood car parks were constructed. In addition, a site was reserved for a third car park in case additional parking was needed (Image 3.1). This was referred to as “virtual parking”. As there has been no need for additional parking, the reserved site is now used as a recreational area. The multistorey car parks are owned by residents, who can either purchase or rent individual parking spaces.



Image 3.1: Traffic plan for the Vauban district. Car parks are marked in red. On the far left, in the green area, is a space reserved for parking if needed, called a “virtual parking space”. Today, the area is still an open space (Szumilas, 2024).

There are no parking spaces on residential plots, and on-street parking is prohibited, although parking is provided at institutions and service centres. Two car parks are located on the edge of the district, where residents can purchase parking spaces. Residents who sign a declaration stating that they do not own a car receive support for the use of public transport and car-sharing schemes. Public transport provides good connections to the city centre. During the development of the district, particular emphasis was placed on ensuring that public transport was available from the outset, so that the first residents would not become dependent on private cars (Stadtteil Vauban, n.d.).

Car ownership in Vauban is around 150 cars per 1,000 inhabitants, compared with an average of around 600 cars per 1,000 inhabitants in Germany as a whole and around 350 cars per 1,000 inhabitants in larger cities with good public transport (Statistisches Bundesamt, 2026).

The space saved by eliminating the need for driveways and parking spaces at individual homes made it possible to achieve relatively high residential density while retaining substantial green space (Image 3.2). Areas along residential streets that would otherwise

have been used for parking could instead be used by residents as shared outdoor space.



Image 3.2: Residents in Vauban are given access to the area by their house that would otherwise be used for parking, the street is open to pedestrians and is used as a play area. It is possible to drive up to the houses, but parking is not allowed in the streets.

The district is planned so that everyday services are within walking distance. There is little through traffic, and vehicle speeds are restricted to a maximum of 5 km/h. Streets can therefore also function as spaces for play, walking and social interaction. Public open spaces include green areas, playgrounds, barbecue areas and sports facilities, while the amount of paved surface is generally limited. This provides numerous opportunities for residents to meet and interact, helping to strengthen social ties within the community. The buildings are designed according to environmental principles, including careful selection of building materials, improved energy efficiency and the use of sustainable energy solutions. Blue-green infrastructure is also incorporated into the district to manage surface water in a more sustainable manner (Stadtteil Vauban, n.d.).

3.2 Mobility hub

In new neighbourhoods with low parking ratios, the experience of districts such as Vauban has often served as a model, as discussed above. The trend has been for multistorey car parks to serve a broader range of functions than simply providing car parking, increasingly functioning as mobility hubs with good connections to public transport and services within the neighbourhood. For example, they can accommodate parcel collection and delivery services, shops, cafés and sports facilities.

Providing electric cargo bikes for hire at mobility hubs can make it easier for residents to transport goods between the car park and their homes, thereby helping to address the “last mile” challenge. In this way, mobility hubs can also become important focal points within the social environment of a neighbourhood.

This section discusses three neighbourhoods in the Netherlands and Sweden where mobility hubs play an important role and considers the lessons that can be applied in an Icelandic context.

3.2.1 *Haarlem in the Netherlands*

The Elements Mobility Hub, located in the Elements neighbourhood in Haarlem, the Netherlands, is designed as a social hub for the neighbourhood, incorporating restaurants, cafés, parcel collection points and other services (Car Parks, 2022). Services are located on the ground floor, while parking is provided on the upper floors. By centralising parking and providing access to other modes of transport and services in one location, the mobility hub supports a car-free or less car-dependent lifestyle within the Elements neighbourhood. The building is privately owned and forms a part of the developer's wider neighbourhood development (Stedenbouw, 2024).

The building is designed with flexibility in mind and can be expanded, relocated or repurposed, contributing to a sustainable and adaptable urban environment. Environmental considerations are also integrated into the design through green façades, electric vehicle charging stations and solar panels on the roof (Image 3.3).



Image: 3.1: The “Elements Mobility hub” in Haarlem. Restaurants and other services are on the ground floor, with car and bicycle parking on the upper floors.

3.2.2 *Lund in Sweden*

The Brunnshög neighbourhood in Lund, Sweden, is planned and designed with the vision of creating an attractive place to live, work and visit. The development builds on experience from neighbourhoods such as Vauban (see chapter 3.1), with a low parking ratio and no parking provided at individual residential buildings. Instead, residents can park in centralised neighbourhood car parks (Jareklew, 2020). The car parks also provide parcel collection and delivery points and various other services for residents. In addition, they function as mobility hubs, offering car-sharing services and parking for e-scooters, as well as electric cargo bikes for hire. The availability of cargo bikes helps address the “last mile” challenge by enabling residents to transport goods and other items between the mobility hub and their homes. The building was built by the municipality and is operated by Lunds Kommune Parking (Lunds Kommuns Parkerings, n.d.).

3.2.3 *Pijnacker in the Netherlands*

The WijCK neighbourhood in Pijnacker, the Netherlands, is currently under constructions (WijCK Pijnacker, e.d.). The development will comprise around 350 homes across four buildings. Each building is planned around a courtyard, while the central area of the neighbourhood will be open and car-free. The neighbourhood includes a mobility hub known as SmartDock, which provides 320 car parking spaces and 500 bicycle parking spaces. It also includes electric vehicle charging facilities powered by solar panels on the roof, parcel collection and delivery points, and a café. The roof is used as a sports and recreational area (Image 3.4). By removing cars from the streetscape, more space is created for people to meet, interact and play, contributing to a more attractive public realm and a higher quality of life within the neighbourhood. Centralising parking and services in the mobility hub can also contribute to a more vibrant neighbourhood, encourage social interaction and improve residents' sense of safety. The ownership is based on the same model as the car park in Elements in Haarlem; it is part of the neighbourhood's development and is privately operated (Stedenbouw, 2024).

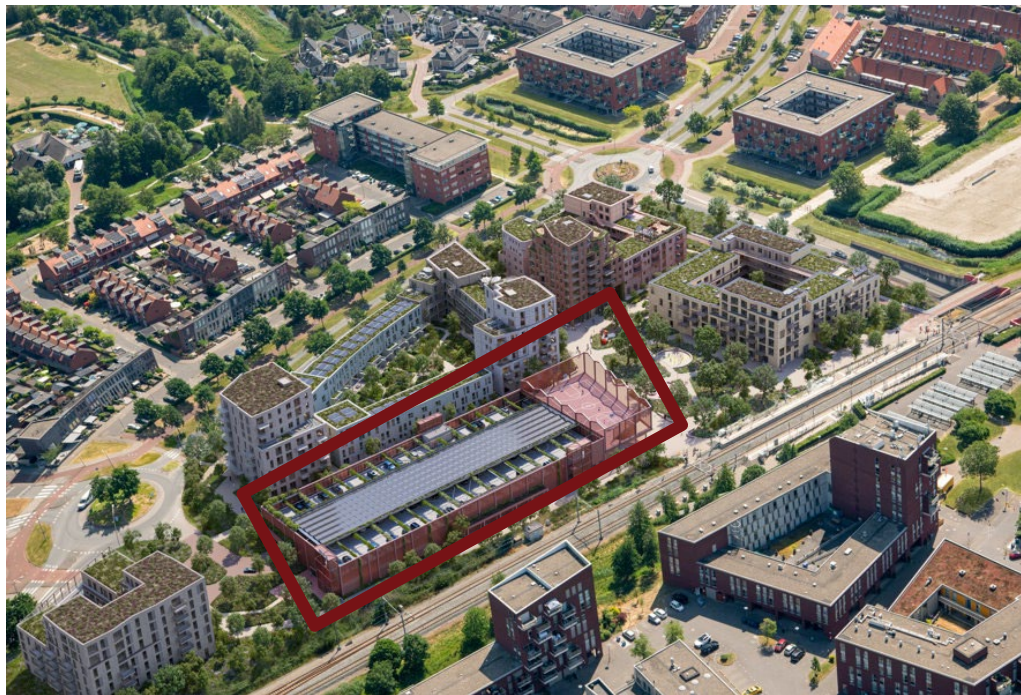


Image 3.2: A computer-generated image of the WijCK neighbourhood, where the “mobility hub” is located between four residential buildings, marked with a red box. Solar panels and an outdoor area can be seen on the roof. It is possible to drive to the residential buildings along the edge of the neighbourhood.

3.2.4 *Older underground car park in Gothenburg*

In 2024, a so-called “Mobility Hotel” opened in central Gothenburg in an underused underground car park beneath a shopping centre. The project is intended to support changes in travel behaviour in the city centre. The concept allows service providers, such as couriers, parcel delivery companies and tradespeople, to arrive by car, park in the underground car park and rent a bicycle, scooter or cargo bike for the remainder of their journey into the city centre. The project draws on concepts such as light transport, micromobility and micrologistics. The facility accommodates companies providing transport services and related activities, including repair services, battery replacement for smaller vehicles and bicycle-based delivery services (Figure 3.5). The project is managed

by Business Region Gothenburg on behalf of the municipality and is funded by the European Union (Business Region Gothenburg, 2024; Nordstan, n.d.).



Image 3.5: A cycle courier with a cargo trailer capable of carrying up to two cubic metres per trip (Pling Transport, n.d.).

4 Calculations of the carbon footprint of parking solutions

Population growth in Reykjavík in recent years has increased demand for housing and contributed to denser urban development. As in many other European cities, private car use remains high, resulting in traffic congestion and considerable demand for parking. In densely developed areas where on-street parking is limited, underground car parks beneath residential buildings are a common solution.

The aim of this project was to compare the carbon footprint of parking spaces in an above-ground multistorey car park with that of spaces in an underground car park. The comparison was carried out using life cycle assessment (LCA), a methodology used to assess environmental impacts over the entire life cycle of a building. The following sections briefly describe the methodology and compare the carbon footprints of two real-world examples: an underground car park beneath an apartment building and an above-ground multistorey car park.

4.1 General information about Life Cycle Assessments

A Life Cycle Assessment (LCA) is a systematic method for assessing the environmental impacts of a product, process or service throughout its entire life cycle. It can be used to identify and minimise adverse environmental impacts by considering all stages of the life cycle, from raw material extraction to end-of-life treatment and disposal. In this project, the analysis focuses specifically on greenhouse gas emissions, expressed as the carbon footprint.

The scope of the analysis is relatively narrow. It compares the carbon footprint of two parking structures designed to accommodate the same number of cars. Potential benefits associated with shared use, as well as variations in construction methods, are not considered.

The calculations were carried out using One Click LCA software, which is widely used in the building sector to conduct life cycle assessments. HMS (the Housing and Construction Authority) has approved One Click LCA for conducting life cycle assessments in Iceland. The software provides databases and analytical tools for carrying out such assessments. The comparison of the carbon footprints of an above-ground multistorey car park and an underground car park involves several steps like those of a conventional LCA, with particular emphasis on factors relevant to these two types of parking structures.

4.1.1 Phases of Life Cycle Assessments for Buildings

The life cycle of a building is divided into modules grouped into phases A, B, C and D (See Image 4.1).

- **Phase A is the product and construction process stage:** This phase covers impacts associated with raw material extraction, transport and the production of building materials. Modules A1–A3 are often referred to as the product stage and cover raw material supply, transport and manufacturing. Modules A4–A5 cover the construction process stage, including the transport of materials to the construction site and the construction and installation process itself.
- **Phase B is the use phase and is divided into 7 sub-phases.** This phase is divided into seven modules: B1 covers use, B2 maintenance, B3 repair, B4 replacement of

building components, B5 refurbishment, B6 operational energy use and B7 operational water use.

- **Phase C is the end-of-life phase.** This phase covers processes occurring at the end of the building's life. C1 covers deconstruction and demolition, C2 transport of waste, C3 waste processing and C4 disposal.
- **Phase D then represents benefits beyond the system boundary:** This phase accounts for potential benefits and loads beyond the building's life cycle, for example through the reuse, recycling and energy recovery of materials after the end of the building's life.

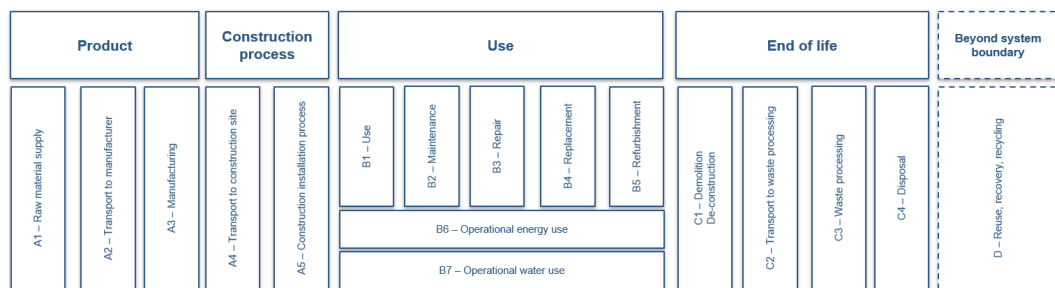


Image 4.1: Phases of life cycle assessments for buildings.

4.1.2 *Life Cycle Assessments according to the Icelandic Building Regulation*

The Icelandic Building Regulation includes requirements for life cycle assessments, and HMS has issued specific guidelines regarding, among other things, which building components must be included in the assessment and the timeframe on which the assessment should be based.

The reference study period used for life cycle assessments is 50 years, in line with the approach used in other Nordic countries. This period is used solely as a basis for the calculations and should not be interpreted as the expected service life of a building or as an indication of when a building or structure is expected to be demolished.

All major building components and technical systems should be included in the assessment. These include foundations, walls, floor slabs, structural frames, doors, roofs, windows, stairs and ramps, floor and ceiling finishes, lifts, electrical systems, ventilation systems and other building services.

4.2 *Underground car park*

This example examines an underground car park located beneath two four-storey (Image 4.2). The car park is shared by and connects the two buildings, while the basement also accommodates technical systems and storage rooms. The underground car park extends beneath both buildings as well as into the areas between and beyond them. The section beneath the garden is covered with precast hollow-core slabs with a reinforced concrete topping. Just over half of the car park walls are below ground level and are therefore subject to lateral earth pressure. The underground car park has a total floor area of approximately 1,325 m² and provides 46 parking spaces, including five accessible parking spaces.

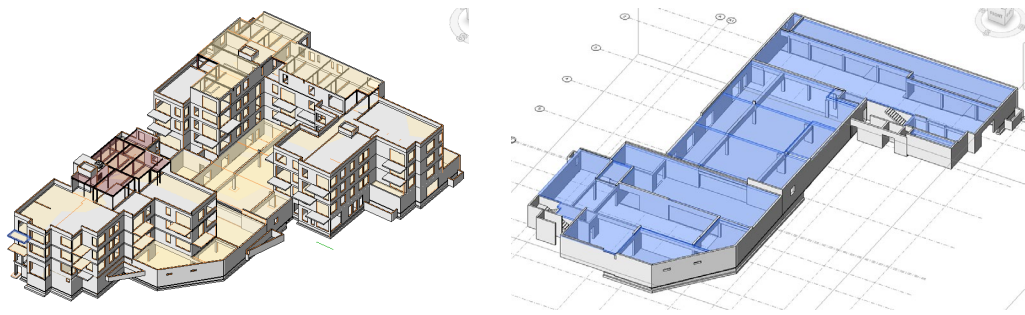


Image 4.2: Schematic diagram of the apartment buildings and the underground car park beneath them, which is used as a basis for calculating the carbon footprint of parking spaces in the underground car park.

4.2.1 *Assumptions for the division between the underground car park and the residential building*

The underground car park forms part of the overall building structure. To estimate the carbon footprint of the car park separately, it is therefore necessary to determine which building components can be attributed to the car park and which would still be required if the residential buildings were constructed without underground parking. The following assumptions were used to allocate structural components, other building materials and energy consumption between the residential buildings and the underground car park:

- Foundations located beneath the residential buildings are attributed to the residential buildings, while foundations serving only the underground car park are attributed to the car park.
- The slab above the underground car park and beneath the residential buildings is attributed to the underground car park. The corresponding area of the base slab beneath this part of the car park is attributed to the residential buildings.
- Similarly, sections of the slab above the underground car park that extend beyond the residential buildings are attributed to the underground car park.
- Walls and columns that define and support the underground car park are attributed to the car park, including all concrete walls within it.
- The base slab is 120 mm thick, while the slabs above the underground car park beneath the residential buildings are 240 mm thick. The hollow-core slabs above sections of the car park that extend beyond the residential buildings are 265 mm thick with a 60 mm reinforced concrete topping.
- Lift shafts and stairwells are attributed to the residential buildings and are therefore excluded from the assessment of the underground car park.
- Energy consumption associated with lighting and ventilation in the underground car park is attributed to the car park.

4.2.2 *Quantities*

The total volume of concrete is estimated at approximately 790 m³, while the total quantity of steel is approximately 69 tonnes. This corresponds to an average steel content of approximately 86 kg/m³ of concrete. Table 4.1 shows the distribution of these quantities among the different building components and provides information on other building materials.

Table 4.1: Quantity of building components in the underground car park.

Building component	Concrete (m ³)	Steel reinforcement (kg/m ³)
Foundations (footings)	25	2.5
Walls (foundation walls and walls)	311	28
Slabs (bottom, reinforced concrete and hollow-core slabs and topping layer)	453	38
Jet fans 4 pcs.	-	-
Exhaust fan 1 pc.	-	-

4.3 Multistorey car park

The multistorey car park is a concrete structure consisting primarily of precast concrete elements, including beams and hollow-core slabs, with cast-in-situ concrete columns and foundations. As the building is an open structure, it requires few building services. These are primarily limited to electricity for lighting and a drainage system. Doors are not required due to the open design of the car park (Image 4.3).

The design is based on solutions used in similar multistorey car parks in Europe. To ensure a realistic comparison with a conventional underground car park forming part of a residential development, the structural design was based primarily on concrete construction.

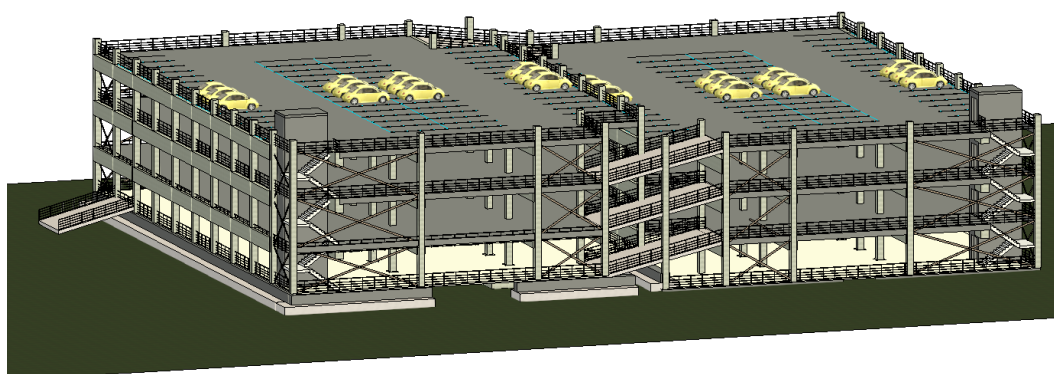


Image 4.1: Schematic diagram of a multistorey car park used as a basis for carbon footprint calculations.

4.3.1 Assumptions and dimensions

The multistorey car park examined in this study is hypothetical, but its design assumptions and structural system are based on current building regulations and common construction practices. The car park is a four-storey building with a total floor area of approximately 12,252 m² and 472 parking spaces, including 16 accessible parking spaces. Two accessible spaces are provided next to each lift on every floor. Each storey is arranged as a split-level structure (Image 4.3). Stairs and lifts are located at both ends of the building, while ramps provide access between the different levels.

The structure consists primarily of concrete, with steel cross-bracing and steel barriers along the outer edges of the building and between floor levels. The ground-level surface is asphalted, while the upper floors consist of precast hollow-core slabs with a reinforced

concrete topping to provide diaphragm action at each floor level. Prestressed hollow-core slabs or ribbed slabs are commonly used in similar structures, partly because they allow for longer spans while limiting deflection. Hollow-core slabs were selected for this example. As their name suggests, the slabs contain longitudinal voids and are prestressed using high-strength steel strands. As a result, they are considerably lighter than conventional cast-in-situ reinforced concrete slabs of equivalent thickness. For this example, 400 mm thick hollow-core slabs with spans of up to 11 metres are assumed.

4.3.2 Quantities

Table 4.2 shows the total volume of concrete, in cubic metres, for each structural component, together with the corresponding amount of steel reinforcement per cubic metre of concrete. An additional allowance of 15% is included for reinforcement associated with detailing and connections. Other building components are also included in the table.

Table 4.2: Quantity of building components in a multistorey car park.

Building component	Concrete (m ³)	Steel reinforcement (kg/m ³)
Foundations - cast-in-situ (C35/40)	1410	90
Hollow-core slabs - precast (C50/60)	4220	50
Topping layer - cast-in-situ (C35/40)	850	90
KB beams – precast (C45/55)	1000	120
Columns – in-situ cast (C50/60)	230	150
Stairs – in-situ cast (C35/40)	30	100
Slabs – in-situ cast (C35/40)	20	100
Walls – in-situ cast (C35/40)	70	100
Ramps – in-situ cast (C35/40)	190	100
Lift, 4 floors	-	-

4.4 Scope, extent and methodology

4.4.1 Objective and scope of the analysis

The objective of the analysis is to compare the carbon footprints of an underground car park and a multistorey car park and determine whether there is a significant difference between the two, both per square metre of floor area and per parking space.

4.4.2 Functional unit

The results are compared using the carbon footprint per square metre per year (kg CO₂-eq/m²/year) and per parking space per year (kg CO₂-eq/parking space/year). As the two car parks differ considerably in size, the results are normalised by both floor area and number of parking spaces to allow for a meaningful comparison. The underground car park has a total floor area of 1,325 m² and provides 46 parking spaces, while the multistorey car park has a total floor area of 12,252 m² and provides 472 parking spaces.

4.4.3 ***System boundaries of the analysis***

The system boundaries determine which life cycle stages and building components are included in the analysis. The requirements of the Icelandic Building Regulation and HMS guidelines were followed when determining which life cycle modules to include in the assessment (Image 4-1). All modules within stage A were included, covering the product and construction process stages, as were all modules within stage C, covering the end-of-life stage. The assessment also includes modules B4, replacement of building components, and B6, operational energy use. In accordance with HMS guidelines, modules B1 (use), B2 (maintenance), B3 (repair), B5 (refurbishment) and B7 (operational water use) were excluded.

The system boundaries primarily encompass the structural components of the two car parks. In addition, operational energy consumption associated with lighting and ventilation is included.

4.4.4 ***Lifespan***

In accordance with the harmonised methodology for life cycle assessments, a reference study period of 50 years is used. This should not be interpreted as the estimated service life of the building, but rather as a defined calculation period used for the purpose of the assessment and comparison.

4.4.5 ***Background data and software***

The two cases examined in the analysis were designed by structural engineers, and material quantities were estimated based on their design data. The life cycle assessment was carried out using One Click LCA software. The software database draws extensively on Environmental Product Declarations (EPDs), which provide standardised information on the environmental impacts of individual building products throughout their life cycles. The database also contains generic and average data for various materials and processes, including average data provided by HMS. For operational energy consumption, design values from comparable projects were used.

The calculations were carried out in One Click LCA using the LCA for Iceland tool.

4.4.6 ***Environmental impact categories***

This analysis considers only the carbon footprint, expressed as Global Warming Potential (GWP). The results are presented in kg CO₂-eq/m²/year and kg CO₂-eq/parking space/year. The carbon footprint is also presented by life cycle stage.

4.4.7 ***Uncertainty and limitations***

Material quantities for the structural systems were calculated based on the structural designs and are therefore based on project-specific design data.

Precise environmental data for the supply and exhaust fans were not available in the software database. The available datasets that most closely represented the specified equipment were therefore selected. Average data from HMS were used to calculate the carbon footprint associated with energy consumption.

4.5 ***Analysis results***

This section presents the results of the analysis for each case individually, followed by a comparison of the two cases.

For the cases examined, the carbon footprint per parking space is lower for the multistorey car park than for the underground car park, with a difference of 6.15 kg CO₂-eq/parking space/year. However, when compared per square metre of floor area, the carbon footprint of the multistorey car park is higher by 0.34 kg CO₂-eq/m²/year. This difference can partly be explained by the more efficient use of floor area in the multistorey car park. The underground car park provides approximately 28.8 m² of floor area per parking space, compared with approximately 26.0 m² per parking space in the multistorey car park. The multistorey car park is designed specifically for parking and can therefore use the available floor area more efficiently. By contrast, the layout of the underground car park must accommodate the structural system and spatial requirements of the residential buildings above, with the design of the residential buildings taking precedence over the layout of the parking area.

The results of the carbon footprint analysis for the underground car park described in chapter 4.2 are presented in Table 4.3, and the results for the multistorey car park described in chapter 4.3, they are presented in Table 4.4. The total carbon footprint was calculated as 5.73 kg CO₂-eq/m²/year for the multistorey car park and 5.39 kg CO₂-eq/m²/year for the underground car park. When calculated per parking space, the corresponding results were 149.02 kg CO₂-eq/parking space/year for the multistorey car park and 155.17 kg CO₂-eq/parking space/year for the underground car park.

Table 4.3: Results of the analysis of the carbon footprint for the underground car park.

Phase		Carbon footprint	
		kg CO ₂ -eq/m ² /year	kg CO ₂ -eq/Parking space/year
A1-A3	Building materials	3.11	89.57
A4	Transport to construction site	0.40	11.40
A5	Construction process	0.85	24.48
B4-B5	Repairs and replacement of building materials	0.02	0.53
B6	Energy consumption	0.14	3.99
C1	Demolition	0.36	10.39
C2	Transport of waste	0.03	0.90
C3	Waste processing	0.00	0.01
C4	Waste disposal	0.48	13.90
Total		5.39	155.17

Table 4.4: Results of the analysis of the carbon footprint for a multistorey car park.

Phase		Carbon footprint	
		kg CO ₂ -eq/m ² /year	kg CO ₂ -eq/Parking space/year
A1-A3	Building materials	3.54	92.04
A4	Transport to construction site	0.40	10.29
A5	Construction	0.85	22.10
B4-B5	Repairs and replacement of building materials	0.04	1.08
B6	Energy consumption	0.03	0.77
C1	Demolition	0.36	9.38
C2	Waste transport	0.03	0.82
C3	Waste processing	0.00	0.01
C4	Waste disposal	0.48	12.55
Total		5.73	149.02

5 **Changes to multistorey car parks and underground car parks**

The buildings used as the basis for the carbon footprint calculations in Chapter 4 represent relatively simple and conventional examples of their respective building types and offer limited flexibility. This chapter considers two factors that may result in more complex designs: the requirements associated with designing a multistorey car park so that it can be converted to other uses in the future, and the challenges that designers may encounter when designing underground car parks. In both cases, these considerations can increase the complexity of the design and construction, potentially increase costs and affect the overall carbon footprint of the building.

5.1 **Circular building**

If future developments in transport lead to a decline in private car use, the demand for parking spaces is also likely to decrease. Underground car parks are generally designed specifically for parking and can be difficult to adapt to other uses. However, there are examples of multistorey car parks that have been designed so that all or part of the building can later be converted to other uses, such as offices, light industrial premises or retail space. The following sections consider the main factors that would need to be addressed if part of the multistorey car park described in chapter 4.3 were to be converted in this way.

Ramps and circulation between floors

Multistorey car parks require ramps to provide vehicular access between floors. In the example described above, the ramps are located between the floor slabs on either side of the building. To allow parts of the building to be converted efficiently to office, industrial or retail use, the location and design of the ramps would need to take potential future conversion into account. This could involve designing the ramps so that they can be relocated or removed from areas intended for conversion, with vehicular circulation accommodated elsewhere.

Vibration from vehicle traffic

If part of the building is converted to uses other than parking while vehicle traffic continues elsewhere in the structure, occupants may experience vibrations generated by vehicles travelling across the floor or roof slabs. It may therefore be necessary to structurally separate areas subject to vehicle traffic from areas intended for occupancy, for example by providing separate structural systems with movement joints between them. This would generally require additional beams and potentially additional columns, increasing material quantities, construction costs and the associated carbon footprint. The potential use of vibration-isolation measures, such as resilient layers or vibration dampers, should also be considered, particularly where the proposed use is sensitive to vibration.

Load-bearing capacity at the building's perimeter

The building perimeter may require larger beams and columns to accommodate the additional loads associated with future external walls, façade systems or other elements of the building envelope. In the car park examined here, however, the same beam and column dimensions are used throughout the structure and are designed for the maximum anticipated loads. No additional increase in their dimensions is therefore assumed to be

required. Potential future changes to the façade and its openings should nevertheless be considered at the design stage, particularly where they may affect the load-bearing structure or be required to accommodate additional escape routes and entrances following a change of use.

Increased permanent loads

Industrial and retail premises may be subject to increased permanent loads due to internal walls, fixtures, ceilings and other building components. The example analysed in Section 4.3 assumes an additional permanent load of 0.5 kN/m², whereas an allowance of 1.0 kN/m² is commonly used for internal partitions. Future changes to floor construction may also increase permanent loads, for example where additional material is required to level floors or install new floor finishes. Greater load-bearing capacity may also be required if the converted space is intended to accommodate heavy machinery, equipment or storage systems.

Openings for building services

Openings through hollow-core slabs and beams for building services, including electrical installations, ventilation and drainage, should be considered during the initial design stage. Providing for such openings in advance is generally simpler and less costly than creating them after construction, when the options for modifying structural elements may be limited. The location of stairwells lifts, and service areas should also be planned with potential future uses in mind. Provision may need to be made for technical rooms and other service spaces that are not generally required in an open multistorey car park but would be necessary following conversion to an occupied use.

Floor levels and gradients

Car parks commonly have steeper floor gradients than would normally be acceptable in office or retail spaces. The design should therefore consider how floors could be levelled if the building is converted in the future and whether this would require additional concrete or another floor build-up. The additional weight of these materials may also need to be considered in the structural design.

Approach and access

Industrial and retail premises may require different forms of access and servicing from those provided in a car park. These may include larger entrances for deliveries and goods handling, improved pedestrian access, and appropriate access for people with reduced mobility. Potential future requirements should therefore be considered in the initial layout of the building.

Windows and natural light

Car parks are generally designed as open structures rather than with conventional windows, whereas office, industrial and retail spaces may require greater access to natural light and external views. The design should therefore consider whether suitable window openings or other means of providing natural light could be introduced in the future without adversely affecting the load-bearing structure. In the example described above, one possible solution would be to create a lightwell between the two halves of the split-level structure.

Fire safety and regulations

A change of use is likely to result in different or more stringent fire-safety requirements than those applicable to a car park. These may include requirements relating to fire compartments, fire protection systems and escape routes. The potential implications of a future change of use should therefore be considered at the design stage.

Acoustics and indoor air quality

Occupied spaces require higher standards of acoustic performance and indoor air quality than car parks. Conversion may therefore require the installation of mechanical ventilation, acoustic treatments and other building services. The potential need for openings and penetrations through structural elements to accommodate these systems should be considered as part of the initial design.

Building regulations and planning requirements

A future change of use would also need to comply with applicable building regulations and planning requirements. It would therefore be necessary to determine whether the municipal plan and local plan permit the proposed use and whether the conversion would affect requirements relating to matters such as the floor area ratio, parking provision, noise and traffic.

5.2 Circular car parks

There are examples of multistorey car parks that have been designed so that they can later be converted to other uses, such as offices, classrooms, event spaces or apartments. Designing buildings according to circular economy principles aims to minimise environmental impacts throughout their life cycle, reduce waste and enable buildings and their components to be adapted or reused as societal needs change. This section presents examples from Germany, the Netherlands and Luxembourg. These buildings often use modular systems and precast elements that can be disassembled and reassembled in a different configuration or, in some cases, at a different location.

5.2.1 Stuttgart, Germany

In Stuttgart's new Neckarpark district, options for underground parking are limited because the area lies within a protected mineral-springs zone. A municipally owned multi-storey car park was therefore constructed (ASP Architekten, n.d.). The building has a modular design, allowing individual floors to be converted into flats or offices, or adapted for other uses, without demolishing the structure. It includes charging facilities for electric cars and secure charging facilities for electric bicycles. The design emphasises circular-economy principles, flexibility and renewable energy generation. A large proportion of the construction materials were recovered from older buildings demolished in the area (Stuttgart, 2025) (Figure 5.1).



Figure 5.1: Neckarpark in Stuttgart is a flexible building, designed as a modular system and can be converted into flats or commercial premises.

5.2.2 *Wendlingen, Germany*

“Holzparkhaus Bahnhof Wendlingen” in Germany is a multi-storey car park located at a railway station near residential and commercial areas (Internationale Bauausstellung 2027 StadtRegion Stuttgart, n.d.). The five-storey building provides parking for 350 cars and 150 bicycles. Charging points for electric cars and bicycles are powered by electricity generated by solar panels on the roof. The structure consists of prefabricated timber modules, minimising the use of steel and concrete and reducing its environmental impact. Its modular design allows the building to be converted into commercial or residential premises in the future or dismantled entirely. Generous ceiling heights and a demountable central ramp facilitate such adaptations. Because the ramps are located in the centre of the building, their removal would allow this space to be converted into a courtyard (Figure 5.2). The car park was built by the municipality as part of the development surrounding the railway station and is operated by a private company (Wendlingen am Neckar, n.d.).



Image 5.2: The Holzparkhaus Wendlingen car park is built from prefabricated timber units, which make it possible to convert the building or disassemble it.

5.2.3 *Limburg, the Netherlands*

The car park forms part of the redevelopment of the Limburg DC innovation and university campus in the Netherlands (Limburg DC, e.d.). The area is run by a development company owned by municipalities at the district level. Sustainability is a guiding principle for the development of the area, with car traffic minimised throughout the campus and some areas designed to be car-free. The five-storey building provides parking for 366 cars and 53 bicycles, with the possibility of future expansion. Solar panels installed on the roof generate electricity for electric vehicle and bicycle charging facilities. The building is constructed primarily from prefabricated timber elements, minimising the use of steel and concrete. Generous floor-to-ceiling heights and a removable central ramp facilitate the future conversion of the building to other uses, such as classrooms, workshops or event spaces (Image 5.3). Life cycle assessments were used during the design process to minimise the environmental impacts of the building throughout its life cycle, including construction, use and end-of-life stages (LDC Wood, e.d.) (Archello, e.d.).



Image 5.3: Multistorey car park in Limburg, Netherlands Prefabricated timber units, generous ceiling height and a movable central ramp make it easy to later convert the building into, for example, classrooms, workshops or an event space.

5.2.4 ***Bissen, Luxembourg***

The Bissen eco-circular car park is an example of a building designed according to circular economy principles, with an emphasis on conserving resources through the reuse of building materials and components (Astron, 2025). The building is operated as a part of the Bissen Automotive Campus innovation cluster, where companies, knowledge institutions and student teams have facilities, and is owned by a development company. The building consists of modular components that allow it to be partially or completely disassembled and subsequently reassembled as either a car park or an office building. Its components are designed for durability and future reuse. The car park is in a commercial area and is connected to an innovation centre. The six-storey building provides 500 car parking spaces and nine motorcycle parking spaces.

5.3 **Challenges related to underground car parks**

Constructing an underground car park beneath an apartment building involves a range of factors that can increase construction complexity, costs and construction time. Many of these are directly related to below-ground construction and site-specific ground conditions and may also affect the carbon footprint per parking space.

- If the ground conditions require rock excavation or blasting to construct the underground car park, this can represent a significant additional cost. Costs arise both from the excavation itself and from transporting excavated material away from the construction site.
- A high groundwater level may require drainage systems, sump pits and pumps. Where the basement is subject to continuous groundwater pressure, it may need to be designed as a fully watertight structure, increasing both construction complexity and cost.

- Watertight basement construction may require waterstops, injection hoses and other sealing measures at construction joints. Base slabs and walls may also need to be thicker and more heavily reinforced to control cracking.
- Lowering the groundwater level through pumping can affect surrounding ground conditions and potentially cause settlement of nearby structures and utilities. Monitoring may therefore be required during construction.
- The effects of groundwater uplift on the basement structure must be assessed. If the self-weight of the building is insufficient to resist uplift, measures such as a thicker base slab, tension piles, rock anchors or other anchoring systems may be required.
- Deep excavations may require temporary shoring, diaphragm walls, shotcrete, rock bolts or anchored retaining structures, particularly close to plot boundaries and neighbouring structures.
- Weak or otherwise unfavourable ground conditions may require soil replacement, deep foundations or more extensive foundation structures.
- Requirements for vehicle circulation and parking spaces restrict the positioning of columns and load-bearing walls within the basement. This may necessitate longer structural spans, thicker slabs, beams or transfer structures beneath the building above.
- Access ramps require considerable space and increase the extent of excavation. Drainage, snow-melting systems and, where necessary, pumping at the lower end of the ramp must also be considered.
- Underground car parks require additional building services, such as ventilation, smoke extraction, fire-protection systems, emergency lighting, sprinkler systems and drainage systems with oil separators.
- Construction joints and service penetrations through the basement structure represent potential leakage points and therefore require appropriate sealing solutions and careful quality control.
- Basement construction generally requires substantially more excavation and material transport than construction without a basement. This can extend the construction period and increase costs associated with site operations, project management, financing and changes in construction prices.
- If contaminated soil is encountered, additional investigations, treatment and appropriate disposal may be required.
- Existing pipes and utilities may need to be relocated or protected as a result of excavation and construction works.
- The overall cost of the basement should be considered in relation to the number of usable parking spaces provided. Ramps, circulation areas, columns and technical rooms can account for a substantial proportion of the total basement floor area.
- The structural design of the building above is closely linked to the structural layout of the basement. If an underground car park is introduced at a later stage of the design process, substantial changes to the design of the entire building may therefore be required.

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