CASE STUDIES

Widening Horizons to the Design of Pre-stressed Concrete Slab: A Case Study of Barcelona

David Requejo Castro and Eva Oller

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GDEE GLOBAL DIMENSION IN ENGINEERING EDUCATION

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Widening Horizons to the Design of Pre-stressed Concrete Slab: A Case Study of Barcelona

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4 WIDENING HORIZONS TO THE DESIGN OF A PRE-STRESSED CONCRETE SLAB: A CASE STUDY IN BARCELONA

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1. Introduction

Only one century ago, 20% of the world's population resided in urban areas. In lower income countries, this proportion was just 5%. Today, approximately half of humanity lives in cities (3.5 billion people).

At the United Nations Conference on Human Settlements in 1976 (Vancouver, Canada), the international community was called to commit to human settlement policies in order to alleviate the worst conditions of "uncontrolled urbanization" within a framework of social justice. Two decades later, within the definition of the Millennium Development Goals (MDGs), world leaders shaped a broad vision to fight poverty in its many dimensions for the next 15 years. Among these goals, and regarding urbanization issues, a specific target was included to achieve, by 2020, a significant improvement in the lives of at least 100 million slum dwellers. The result during the MDG period was a reduction of the proportion of urban population living in slums in the low-income regions from approximately 39.4% to 29.7%. Nevertheless, key current and new urban challenges have emerged over the years. In 2015, countries adopted the 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals (SDGs). In this context, a more ambitious spectrum was defined — to "make cities inclusive, safe, resilient and sustainable" (Goal 11).

Undoubtedly, engineers, as well as other practitioners, play a key role in achieving more sustainable cities. Further, simply applying only technical solutions is unrealistic. In this sense, a shift towards a wider perspective is needed, and professionals are being called on to extend their role to include ensuring that the real needs of all present end users are met, as well as recognizing impacts on both the natural environment and future generations.

In this case study, students are invited to apply their technical skills while, at the same time, are encouraged to discuss different aspects that integrate a wider perspective into decision-making. To do this, an introduction is provided for the international context addressing the human settlements as well as for the concept of sustainable development. In addition to this, basic knowledge will be provided regarding index construction for supporting decision-making. Finally, a specific context and problem will be introduced in order to set up the starting point for the proposed activities development.

1.1. Disciplines covered

The main discipline covered in this case study refers to pre-stressed concrete structures. Nevertheless, several concepts, including teaching methodology, can be the base for disciplines related to reinforced concrete structures or to steel structures.

In parallel, teamwork is promoted, as the proposed activities are to be carried out in small groups, which ultimately should stimulate both group enrichment discussions and a general debate in the classroom.

1.2. Learning outcomes

It is expected that, as a result of this case study, students will be able to:

- Understand current situation regarding human settlements and the importance of sustainable approaches;
- Deal with the definition of a solution to a real project, trying to understand the problem in hand from its conception;
- Learn to think as an engineer, by solving problems with multiple solutions and trying to choose the optimal one;
- Wide their perspectives when dealing with any project, integrating into their decisions several aspects rather than only the technical ones;
- Define the structural solution (geometry, active and passive internal reinforcement) by accomplishing the conditions given by the existing concrete codes (in this case, the Spanish Concrete Code EHE-08 and Eurocode-2).

1.3. Activities

In this case study, two activities are requested from the students. The first will be a reflection about the complexity of human development from the perspective of civil engineering. This should encourage not only an enriching debate but also a discussion that reaches beyond the technical and economic aspects that are usually considered during the design of a project.

The second activity, designed to be solved during an academic semester, aims to work on the technical solution associated with the presented problem. Furthermore, the solutions proposed are expected to be justified and linked to the deontological code of engineers.

2. Description of the context

In this section, we present an introduction of the international context addressing human settlements and a global overview of the urbanization, to provide the students with a general perspective of this global issue. Additionally, we present a brief description of an example related to what is understood as a sustainable city, as well as a conceptual framework for civil engineers in order to integrate the concept of sustainable development into their activities. Next, we give some basic knowledge regarding composite indicators, to support decision-making. Finally, we introduce the case study is in order to contextualize the related activities.

2.1. International context addressing human settlements

The United Nations Human Settlements Programme (UN-Habitat) started in 1976 with the UN Conference on Human Settlements in Vancouver, Canada, at a time when the governments began seriously to perceive cities under their jurisdictions as "emerging futures" in their own right (United Nations Human Settlements Programme, 2016). There were two major outcomes of this path-breaking event. The first was the Vancouver Declaration, which urged both individual countries and the international community to commit to human settlement policies that combine spatial planning with elements of economic, social, and scientific thinking, in order to alleviate the worst conditions of "uncontrolled urbanization" within a framework of social justice. The second outcome, announced in a UN General Assembly document of December 1977, was the establishment of the United Nations Centre for Human Settlements as a focal point for coordinating activities within the UN (United Nations General Assembly, 1977).

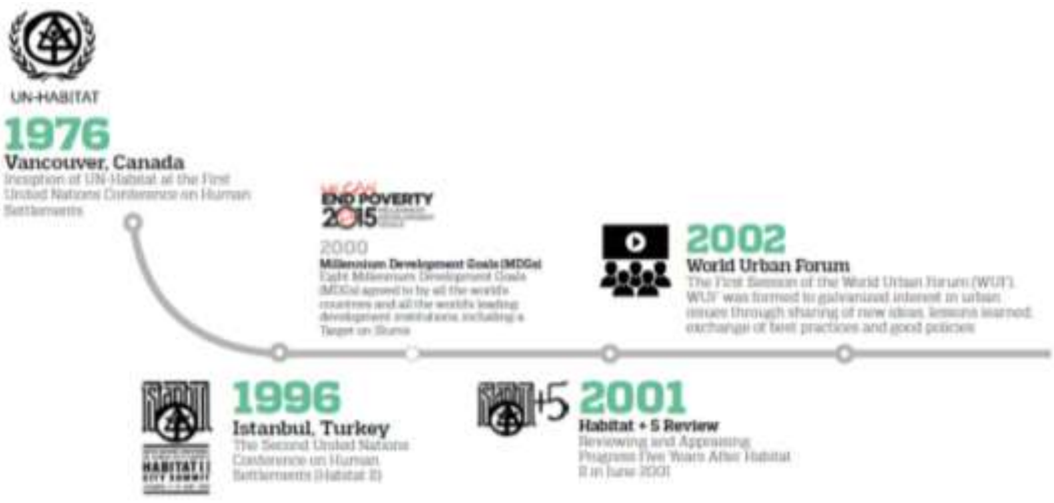

Figure 1 *Relevant international events from 1976 to 2002 associated with human settlements. Source: United Nations Human Settlements Programme, 2016.*

Two decades later, in June 1996, in Istanbul, the Second UN Conference on Human Settlements (Habitat II) further contributed to raising global awareness about urban and human settlements issues. As a remarkable turning point, this event marked the first time in a UN conference that NGOs and civil society organizations were invited to speak and participate in drafting recommendations (United Nations Human Settlements Programme, 2016). The main issues discussed were recognition of cities as the forefront in strategies for development, although poverty and poor housing conditions were increasing in incidence. In addition to this, citizen groups, community organizations, and NGOs were identified as important stakeholders to which more attention should be provided. Finally, the key role of the governance was highlighted, affirming that future governments would be enablers much more than providers.

At the beginning of the new millennium, world leaders gathered at the United Nations to shape a broad vision to fight poverty in its many dimensions. That vision, which was translated into eight Millennium Development Goals[1] (MDGs), remained the overarching development framework for the world for the next 15 years (United Nations, 2015). In this context, and regarding urbanization issues, a specific target (7.D) was included that aimed to achieve, by 2020, a significant improvement in the lives of at least 100 million slum dwellers. The result during the MDG period was a reduction of the proportion of urban population living in slums in the low-income regions, from approximately 39.4% in 2000 to 29.7% in 2014 (United Nations, 2015). In other words, between 2000 and 2014, more than 320 million people gained access to either improved water, improved sanitation, durable housing, or less crowded housing conditions, which means that the MDG target was largely surpassed. Although this target was met, the absolute numbers of urban residents living in slums continue to grow, partly due to accelerating urbanization, population growth, and the lack of appropriate land and housing policies. Over 880 million urban residents were estimated to live in slum conditions in 2015, compared to 792 million reported in 2000 and 689 million in 1990.

Figure 2 *International events regarding human settlement issues from 2002 to date. Source: United Nations Human Settlements Programme, 2016.*

[1] *More information related to the MDGs can be found at http://www.un.org/milleniumgoals.*

In 2015, countries adopted the 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals[2] (SDGs). These SDGs aim to go further to end all forms of poverty. The new Goals are unique in that they call for action by all countries - low, high, and middle-income - to promote prosperity while protecting the planet. They recognize that ending poverty must go hand-in-hand with strategies that build economic growth and addresses a range of social needs including education, health, social protection, and job opportunities, while tackling climate change and environmental protection (United Nations). Specifically, Goal 11 sets out to "make cities inclusive, safe, resilient and sustainable". In so doing, this goal proposes to focus on 10 Targets[3].

In 2016, the United Nations Conference on Housing and Sustainable Urban Development took place in Quito, Ecuador. It was the first UN global summit on urbanization since the adoption of the 2030 Agenda for Sustainable Development the previous year. There, world leaders adopted the New Urban Agenda that set global standards of achievement in sustainable urban development, rethinking the way cities are built, managed, and lived in by combining cooperation with committed partners, relevant stakeholders, and urban actors at all levels of government as well as in the civil society and private sector (United Nations). Above all, this urban agenda should prescribe conditions that facilitate a shift towards more sustainable patterns of urbanization, seeking to achieve inclusive, people-centred, and sustainable global development. Therefore, the policies that emerge must be implementable, universal, sensitive, and relevant to the local context. They must be participatory and collaborative. They must be inclusive and recognize the rights of minorities and vulnerable groups. Above all, the policies must be sustainable (United Nations Human Settlements Programme, 2016).

2.2. URBANIZATION: GLOBAL OVERVIEW

It is remarkable that only one century ago, 20% of the world's population resided in urban areas. In lower-income countries, this proportion was just 5%. The world has been rapidly urbanized, and in 2008, for the first time in history, the urban population outnumbered the rural population. This milestone marked the advent of a new 'urban millennium'. By 2050, it is expected that two-thirds of the world population will be living in urban areas (United Nations Human Settlements Programme, 2015).

Today, approximately half of humanity lives in cities (3.5 billion people). As a direct result of this situation, the world's cities occupy just 3% of the Earth's land, but account for 60% to 80% of energy consumption and 75% of carbon emissions. Thus, rapid urbanization is exerting pressure on fresh water supply, sewage, the living environment, and public health.

[2] *Detailed information regarding the SDGs can be consulted at http://www.un.org/sustainabledevelopment.*
[3] *A description of the 10 Targets can be found at http://www.un.org/sustainabledevelopment/cities.*

However, the high density of cities can bring efficiency gains and technological innovation while reducing resource and energy consumption (United Nations). Urban planning requires a shift from viewing urbanization mainly as a problem, to seeing it as a powerful tool for development (United Nations Human Settlements Programme, 2015).

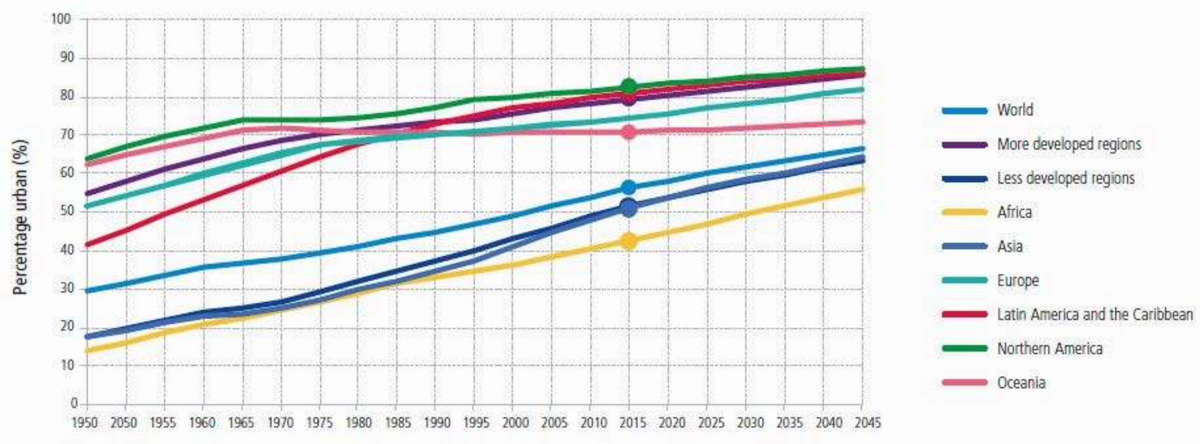

Figure 3 *Global trends in urbanization from 1950 to 2050 (% urban). Source: United Nations Human Settlements Programme, 2015.*

Undoubtedly, cities are hubs for ideas, commerce, culture, science, productivity, social development, and much more. At their best, cities have enabled people to advance socially and economically. However, key current and new urban challenges have emerged over the years. Several examples are presented in the Habitat Global Activities Report (2015).

As a first example, the UN-Habitat report highlights that meteorological-based phenomena (i.e., storms, sea-level rises, inland flooding, droughts, etc.), associated with climate change have produced heavy losses, particularly among slum dwellers and the poorest populations (predominantly in the coastal areas). As a result, the average number of people killed as a consequence of these phenomena rose from 53,678 to 106,597, and the reported economic damage rose from an annual average of USD 55 billion to USD 156 billion, in the periods between 1994 - 2003 and 2003 - 2012. Thus, it is crucial to recognize that cities must also be part of the solution to the problem of climate change.

A second challenge is associated with the differentials in access to opportunities, income, consumption, location, information, and technology, which are now the norm rather than the exception. The report notes that gender inequalities persist in many countries and contexts (lower rates of secondary education, less access to decent employment, lower political representation, etc.). In addition to this, youth inequalities manifest in discrimination in access to education, differentiated levels of employment and livelihood opportunities, lack of participation in decision-making, and prejudice against sexual preferences. Finally, the report concludes that income inequalities combined with other forms of inequalities in society reinforce the deprivation faced by many groups and individuals based on gender, age, ethnicity, location, disability, and other factors. Thus, inequalities generate an urban geography of concentrated disadvantage.

A last example detailed in the UN-Habitat report is the emergence of new forms of urban poverty, risk, and marginalization in high-income countries. An increasing number of urban residents in high-income countries experience, or are at risk of, poverty and/or social exclusion. In the European Union, 24% of the population falls in this category, with one out of ten people living in severe material deprivation, and 17% living on less than 60% of their country's average income. In many other cities, the persistence of intergenerational poverty and economic disadvantage is inextricably linked to location and place. However, in addition to these 'conventional' forms of poverty, new forms of social exclusion and marginalization are emerging, including 'infrastructure-poor', immigrant poverty, young people at risk, and vulnerable elderly, among others.

2.3. SUSTAINABLE CITIES AND SUSTAINABLE DEVELOPMENT IN CIVIL ENGINEERING

As defined in the report developed by BCNecologia (2010) regarding the city of Vitoria-Gazteiz (Spain), the city is an ecosystem, and contacts, regulation, exchange, and communication are the essence of its operation. In addition to this, the structure and the form of producing a city are considered to constitute the framework for the development of the interaction among citizens through their activities.

The BCNecologia report further points out that the city as a system increasingly requires the renewal of its functional structures, with the aim of building a city that is more sustainable and, at the same time, a model of knowledge. Thus, the objective lies in increasing the degree of organization of the territory as well as its potential for exchange of information, and decreasing the consumption of local resources - that is, of achieving the maximum efficiency of the urban system.

Against this background, the BCNecologia report presents a set of indicators with the aim to quantitatively and qualitatively assess the urbanization process of the studied city from an integral and systemic point of view with sustainability criteria. This indicator-based methodology deals with the large areas involved in the achievement of a sustainable city model from an ecosystem vision: occupation of the soil, public space and habitability, mobility and services, urban complexity, urban metabolism, green spaces, and urban biodiversity and social cohesion.

Figure 4 *Proposed conceptual framework to assess urbanization processes from a sustainable perspective. Source: Barcelona Urban Ecology Agency, 2010.*

Sustainable development could become a guiding concept for engineers in the 21st century. In the context of civil engineering, this means that building infrastructure and providing associated services should be delivered to satisfy a broad diversity of interests and responsibilities (Fenner, et al., 2006). Engineers must continue to fulfil obligations to clients, ensure business viability, and strive for excellence and robustness in the application of engineering principles. In addition, by adopting a sustainable development perspective, they must extend their role to ensure that the real needs of all present end users are met, as well as recognizing impacts (and the opportunity for mitigation and benefit) on both the natural environment and future generations (Fenner, et al., 2006).

The term “sustainable development” is intrinsically value-laden and open to wide interpretation, with much debate about its definition. There is a real debate about whether the complexity of current problems is so great that it makes relying solely on technical solutions alone unrealistic. Nevertheless, engineers in their professional roles will still rely on applying technical solutions to problems, such as energy provision and adaptation to climate change. To get to such solutions, (civil) engineering practice needs to learn to handle a range of often unfamiliar non-technical challenges. The difficulty lies in finding ways to meet these challenges through practical, everyday engineering operations. Ideally, the sustainable development concept can be used simply to help define a wider problem boundary than those limits traditionally adopted by engineers. This then leads to the creation of a wider design space in which more holistically-conceived solutions can be formulated for any given problem.

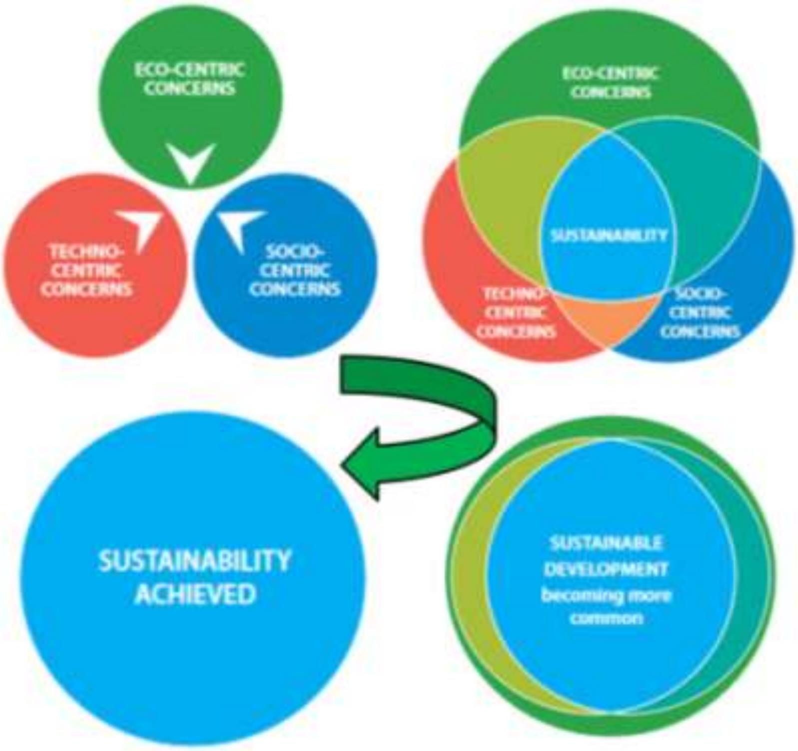

Figure 5 *Moving towards sustainable development. Source: The Royal Academy of Engineering, 2005.*

As accurately explained in Fenner et al. (2006):

> "This challenge may be highlighted by considering the three broad stages that a civil engineering project goes through: i) defining the problem, ii) choosing a solution, and iii) implementing it through design, construction and operation. Defining the problem requires recognition that most engineering services needed by society are framed by the whole socio - economic - environmental reality. At the other end of the process, design, construction and operation require the use the traditional deterministic mechanics and reductionist analytical techniques, which have been proved highly appropriate over the last three centuries for providing safe, working solutions, and rely completely on measurement. In between, choosing a solution requires making the transition between these two different sciences. To achieve this, more options need to be considered and evaluated, and more choice criteria developed, than are often adopted using the traditional approach. Furthermore, several of these criteria will not be conveniently measurable. Engineers will be forced to acknowledge that it is needed to apply values, as well as mathematics, to the trade-offs or compromises involved in the decision. These also need to be transparent and accountable to a wide constituency of interested parties.
>
> Sustainable development is often discussed in terms of balancing the triple bottom line constraints of economic, social and environmental factors (see *Figure 5*). For many, this

remains vague. In response, and as examples, the Government of United Kingdom amplified these three pillars to a set of five key principles: i) living within environmental limits, ii) ensuring a strong, healthy and just society, iii) achieving a sustainable economy, iv) promoting good governance, and v) using sound science responsibly. On the other hand, the Royal Academy of Engineering has recently published a set of twelve guiding principles[4]. The RAE principles offer high-level advice such as: “Practice what you preach”, “Plan and manage effectively” and “Do things right, having decided on the right thing to do”. A last example, introduced by Fenner et al. (2006), provides a visualization of a knowledge map developed by Jabareen (2004). This last author provided a comprehensive representation of sustainable development thinking, encompassed in eight domains: ethics, fairness, urban form, preservation of natural capital, integrative management, global discourse, utopian ambition and financial management[5].”

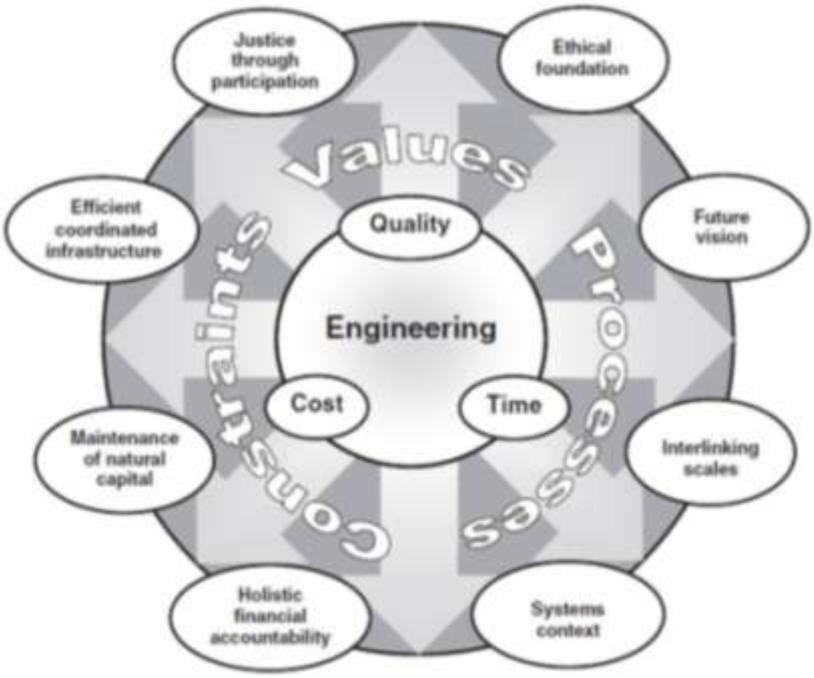

Figure 6 *A sustainable framework for civil engineers. Source: Fenner et al., 2006.*

[4] *More information available at http://www.raeng.org.uk/publications/other/engineering-for-sustainable-development*

[5] *A detailed explanation of each domain can be found on Fenner, R. A., Ainger, C. M., Cruickshank, H. J., and Guthrie, P. M. 2006. “Widening Engineering Horizons: Addressing the Complexity of Sustainable Development”. In Proceedings of the Institution of Civil Engineers - Engineering Sustainability 159, pp 145-154.*

2.4. INDICES AND INDICATORS AS TOOLS TO SUPPORT DECISION-MAKING

In general terms, an indicator is a quantitative or a qualitative measure derived from a series of observed facts that can reveal relative positions (e.g. of a country) in a given area. When evaluated at regular intervals, an indicator can point out the direction of change across different units and through time. In the context of policy analysis, indicators are useful for identifying trends and drawing attention to particular issues. They can also be helpful for setting policy priorities as well as for benchmarking or monitoring performance. On the other hand, a composite indicator is formed when individual indicators are compiled into a single index on the basis of an underlying model. The composite indicator should ideally measure multidimensional concepts that cannot be captured by a single indicator, e.g. competitiveness, industrialization, sustainability, single market integration, knowledge-based society, etc. (Nardo et al., 2005).

In terms of method and technique, index construction relies on a step-by-step procedure initially suggested by Nardo et al. (2005), which was subsequently applied to different conceptual frameworks[6] (e.g. water and sanitation sector). In this case study, the focus will be directed to some specific steps, but it should be highlighted that, ideally, the whole procedure must be considered for composite index construction. This complete procedure is detailed in Nardo et al. (2005); explanatory information regarding to each step is briefly given below.

Step 1. Data selection. Indicators should be selected on the basis of their analytical soundness, measurability, country coverage, relevance to the phenomenon being measured, and relationship to each other. Ideally, and as a previous step, a theoretical framework should be developed to provide the basis for the selection and combination of single indicators into a meaningful composite indicator under a fitness-for-purpose principle.

Step 2. Normalization. Indicators should be normalized to render them comparable. Attention needs to be paid to extreme values, which may influence subsequent steps in the process of building a composite indicator. Skewed data should also be identified and accounted for.

Normalization is required prior to any data aggregation, as the indicators in a data set often have different measurement units. As a normalization example, we present the so-called “re-scaling” or “min-max” process, in which indicators are normalized to have an identical range [0, 1] by subtracting the minimum value and dividing by the range of the indicator values. In this sense, attention should be paid to extreme values or “outliers”, as they could distort the transformed indicator. On the other hand, “min-max” normalization could widen the range of

[6] *Detailed examples for composite indicator construction are given in Flores-Baquero et al. (2016) and Giné-Garriga & Pérez-Foguet (2010; 2013).*

indicators lying within a small interval, increasing the effect on the composite indicator. Mathematically, it is represented by the following expressions:

$$I^t_{qc} = \frac{x^t_{qc} - \min_c (x^t_q)}{\max_c(x^t_q) - \min_c (x^t_q)} \qquad \text{(eq. 1)}$$

where I^t_{qc} is the normalized indicator value, x^t_{qc} the value of the sample indicator for a time t of analysis, $\max_c(x^t_q)$ the maximum value of the sample indicator for a time t of analysis, and $\min_c(x^t_q)$ the minimum value of the sample indicator for a time t of analysis.

The above formula addresses a "more is better" indicator. However, as the opposite might also be true, the indicator is a "less is better" type (e.g. less concentration of immigrants in a given area is better in terms of integrated society). In this sense, the first expression should take the following form:

$$I^t_{qc} = 1- \frac{x^t_{qc} - \min_c (x^t_q)}{\max_c(x^t_q) - \min_c (x^t_q)} \qquad \text{(eq. 2)}$$

Step 3. Weights and aggregation. Indicators should be aggregated and weighted according to the underlying theoretical framework. Additionally, correlation and compensability issues among indicators need to be considered and either corrected for, or treated as features of, the phenomenon that will be retained in the analysis.

For weighting methodologies, there are several numerical and participatory processes with the aim to assess the relative importance among the indicators and composite indicators on hand. In this sense, there is the possibility of either providing equal weights to the considered variables or of using any of the existing methods to define the different weights. In terms of use, equal weights are considered more transparent when dealing with composite indicators, and they facilitate interpretation of the results. On the other hand, different weights might be more adjusted to reality, but the results are more difficult to interpret accurately.

Two alternatives are presented for the aggregation methods, although more possibilities are available. These are the additive aggregation (arithmetic mean calculation) and geometric aggregation (geometric mean calculation).

The additive aggregation method has the advantage of compensating the final value of a composite indicator. However, this compensation comes with the loss of being able to clearly communicate the information. That is, a composite indicator might have a desirable value as a result of two indicators. This value could be the result of a very high value of one of the indicators and an undesirable value of the other. By using this aggregation method, this information could not be properly transmitted, and there could be comparative errors among the contexts that are assessed. The mathematical expression behind this method can be represented as follows:

$$\mathrm{CI} = \frac{1}{\mathrm{n}} \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{w_i} \, . \, \mathrm{X_i} \qquad \text{(eq. 3)}$$

where CI is the composite indicator value and w_i the weight assigned to the n indicators considered X_i.

The geometric aggregation method, on the other hand, implies penalizing the dispersion of the variables that are aggregated. In this sense, and in order to achieve high values of the composite indicator, it is necessary to have high values in all considered indicators. Contrary, one of the drawbacks is that if one of the indicators is zero, the geometric mean will be zero as well. Mathematically, this method is expressed as follows:

$$\mathrm{CI} = \prod_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{X_i}^{\mathrm{w_i}} \qquad \text{(eq. 4)}$$

As mentioned above, one of the advantages of the additive aggregation is that it allows the compensation between different indicators, particularly the compensation of a null value in any of the variables to be aggregated. In addition to this, it is conceptually simpler, both at the level of implementation and for the interpretation of the results obtained. However, this method hides the existence of very low values (compensation), which is not recommended in some cases.

Against this background, when dealing with composite indicator construction, the different aspects described above should been taken into consideration. It is not possible to point out a better methodology, as it depends of the potential use of the composite indicator, the public to whom the results will be transmitted, etc. In this sense, it is recommended whenever possible to apply a comparison exercise in order to assess the impacts of the selected option.

2.5. Case study of Barcelona

Barcelona is the capital and largest city of Catalonia, an autonomous community in Spain, and the country's second most populous municipality, with a population of 1.6 million within the city limits. Its urban area extends beyond the administrative city limits, with a population of around 4.7 million people, making it the sixth most populous urban area in the European Union. It is the largest metropolis on the Mediterranean Sea, located on the coast between the mouths of the rivers Llobregat and Besòs, and it is bounded to the west by the Serra de Collserola mountain range, the tallest peak of which is 512 meters high. Barcelona is divided into 10 districts. These are administrated by a councillor designated by the main city council, and each of them has some competences relating to issues such as urbanism or infrastructure in their area. The current division of the city into different districts was approved in 1984. In 2009, a new division of 73 neighbourhoods was implemented (the 10 districts are still in use), a division that was done to offer a better service from the City Council.

Figure 7 *Division of Barcelona city into its different districts. Source: Own elaboration, from w33.bcn.cat.*

Urban development in Barcelona in recent years, its commitment to design and innovation, and its linking of urbanism with ecological values and sustainability have made Barcelona one of the leading European cities in the urban area. This fact has been recognized with numerous awards and distinctions, such as the Prince of Wales Award for Urbanism at Harvard University in 1990 and the Royal Institute of British Architects Gold Medal in 1999. The work done and the awards received have led to talk of a "Barcelona Model" in urbanism, which has served as a guide for many cities that have undertaken similar paths.

Nevertheless, Barcelona is still struggling with aspects related to sustainability and the entry into a society of information and knowledge. The compact and diverse city model is the one that best positions itself in this process towards sustainability in the information age. This model permits an increase in the complexity of its internal parts, which is the basis for a cohesive social life and a competitive economic platform. At the same time, the objective is to save land, energy, and material resources, and to contribute to the preservation of agricultural and natural systems.

Figure 8 *Main mobility arteries in Barcelona, where Ronda de Dalt is located at the upper side. Source: http://www.ub.edu/biometa/lugarcelebracion.html.*

Nowadays, several projects are taking place in Barcelona to achieve a more sustainable and cohesive city. Specifically, this case study presents the project of the Ronda de Dalt, which is a mobility artery that crosses several districts of the city (see *Figure 8*). Different neighbourhoods of these districts are affected by the noise and pollution level generated by the Ronda de Dalt. The Plenary of the Municipal Council agreed that it was necessary to improve this situation, and to help humanize the urban surroundings of the Ronda de Dalt. Changing the perception that the mountain districts have of it, as well as improving the environmental and acoustic conditions of connecting the districts of Gràcia, Horta-Guinardó, and Nou Barris with the rest of the city, are primary goals. The main idea is to cover some sections of the Ronda de Dalt, with the aim of recovering and creating new spaces to increase urban greenery and public facilities, as well as to boost civic, neighbourhood, and commercial activities and to mobilize resources and investments in the area.

3. CLASS ACTIVITY

The proposed class activity aims to encourage a discussion beyond those technical and economic aspects that are usually considered during the design of a project. These further aspects are not intended to replace the traditional cost/time/quality approach, which must be still regarded as essential ingredients in successful projects. However, the traditional engineering requirements have evolved to encompass a broader range of considerations.

These are necessary to enable civil engineering to contribute effectively to sustainable development.

This class activity is divided in two sections or blocks, with a total duration of two hours. For the methodology, we propose working in small groups (i.e. 3 to 4 people); further details are given in each block of the activity.

Class activity: Block I

In the first part of the class activity, programmed for one hour of work, students should read the paper titled “Widening engineering horizons: addressing the complexity of sustainable development” (Fenner et al., 2006).

In small groups, students should first read the eight dimensions detailed within the academic article and then select and justify which one of those dimensions appears more relevant to them. For this, 20 minutes will be given for the lecture and 10 to 15 minutes, to discuss and select the most relevant dimension from their point of view.

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Finally, the student should share the group points of view in a general debate that should be expected to last between 25 and 30 minutes.

Class activity: Block II

This second part is expected to take another hour of work. We suggest that the same working groups are maintained. As in Block I, the idea is to encourage discussion, first in each group and then with all participants for closing the activity, with 30 minutes allotted for each discussion.

During the proposed activity, *Table 1* should be filled out. In this table, several indicators are identified, with a short definition of each one. The proposed indicators have been extracted from those detailed in the report developed by BCNecologia (2010). We do not recommend providing the reference source to the students; rather, the teacher should highlight that these indicators might be used in decision making, both for designing a project and for prioritizing where to execute it, such as for the example of Barcelona (i.e. which section of the Ronda de Dalt to cover first). The objective of this exercise is to detail the direct and indirect impacts related to a high value of the proposed indicators. A low value would have the opposite impacts, so it is avoided as not to be redundant.

Table 1 *Proposed indicators on which the discussion regarding potential direct and indirect impacts should be based.*

Indicator	Definition	Direct impacts	Indirect impacts
Population density	Existing population per hectare of land		
Aging index	Quantitative relationship between older and younger people in a given territory		
Foreign population	Spatial distribution of the immigrant population, taking into account their number and that of the total population		
Higher education	People with higher studies, taking into account their number and that of the total population		
Protected housing	Access to housing for those people with less acquisitive level		
Public transport	Access to an affordable and effective public transport network		
Green spaces	Proximity to green areas in a given part of a city		

3.1. Solution and evaluation criteria

Class activity solution: Block I

There is no a specific solution for this activity, as it is an open-answer one. The main idea is to give the students the chance to select the dimension they consider more relevant and then, more importantly, to share and defend their arguments.

As a support for the professor, who should be the moderator for this activity, we are providing extra guidance (extracted from Fenner et al.; 2006):

- An ethical foundation and justice through participation lead to **new values** to apply when making engineering decisions;

- A future vision, interlinking scales, and system context provide the basis for **new processes** that can be used to better define problems and to offer guidance in choosing appropriate strategies for development;

- Holistic financial accountability, maintenance of natural capital, and efficient provision of coordinated infrastructure provide **new constraints** in formulating solutions.

In the case all groups have selected same dimension, the discussion might be directed to expose the reasons for not choosing any other dimensions as the most relevant ones.

Class activity solution: Block II

To evaluate the second part of the activity, we have provided several impacts when the indicator at hand acquires a high value (*Table 2*). Note, however, that these solutions are only provided to offer guidance for supporting the general discussion.

Table 2 *Examples of potential direct and indirect impacts regarding the proposed indicators.*

INDICATOR	DIRECT IMPACTS	INDIRECT IMPACTS
Population density	- Congestion in terms of public space and services - Compactness of the city	- In some way, it represents a cost in terms of time when accessing several services. Less space is associated with each individual, which might cause health problems - Less consumption of resources (i.e. transport to provide food). In disperse areas, it would be less efficient
Aging index	- Less cohesion of diverse age groups through the contact in the same physical space - Changes in social demands (more health and social assistance)	- Loss of intergenerational experience transfers - Potential losses in several socio-economic activities
Foreign population	- Less cohesion of groups from different countries through the contact in the same physical space	- Prevalence of existing stereotypes
Higher education	- Less cohesion of the groups of diverse incomes through the contact in the same physical space. Less diverse groups of population	- Potential generation of new stereotypes associated to income aspects
Protected housing	- Mitigation of the spatial segregation within the city	- Increased social cohesion
Public transport	- Facility to improve collective mobility - Less atmospheric and acoustic pollution	- Expenditure on transport is possibly lower than that for supporting use of cars - Positive effects on health
Green spaces	- Increased recreation activities - Less atmospheric pollution - Maintenance of urban ecosystems and biodiversity	- Increased social cohesion - Positive effects on health - Satisfaction of human's "need of nature"

Evaluation criteria

In order to provide the students with an objective and transparent evaluation system, we suggest using the provided rubric (see *Annex IX*), which details: i) the knowledge that students are expected to acquire, and ii) the criteria that will be used to evaluate the content of the resolution associated with the proposed activities.

Before carrying out these activities, the rubric must be shared among the students with the aim to inform which contents will be evaluated. Thus, some guidance is given to students to allow them to carry out the proposed activities.

Specifically, to evaluate both Blocks I and II, each group must submit a written document answering the questions raised. These answers will be evaluated based on the proposed rubric. However, the teacher is free to choose an alternative evaluation method if she/he considers it more appropriate.

4. Homework activity

This activity is organized into two different complementary parts. The first one deals with the construction of a composite indicator as a tool to support decision-making. The second falls on proposing a technical design by using pre-stressed concrete solutions. In both cases, the requested activities will be applied to the context of Barcelona, which was introduced previously.

The entire activity will be developed in small groups (i.e. 3 to 4 people). We recommend using the same groups created in classroom activity, in order to facilitate evaluation. While the first part requires about 2 - 4 hours of work, the second part might be developed over an academic semester. In this sense, and with the constant support of the professor, this last part might be associated with the Project-Based Learning (PBL) methodology. PBL is a teaching method in which students gain knowledge and skills by working for an extended period of time, during which they are invited to investigate and respond to an authentic, engaging, and complex question, problem, or challenge. Therefore, students will develop the generic competence of teamwork and, in addition, they will experience a short of professional environment.

Specifically, in terms of methodology, the achievement of this activity is organized through several workshops, which are parallel to the progression of course contents (for an applied example, see *Annex X*). In these workshops, the professor should give a guided presentation at the beginning of the session, and the students should work within their teams to develop the project. Some specific objectives are advised at the beginning of each session. Thus, students are expected to progress in their projects by setting their own learning pace. Briefly, and after receiving the topographic drawing, students should establish a list of contour conditions. Considering the different contour conditions, students should define the plan view and elevation of the pedestrian covering. In addition, students should predefine the dimensions of the structural elements (deck, piles, and abutments). Afterwards, students should develop a structural model in order to obtain the envelopes of axial forces, shear forces, and bending moments for the ultimate limit state (ULS) and serviceability limit state (SLS) combinations. Then, team groups should calculate the internal steel reinforcement and the pre-stressed reinforcement required to achieve the different ULS and SLS. Finally, a bill of materials required for constructing the pedestrian covering should be included in the report, considering the following items: concrete, formwork, pre-stressing reinforcement, and internal steel reinforcement. On the final day of class, the students might present a short summary of the rationale of action area selection and the structural solution, showing the plan view, the elevation, and the transverse section together with the total bill of quantities of the structure.

Homework activity: Part I

In this first part, students are required to design a composite indicator as a decision tool to prioritize which section of the Ronda de Dalt should be covered first. In addition, students are required to reflect on and then link their solutions from the perspective of the deontological code of engineers (code of ethics) provided in *Annex XI*.

Table 3 *Division of selected districts and neighbourhoods into different groups.*

Group	District	Affected neighbourhoods
I	Horta - Guinardó	La Vall d'Hebron Horta
II	Nou Barris	La Guineueta Canyelles
III	Nou Barris	Les Roquetes Verdun
IV	Nou Barris	La Prosperitat La Trinitat Nova

As pointed out by the Plenary of the Municipal Council, the districts that have a greater need for urgent intervention are Horta-Guinardó and Nou Barris[7]. Considering the location of the Ronda de Dalt and the neighbourhoods of these districts, it is possible to define four separate groups (*Table 3*). The potential intervention will join the neighbourhoods of these groups.

To design the composite indicator, the different steps introduced in section 2.4 should be followed. At least one set of indicators should be used, as well as a weighting methodology and an aggregation method. Regarding this last point, a hierarchical composite indicator could be developed by using several partial indices. Indicators and data are available in

[7] *Related news on this regard can be found at: http://mobilitat.ajuntament.barcelona.cat/es/noticia/impulso-a-la-cobertura-de-la-ronda-de-dalt; http://mobilitat.ajuntament.barcelona.cat/es/noticia/la-cobertura-de-la-ronda-de-dalt-cada-dza-mzas-cerca*

Annexes from *I to VIII*. Additional data might be used from the Barcelona Council website (*http://www.bcn.cat/estadistica/angles/dades/barris/index.htm*).

Finally, students should provide a discussion about the designed composite indicator, including the reasons for selecting the indicators and methods employed.

Homework activity: Part II

Once the location of the area of the Ronda de Dalt to be covered is selected, according to the composite indicator developed, the constructive solution of the project must be developed. In this sense, several aspects should be taken into consideration.

The City Council provides the topography of the area at a scale of 1:1000 (see *Annex XII*), and sets as a condition that the structure should be independent of the existing one. The minimum gauge of Ronda de Dalt and the ramps will be 5.0 m. A specific study considering the slope of the ramps and the gauge will allow the area that will be covered in the project to be defined.

Since the activity is designed for a pre-stressed concrete course, the slab will be designed in a pre-stressed concrete solution (in situ or precast). The cross-section can be a solid slab, a lightened slab, or a box girder, depending on the designer’s decision. The slab depth can be constant or variable.

The covered area will be dedicated to public space and a possible landscaped area, which will require an earth filling of approximately 1.50 m thickness.

The slab will follow a two-cantilever scheme, being supported in a wall along the central median strip of the Ronda de Dalt.

Loads should be considered according to the Spanish Code of Actions in road bridges (IAP-11). This document can be downloaded from the Ministerio de Fomento[8] (Spanish Ministry of Development). In a simplified manner, the live load can be assumed with a uniform value of 15 kN/m^2. The horizontal, wind, and thermal loads will be neglected in this activity.

In case a post-tensioned solution is adopted, the system employed will be according an existing commercial catalogue (i.e. Mk4, Diwidag, Stronghold, VSL, etc.), active anchorages will be placed in one or both ends, and their dimensions will set be according to the catalogue. The mechanical anchorage will have a 5 mm wedge penetration, μ = 0.21, k/μ = 0.008m^{-1}.

[8] *https://www.fomento.gob.es/NR/rdonlyres/2E268DB6-87AC-41C9-A331-32C63C25195C/111523/0820303.pdf*

The quality control will be intense.

All calculations of the homework will be according to the Spanish Concrete Code (EHE-08[9] or Eurocode-2). Assumptions should be explained throughout the solution.

Points that are required to be included:

A) Pre-design of the pre-stressed slab

- Define the geometry of the solution through a plan and elevation drawing, placing intermediate supports using the topography and Autocad software (*Annex XII*). The presentation format should be clear enough to submit to the City Council;
- Pre-design of the cross section of the cover slab, including a sketch of it;
- Obtain the envelope of axial, shear forces, and bending moments of the ultimate limit state (ULS) and serviceability limit states (SLS) combinations;
- Obtain the mechanical properties of the slab cross-section.

B) Design of the pre-stressed slab

- Pre-design the pre-stressing force and the eccentricity required in the support section to satisfy the cracking limit state;
- Obtain the pre-stressing force at the mechanical anchorage, the pre-stressing area, the number of tendons, and the diameter of the duct. For the support section (end of cantilever), draw the Magnel diagram and propose a solution for this section in terms of "P" and "e". Based on the results obtained up to this point, reflect and discuss about the suitability of this section for resisting external loads. Draw the layout of the active reinforcement in several sections as well as the layout of the equivalent tendon, verifying that it is within the approximate central kern;
- Obtain the short- and long-term stresses for at least 20 sections of the deck, and verify cracking SLS. It is recommended to calculate the stress state in all sections equidistant from each other 0.50 m;

[9] *https://www.fomento.gob.es/MFOM/LANG_CASTELLANO/ORGANOS_COLEGIADOS/MASORGANOS/CPH/instrucciones/EHE_es*

- Estimate the cable elongation, as well as the vertical displacement due to the pre-stressing force at the free end of the cantilever. Estimate the long-term vertical displacement as well;

- Check the flexural ULS in the worst section, arranging the necessary longitudinal passive reinforcements;

- Check the ULS of shear, calculating the necessary transverse reinforcements;

- Select the appropriate anchorage devices, checking the stresses in the concrete under them and define the required passive reinforcement;

- Present drawings of the overall solution geometry and drawings of the passive and active reinforcements.

C) Obtain the bill of quantities for the design project

4.1. Solution and evaluation criteria

Homework activity solution: Part I

First, indicators used for the composite indicator construction are presented (see *Table 4*). Additionally, indicator definitions and the composite indicator structure are detailed as well. The rationale of the general index, named “Priority Index”, is to assess those socio-economic aspects of the neighbourhoods at hand. Access to public services is evaluated as well. As covering the Ronda de Dalt is designed to provide a green connection between the neighbourhoods, environmental aspects should not be considered, in order to simplify the composite indicator. Nevertheless, the proposal might be amplified with those indicators and aspects that the students consider relevant.

As the selected indicators are measured in different units, a normalization process is carried out in order to be able to work with them all together. The indicators of population density and population income index have been chosen to illustrate the methodology employed. Thus, neighbourhoods with a higher density and low income (population income index; “RFD” for Spanish “Renta Familiar Disponible”) will have lower values (see *equations 1* and *2*). The normalization of these indicators is calculated for the La Guineueta neighbourhood, and the results for the remaining ones are presented in *Table 5*.

$$\text{Density}_{norm} = 1 - \frac{x_{qc}^{t} - \min_c(x_q^t)}{\max(x_q^t) - \min_c(x_q^t)} = \frac{674-622}{957-622} = 0.54$$

$$\text{RFD}_{norm} = \frac{x_{qc}^{t} - \min_c(x_q^t)}{\max(x_q^t) - \min_c(x_q^t)} = \frac{55.9-47.8}{92.6-47.8} = 0.36$$

Table 4 *Structure of the "Priority Index" in indicators and partial and general indices.*

General Index	Partial indices	Indicators	Definition
PRIORITY INDEX	Social aspects	S.1. Density	inhabitants / residential area
		S.2. Percentage of immigrants	Foreign population / total population
		S.3. Aging index	(People aged 65 / people aged 15)*100
		S.4. Percentage of people with disabilities	People with disabilities / total population
	Economic aspects	E.1. Population income index (RFD)	Average level of family income available per capita of the inhabitants of the neighbourhood in relation to the average of Barcelona (Index 100)
		E.2. Registered unemployment	Percentage of unemployed / population between 16 and 65 (inter-annual variation)
		E.3. Higher education	Population with higher education / population over 16
	Public and cultural equipment	P.1. Public libraries	Absolute value
		P.2. Usage of public equipment area	(Area of public equipment usage / total area)*100

Table 5 *Results associated to the normalization process for density and RFD indicators.*

Neighbourhood	Density	Density $_{norm.}$	RFD	RFD $_{norm.}$
La Vall d'Hebron	732	0.42	92.6	1.00
Horta	419	1.00	80.9	0.80
La Guineueta	674	0.53	55.9	0.36
Canyelles	622	0.62	55.6	0.35
Les Roquetes	846	0.21	47.8	0.21
Verdun	859	0.18	55.4	0.35
La Prosperitat	957	0.00	54.0	0.32
La Trinitat Nova	577	0.71	35.6	0.00

The results related to all normalized indicators are presented below:

Table 6 *Results associated with the normalization process for all indicators.*

Neighbourhood	S.1	S.2	S.3	S.4	E.1	E.2	E.3	P.1	P.2
La Vall d'Hebron	0.42	0.73	0.25	1.00	1.00	0.00	1.00	0.00	1.00
Horta	1.00	0.60	0.24	0.83	0.80	1.00	0.74	1.00	0.18
La Guineueta	0.53	0.80	0.00	0.18	0.36	0.68	0.57	1.00	0.39
Canyelles	0.62	1.00	0.07	0.00	0.35	0.68	0.22	1.00	0.48
Les Roquetes	0.21	0.00	1.00	0.47	0.21	0.68	0.06	0.00	0.18
Verdun	0.18	0.07	0.51	0.46	0.35	0.68	0.20	1.00	0.00
La Prosperitat	0.00	0.40	0.25	0.69	0.32	0.83	0.27	0.00	0.17
La Trinitat Nova	0.64	0.07	0.95	0.16	0.00	0.77	0.00	0.00	0.29

At this point, it is noteworthy to mention that an alternative method is to take into account the tendency of the indicators, instead of a fixed image of 2016 (as for the example). Considering time aspects might provide a different analysis and, in consequence, lead to making different decisions. This has been done for the indicator related to the registered unemployment.

Table 7 *Structure of the "Priority Index": i) indicators and partial and general indices; ii) weight assignment; and iii) aggregation methodology.*

General Index		Partial indices		Indicators
PRIORITY INDEX	Equal weights & Geometric aggregation	Social aspects	Equal weights & Additive aggregation	S.1. Density
				S.2. Percentage of immigrants
				S.3. Aging index
				S.4. Percentage of people with disabilities
		Economic aspects	Equal weights & Additive aggregation	E.1. Population income index (RFD)
				E.2. Registered unemployment
				E.3. Higher education
		Public and cultural equipment	Equal weights & Additive aggregation	P.1. Public libraries
				P.2. Usage of public equipment area

The next step for composite indicator construction is to assign weights and to select the aggregation methodology. For the first aspect, equal weights are chosen in this example for both indicators and partial indices aggregation. However, it is possible to use different weights depending on the priorities of the designer. In relation to the second aspect, first, and additive aggregation is selected to partial indices construction. The main reason falls on the existence of zero values as a result of the normalized process. In this way, compensation among indicators is allowed. Finally, a geometric aggregation is employed for general index construction. As a first compensation has already been carried out, the main idea is to penalize those partial indices that are already low. A representation of all these considerations is shown in *Table 7*.

Finally, results regarding partial and general indices are presented in *Table 8*. As it can be seen, the neighbourhood of Les Roquetes would be the candidate where to execute the covering of the section of the Ronda de Dalt, according to the composite indicator developed (PI = 0.23). However, the execution of the project aims to join two neighbourhoods. Based on this, and taking into account the values of the grouped neighbourhoods (see *Table 3*), the decision would fall on La Prosperitat and La Trinitat Nova (PI = 0.24 and PI = 0.26, respectively).

Table 8 *Results regarding partial and general indexes. Lower values indicate a higher priority as reflected in the ranking (whereby 1 indicates the highest priority, and 8, the lowest one).*

Neighbourhood	Social aspects	Economic aspects	Public and cultural equipment	PRIORITY INDEX (PI)	Ranking
La Vall d'Hebron	0.60	0.67	0.50	0.59	7
Horta	0.67	0.85	0.59	0.69	8
La Guineueta	0.38	0.53	0.69	0.52	6
Canyelles	0.42	0.42	0.74	0.51	5
Les Roquetes	0.42	0.32	0.09	0.23	1
Verdun	0.31	0.41	0.50	0.40	4
La Prosperitat	0.34	0.48	0.09	0.24	2
La Trinitat Nova	0.47	0.26	0.15	0.26	3

The link with the deontological code of engineering (*Annex IX*) will depend on the selected indicators. In this case, for example, designing and using the proposed index would respect the first two principles of the ethics code:

- Enhancement of human welfare and the environment;
- Honesty and impartiality, serving with fidelity the public.

In addition, some of the fundamental canons are followed as well:

- Comply with the principles of sustainable development;
- Perform services only in areas of their competence;
- Issue public statements only in an objective and truthful manner;
- Avoid conflicts of interest.

Homework activity solution: Part II

Once the neighbourhoods have been selected, the next decision is which area should be covered. In this case, the section between Via Julia and Carrer de Fenals has been chosen. It should be noted that, due to the existence of two ramps (Exit 2 of Ronda de Dalt), it will not be possible to cover the whole section mentioned above. A specific study will be performed by analyzing the elevation.

In the following pages, a step-by-step solution is provided with respect to the most relevant aspects and calculations. In *Annex XIII*, a detailed consultation of all calculations can be done. The students are expected to provide a similar solution for activity evaluation.

A) Pre-design of the pre-stressed slab

- Geometry of the solution.

Figures 9 and *10* show a scheme of the drawings included in *Annex XIV*.

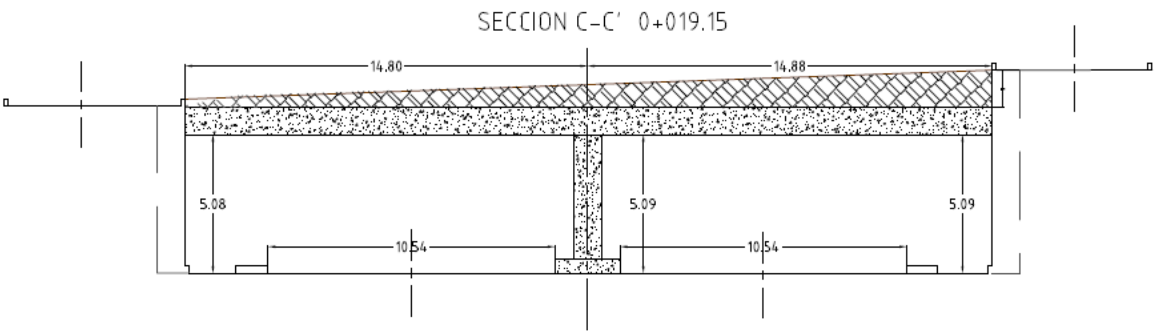


Figure 9 *Transversal section.*

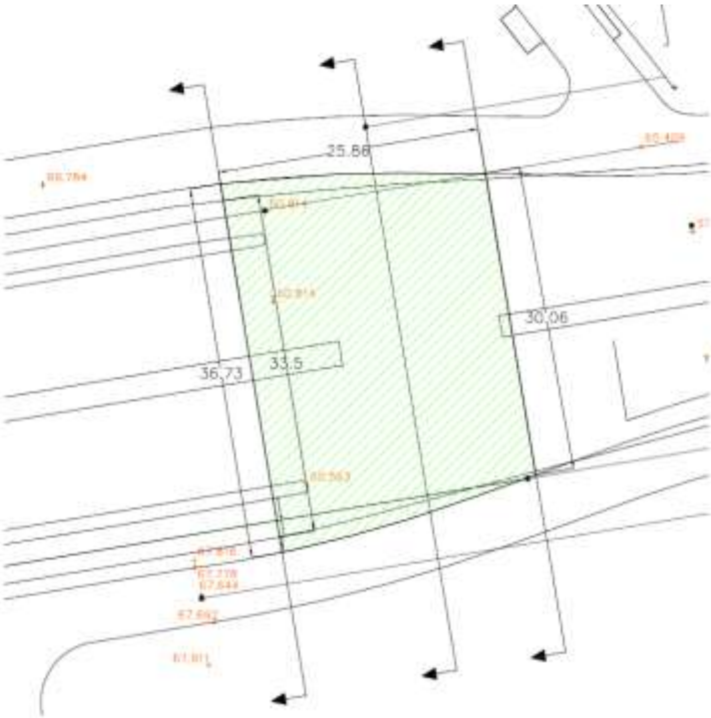


Figure 10 *Plan view of the area to cover.*

- Pre-design of the cross section of the cover slab, including a sketch of it.

The pre-stressed post-tensioned slab will have a cantilever scheme with a span of 14.85 m. The slab will be 1.2 m thick and will be lightened with EPS blocks with a cross section of 0.80 × 0.80 m and a spacing of 1.3 m between axes. This is not the only possible solution, and students could select another one.

- Envelope of axial, shear forces, and bending moments of ULS and SLS combinations

The loads considered in the calculations according to the guidelines of IAP-11 are:

Concrete self-weight: γ_c=25 kN/m^3

Soil fill weight (dead load): γ_{soil}=20 kN/m^3, 1.5 m thickness

Live load: Q_{k1}-IAP11=5 kN/m^2

Combination of actions:

Ultimate limit states

Permanent or temporary situations:

$$\sum_{j>1}^{n} \gamma_{G,j} G_{k,j} + \gamma_P P_k + \gamma_{Q,1} Q_{k1}$$

<u>Serviceability limit states</u>

Only persistent design situations are considered for these limit states.

Unlikely or characteristic combination:

$$\sum_{j>1}^{n} \gamma_{G,j} G_{k,j} + \gamma_P P_k + \gamma_{Q,1} Q_{k,1}$$

Frequent combination:

$$\sum_{j>1}^{n} \gamma_{G,j} G_{k,j} + \gamma_P P_k + \psi_{1,1} \gamma_{Q,1} Q_{k,1}$$

Quasi-permanent combination:

$$\sum_{j>1}^{n} \gamma_{G,j} G_{k,j} + \gamma_P P_k + \sum_{i>1}^{n} \psi_{2,i} \gamma_{Q,i} Q_{k,i}$$

The representative values of the actions have been calculated according to IAP-11.

Table 9 shows the total load of each combination and the maximum bending moments in the most unfavourable section of the slab (e.g., at the connection with the support).

Table 9 *Load values and bending moments at the support connection section.*

LOAD VALUES AND BENDING MOMENTS			
Ultimate limit state (ULS)			
q_{ELU} (kN/m)	98.5	M_{ELU} (kN.m)	10,855.22
Serviceability limit states (SLS)			
q_{PP} (kN/m)	23.0	M_{PP} (kN.m)	-2,536.01
q_{p-p} (kN/m)	68.5	M_{p-p} (kN.m)	-7,552.90
q_{FREC} (kN/m)	54.6	M_{FREC} (kN.m)	-7,122.88
q_{cp} (kN/m)	62.0	M_{cp} (kN.m)	-6,836.20

- Mechanical properties of the slab cross-section.

A_c = 0.92 m^2, I_c = 0.153 m^4, v = 0.6m, v'= - 0.6 m

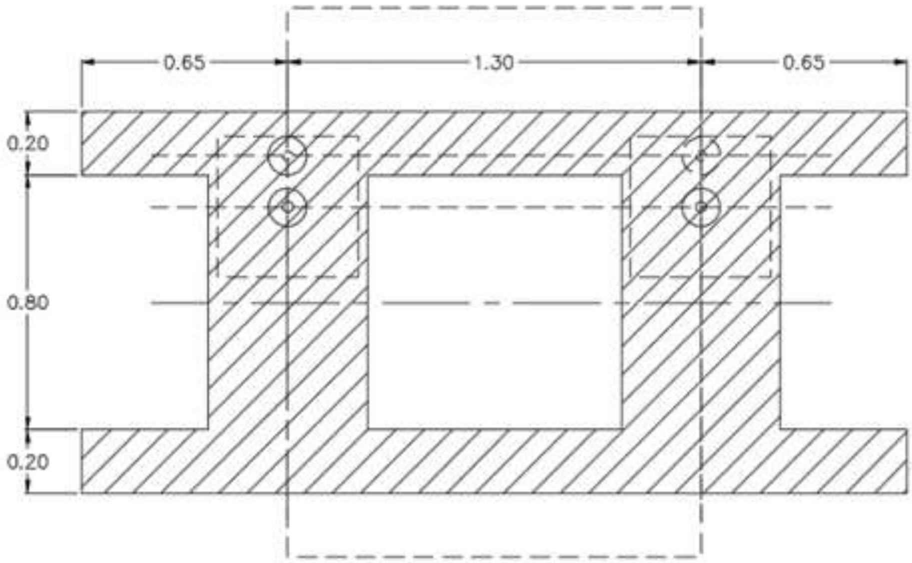


Figure 11 *Slab section.*

Materials

Concrete: HP-50/B/20/IIa

Active reinforcement: Y1860/S7 f_{puk} =1,860 N/mm^2 f_{pyk} = 1,770 N/mm^2; ρ∞ = 7 %; E_p = 190 GPa, μ = 0.21, k/μ = 0.008m^{-1}, anchorage system: a = 5 mm

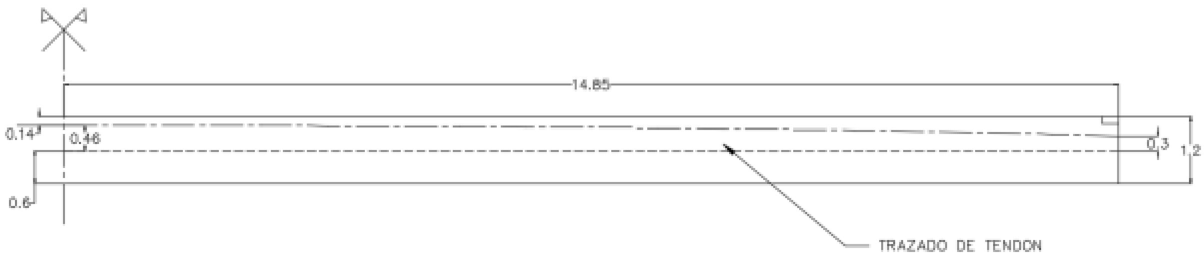
Passive reinforcement: B500 SD, f_{yk} = 500 N/mm^2; E_s=200GPa

B) Design of the pre-stressed slab

- Pre-stressing force and the eccentricity required;

- Pre-stressing force at the mechanical anchorage, pre-stressing area, number of tendons, and diameter of the duct. Magnel diagram and solution in terms of “P” and “e”. Reflection and discussion. Layout of the active reinforcement in several sections and layout of the equivalent tendon;

- Short- and long-term stresses in 20 sections of the deck.



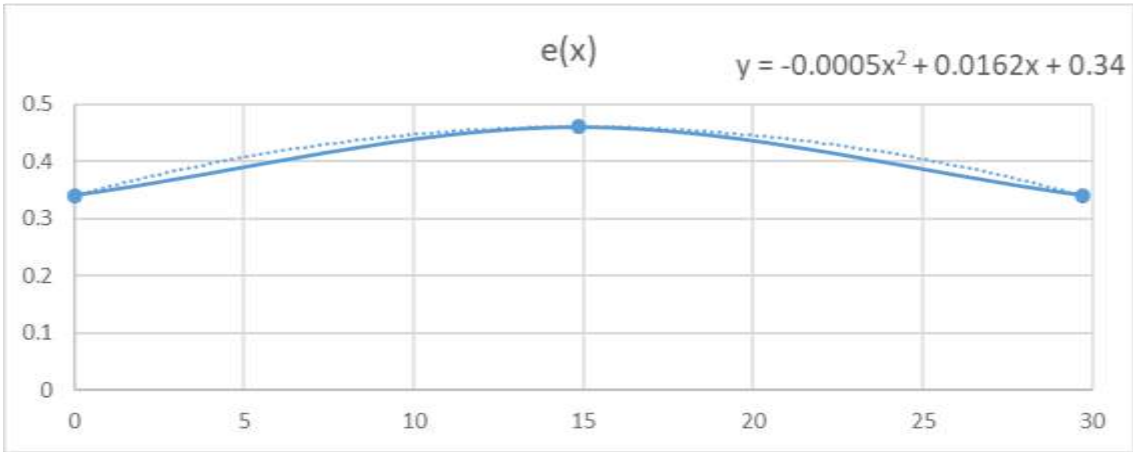


Figure 12 *Layout of the pre-stressing reinforcement.*

Figure 12 shows the layout of the pre-stressing reinforcement, which was defined through an iterative procedure by trying to satisfy the conditions of the central kern along the whole length of the cantilever. The maximum eccentricity according to the durability specifications was adopted in the support section.

The pre-stressing force at the anchorage P_o should be lower than or equal to $A_p\sigma_{po}=A_p\cdot\min\{0.75f_{p,max};\ 0.85f_{pk}\}$.

According to the exposure class IIa of EHE-08 (XC2 according to Eurocode-2, UNE-EN_1992 § 4.2), the maximum crack width should be limited to 0.2 mm for the frequent combination, and the active reinforcement should be located in the compressed area of the section under the combination of quasi-permanent loads. The first condition will be accomplished directly if the tensile stresses in the concrete are limited to the concrete tensile strength, f_{ctm}.

To avoid the occurrence of compression cracks, for all persistent situations with the least favourable combination of actions, the compressive stresses in the concrete should satisfy $\sigma_c \leq 0.60 f_{ck}(t)$, where $f_{ck}(t)$ is the design characteristic strength at t days.

The least favourable section is the support section at the cantilever. Therefore, the pre-stressing force is design accomplishing cracking SLS at this section; in other words, Magnel conditions should be satisfied during transfer and in service in a long-term situation.

Table 10 *Material properties to be considered when designing the pre-stressing force*

MATERIAL PROPERTIES			
CONCRETE		ACTIVE REINFORCEMENT	
f_{ck} (MPa)	50	f_{yp}	1,770
f_{cm}, 28 (MPa)	58	f_{up}	1,860
f_{ck}, 7 (MPa)	35.2	E_p	190,000
σ_{max}, c (MPa)	30	ε_{pyd}	8.10E-03
f_{ctm}, IIa (MPa)	(f_{rec}: f_{ctm}, 7 - p-p:0)	ε_{pu}	8.90E-03
f_{ctm}, 7 (MPa)	2.9	γ_{p_fav}	0.9
f_{ctm}, 28(MPa)	4.1	γ_{p_des}	1.1
E_c, 7 (MPa)	27,808	n_p, 7300	5.57
E_c, 28 (MPa)	30,887	F_{pmax}, A_p (kN)	
E_c, 7300 (MPa)	34,084	EC-2	EHE-08
n_s, 28	6.47	12,499.20	12,499.20
n_p, 28	6.15		

$$(1)\rightarrow \text{ Transfer:}(f_{upper}) \rightarrow \frac{M_{pp}v}{Ic}+\frac{\gamma_p P_{ki} e_p^{'} v}{Ic}+\frac{\gamma_p P_{ki}}{Ac} \leq \sigma_{max,c(7)} = 21.12 \text{ MPa}$$

for $e_p^{'} = 460$ mm $\rightarrow$ $P_{ki}<9{,}770$ kN

$$(2)\rightarrow \text{ Transfer:}(f_{lower}) \rightarrow \frac{M_{pp}v'}{Ic}+\frac{\gamma_p P_{ki} e_p^{'} v'}{Ic}+\frac{\gamma_p P_{ki}}{Ac} \geq -f_{ctm,7} = -2.9 \text{ MPa}$$

for $e_p^{'} = 460$ mm $\rightarrow$ $P_{ki}<16{,}299$ kN

$$(3)\rightarrow \text{ Service:}(f_{upper}) \rightarrow \frac{M_{frec}v}{Ic}+\frac{\gamma_p P_{\infty} e_p^{'} v}{Ic}+\frac{\gamma_p P_{\infty}}{Ac} \geq -f_{ctm,28} = -4.1 \text{ MPa}$$

for $e_p^{'} = 460$ mm $\rightarrow$ $P_{\infty}>9{,}158$ kN

$$(4)\rightarrow\ \text{Service:}(f_{lower})\rightarrow\ \frac{M_{p\text{-}p}v'}{Ic}+\frac{\gamma_p P_\infty e_p' v'}{Ic}+\frac{\gamma_p P_\infty}{Ac}\leq\sigma_{max,c(28)}=30\ \text{MPa}$$

for $e_p' = 460$ mm $\rightarrow$ P_∞>-611 kN

$$(5)\rightarrow\ \text{Service:}\left(f_{\text{pre-stressed tendon}}\right)\rightarrow\ \frac{M_{cp}e_p'}{Ic}+\frac{\gamma_p P_\infty e_p' e_p'}{Ic}+\frac{\gamma_p P_\infty}{Ac}\geq 0$$

for $e_p' = 460$ mm $\rightarrow$ P_∞>9,244 kN

$P_{min,max}$ = {9,244 kN, 9,770 kN}

Assuming 25% of pre-stressing losses, P_0=12,295 kN, and dividing this value by the maximum stress value, the required pre-stressing area is 8,813 mm^2. Two tendons of 33 strands of 0.6” were chosen, the total pre-stressing area is equal to 9,240 mm^2, and a duct of 120 mm diameter has been assumed. Therefore, the maximum eccentricity allowed due to concrete cover requirements is equal to 0.46 m.

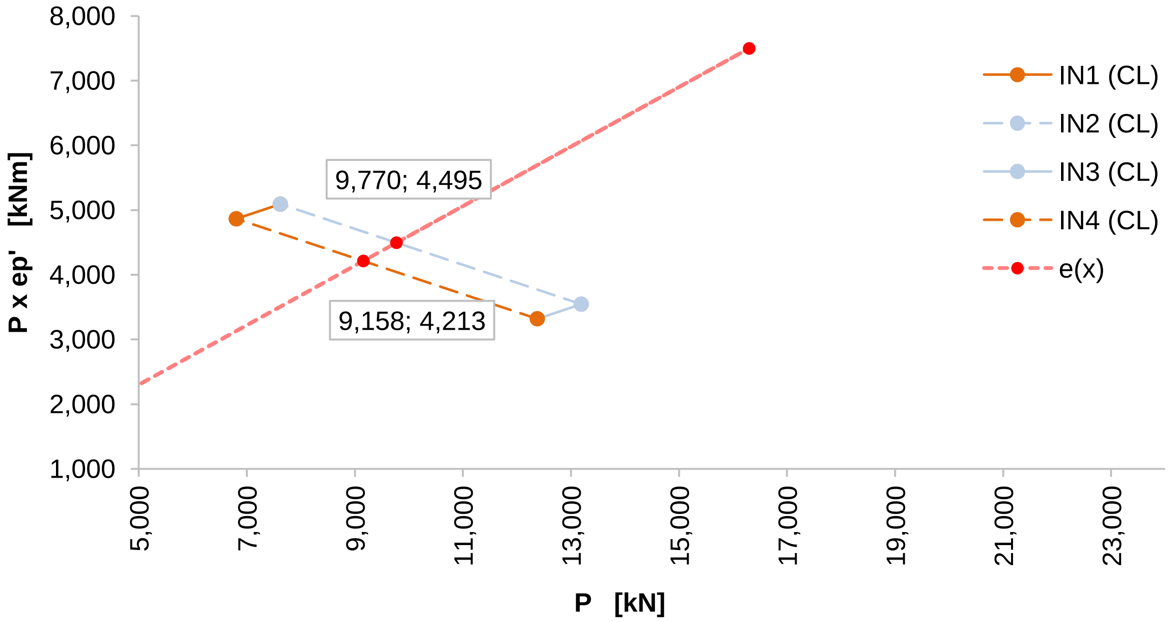


Figure 13 *Magnel inequalities.*

After defining the pre-stressing layout, the pre-stressing losses are calculated and then the concrete pre-stressed kern is calculated along the entire cantilever length. If the pre-stressing layout is inside the kern, and the active reinforcement is always pre-stressed for the quasi-permanent combination, the pre-stressing reinforcement design has been successfully accomplished. An iterative procedure should be applied in order to accomplish all the Magnel inequalities.

Pre-stressing losses

1) Instantaneous pre-stressing losses

a. Loss of force due to friction

$$\Delta P_1(x) = P_0(1\text{-}e^{-(\mu\alpha(x)+kx)})$$

$\mu \rightarrow 0.021$

$\alpha(x) \rightarrow e'^{(x)} - e'^{(x=0)}$

$\frac{K}{u} \rightarrow 0.008\ m^{-1}$

$x \rightarrow$ Distance (m) between the studied section and the active anchorage

b. Loss due to wedge penetration

$$\Delta P_2(x) = \Delta P_{2,(x=0)} \frac{l_a\text{-}x}{l_a}$$

$$\Delta P_{2,(x=0)} = 2P_O\left(1\text{-}e^{-(\mu\alpha(l_a)+kl_a)}\right) = 1{,}052.13\ kN$$

$$l_a = \frac{aE_pA_p}{\Delta P_1(l_a)} = \frac{aE_pA_p}{P_O(1\text{-}e^{-(\mu\alpha(l_a)+kl_a)})} = 21.83\ m$$

c. Loss due to elastic shortening of concrete

$$\Delta P_3(x) = \frac{n\text{-}1}{2n}\sigma_{cp}(x)\frac{A_pE_p}{E_{c(7)}}$$

$$\sigma_{cp}(x) = \frac{\gamma_p(P_o\text{-}\Delta P_1\text{-}\Delta P_2)}{Ac} + \frac{\gamma_p(P_o\text{-}\Delta P_1\text{-}\Delta P_2)e_p'^{\,2}}{Ic} + \frac{(M_{pp}(x))e_p'}{Ic}$$

$$\Delta P_{ins}(x) = P_o\text{-}\Delta P_1(x)\text{-}\Delta P_2(x)\text{-}\Delta P_3(x)$$

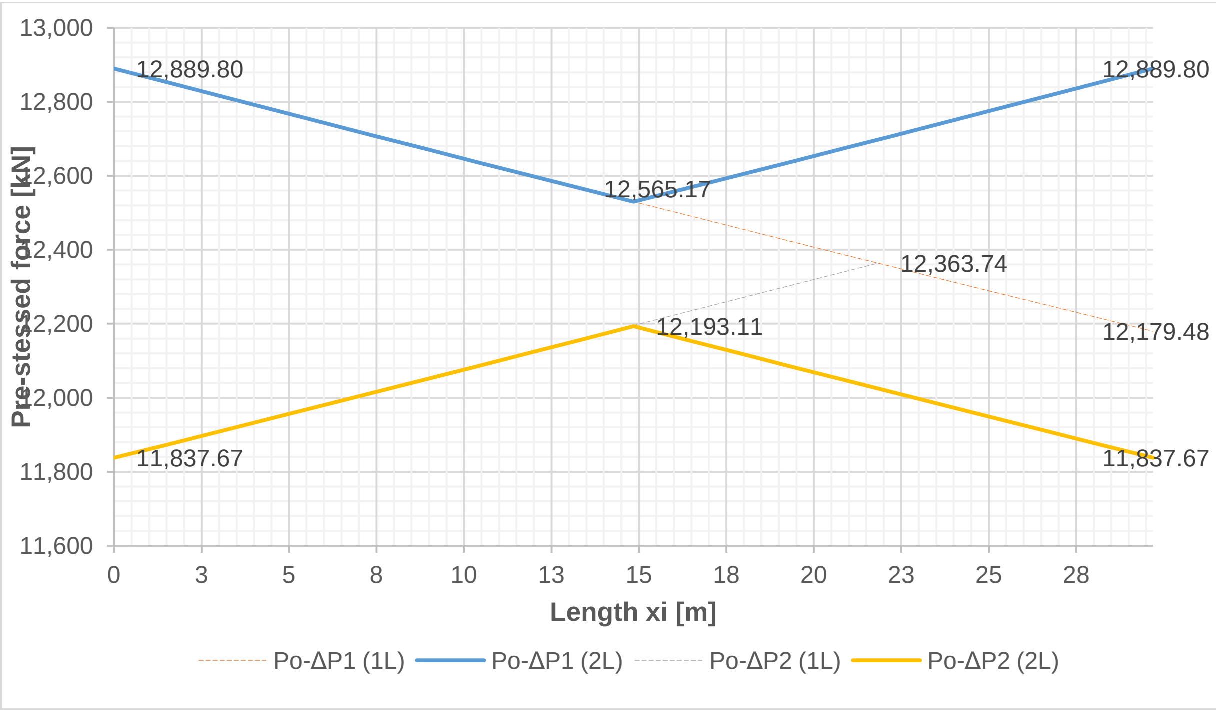


Figure 14 *Pre-stressing losses due to friction and wedge penetration when applying the tensile force in both free cantilever ends.*

2) Deferred losses of pre-stressing

$$\Delta P_{dif}(x)=\frac{n\varphi(t,t_o)\sigma_{cp}(x)+E_p\varepsilon_{cs}(t,t_o)+0{,}80\Delta\sigma_{pr}(x)}{1+n\frac{A_p}{A_c}\left(1+\frac{A_c y_p^2(x)}{I_c}\right)[1+\chi\varphi(t,t_o)]}A_p$$

$$y_p(x)=e'_p(x)=460mm;\ n_p=\frac{E_p}{E_c}=5.57;\ \varphi(t,t_o)=\varphi_o\beta_c(t,t_o)=1.5036;$$

$$\varepsilon_{cs}(t,t_o)=\varepsilon_{cs(7300)}-\varepsilon_{cs(7)}=2.83x10^{-4}$$

$$\sigma_{cp}(x)=\frac{\gamma_p P_{ki}(x)}{Ac}+\frac{\gamma_p P_{ki}(x){e'_p}^2}{Ic}+\frac{(M_{(PP+CM)}(x))e'_p}{Ic};\quad \Delta\sigma_{pr}(x)=\rho_f\frac{P_{ki}(x)}{A_p};\ \rho_f=7\%;\ \chi=0.80$$

Table 11 *Pre-stressing force after instantaneous and deferred losses*

x	e(x)	Pki	ΔPi(x)	%	P∞	ΔPdif(x)	%
0.00	0.34	11,459.12	1,431	11.10	9,300.56	3,589.24	27.85
1.49	0.36	11,474.05	1,416	10.98	9,377.70	3,512.10	27.25
2.97	0.38	11,495.73	1,394	10.82	9,365.48	3,524.32	27.34
4.46	0.40	11,525.28	1,365	10.59	9,388.68	3,501.12	27.16
5.94	0.42	11,563.57	1,326	10.29	9,450.94	3,438.86	26.68
7.43	0.43	11,611.23	1,279	9.92	9,554.83	3,334.97	25.87
8.91	0.44	11,668.63	1,221	9.47	9,701.79	3,188.01	24.73

x	e(x)	Pki	ΔPi(x)	%	P∞	ΔPdif(x)	%
10.40	0.45	11,735.91	1,154	8.95	9,892.22	2,997.58	23.26
11.88	0.46	11,812.95	1,077	8.35	10,125.42	2,764.38	21.45
13.37	0.46	11,899.39	990	7.68	10,399.63	2,490.17	19.32
14.85	0.46	11,994.62	895	6.94	10,712.00	2,177.80	16.90
16.34	0.46	11,899.39	990	7.68	10,399.63	2,490.17	19.32
17.82	0.46	11,812.95	1,077	8.35	10,125.42	2,764.38	21.45
19.31	0.45	11,735.91	1,154	8.95	9,892.22	2,997.58	23.26
20.79	0.44	11,668.63	1,221	9.47	9,701.79	3,188.01	24.73
22.28	0.43	11,611.23	1,279	9.92	9,554.83	3,334.97	25.87
23.76	0.42	11,563.57	1,326	10.29	9,450.94	3,438.86	26.68
25.25	0.40	11,525.28	1,365	10.59	9,388.68	3,501.12	27.16
26.73	0.38	11,495.73	1,394	10.82	9,365.48	3,524.32	27.34
28.22	0.36	11,474.05	1,416	10.98	9,377.70	3,512.10	27.25
29.70	0.34	11,459.12	1,431	11.10	9,300.56	3,589.24	27.85

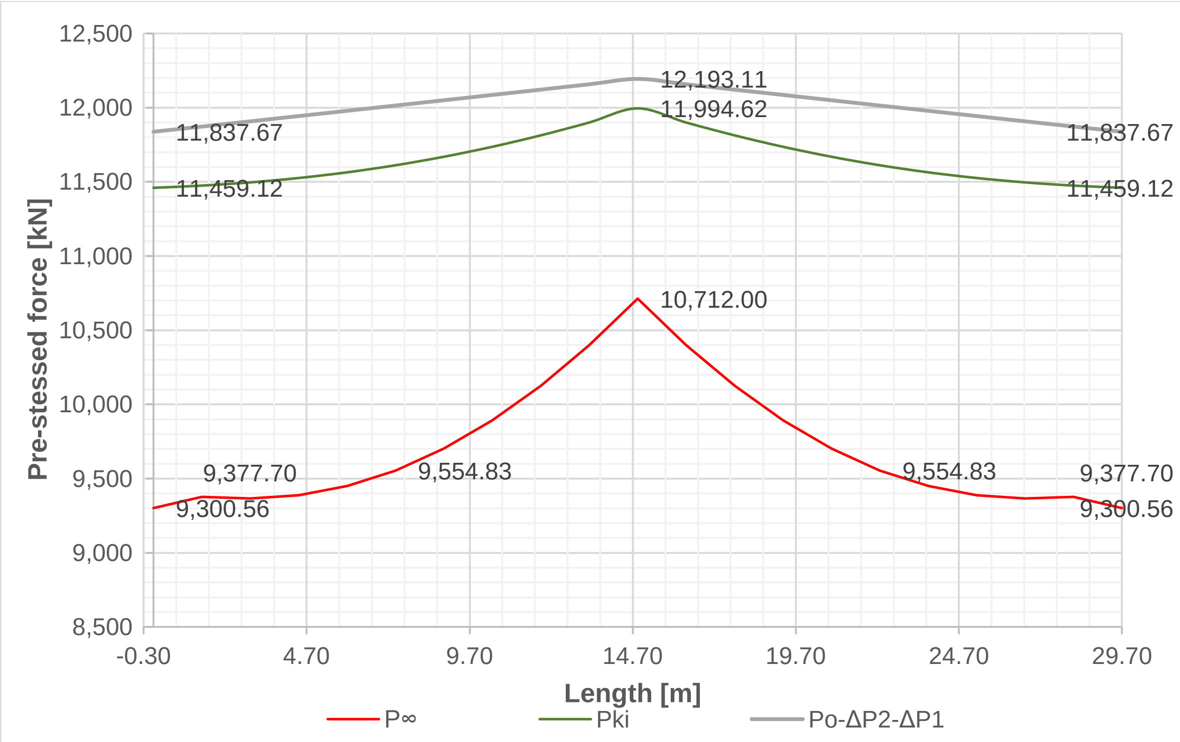


Figure 15 *Pre-stressing force after instantaneous and deferred losses.*

Finally, the central kern has been obtained along the length of the cantilever. As observed in *Figure 16a*, in which the section has been plotted together with the eccentricity and the compression central kern, the eccentricity is between both limits related to inequalities (1) and (4) Magnel. Therefore, both inequalities are directly met along the whole length of the studied slab. In addition, *Figure 16b* shows that the eccentricity fits in between the tensile central kern, accomplishing inequalities (2) and Magnel (3).

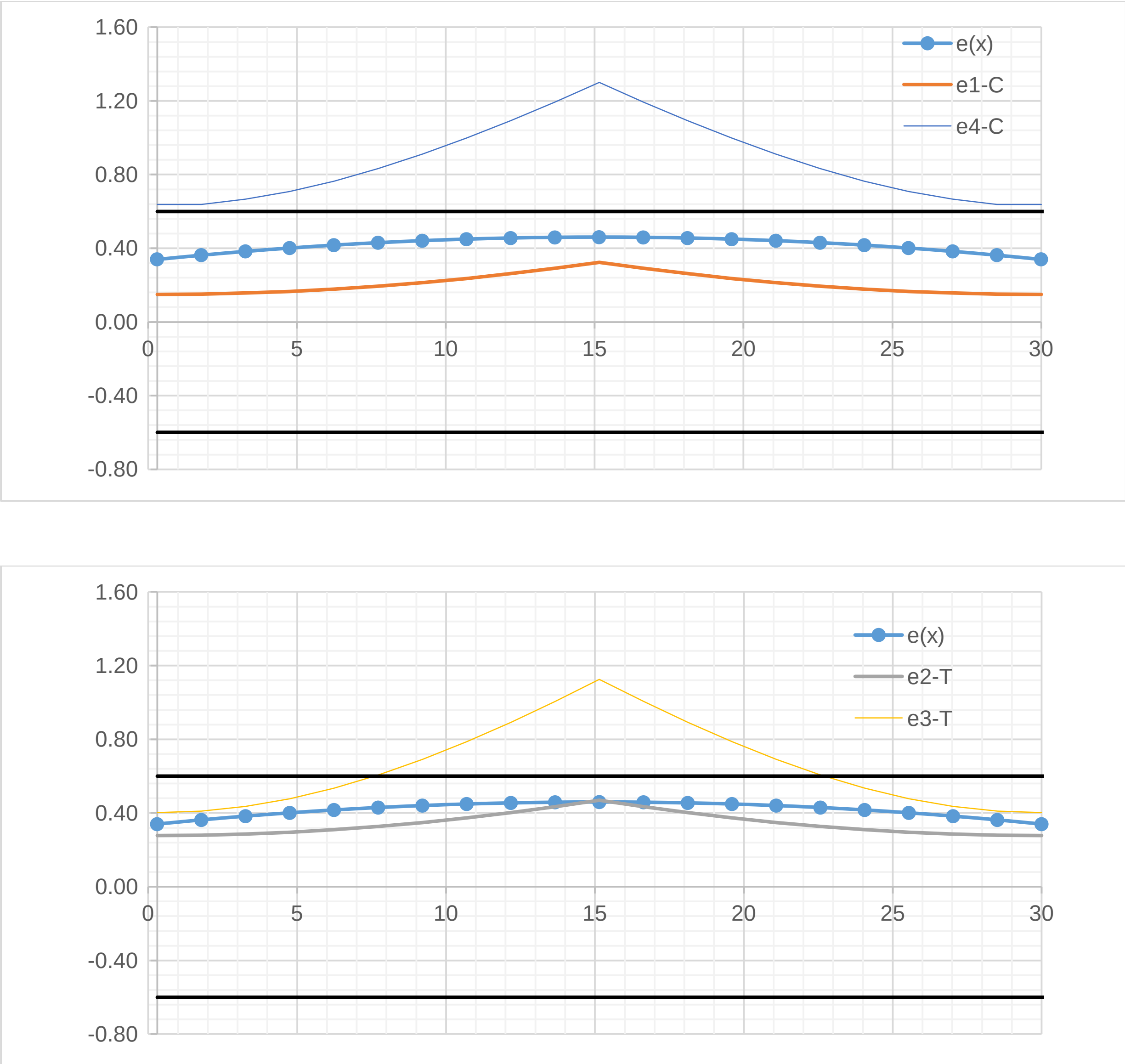


Figure 16 *a) Compression central kern; b) Tensile central kern.*

Table 12 *Stress at the pre-stressing reinforcement for the quasi-permanent load-combination.*

x	Ineq. (5) Magnel	
0.00	15,537	ok
1.49	16,385	ok
2.97	16,690	ok
4.46	16,591	ok
5.94	16,056	ok
7.43	15,067	ok
8.91	13,612	ok
10.40	11,694	ok
11.88	9,321	ok
13.37	6,512	ok

x	Ineq. (5) Magnel	
14.85	3,297	ok
16.34	6,512	ok
17.82	9,321	ok
19.31	11,694	ok
20.79	13,612	ok
22.28	15,067	ok
23.76	16,056	ok
25.25	16,591	ok
26.73	16,690	ok
28.22	16,385	ok
29.70	15,537	ok

- Cable elongation and vertical displacement due to the pre-stressing force at the free end of the cantilever. Long-term vertical displacement.

From the pre-stressing force after the friction losses, the cable elongation can be obtained as the integral of this profile along the cantilever length divided by the pre-stressing modulus of elasticity and the pre-stressing area.

$$\Delta l = \frac{P_0 - \Delta P_1(x=0) + P_0 - \Delta P_1(x=14.85)}{2A_pE_p} 14.85 = 0.108 \text{ m}$$

The total vertical deflection of the free end of the cantilever due to the pre-stressing force is the sum of the instantaneous and the long-term deflection.

$$\delta_{p,tot}=\delta_{p,inst}+\delta_{p,long\text{-}term}$$

$$\delta_{p,inst}=\frac{\overline{P_{ki}}\sin\alpha L^3}{3E_{c,7}I_c}+\frac{\overline{P_{ki}}\cos\alpha\cdot e_p(x=0)\cdot L^2}{2E_{c,7}I_c}-\frac{\eta_p L^4}{8E_{c,7}I_c}=$$

$$=\frac{188.39\cdot 14.85^3}{3\cdot 29{,}619{,}000\cdot 0.153}+\frac{11678\cdot 0.34\cdot 14.85^2}{2\cdot 29{,}619{,}000\cdot 0.153}-\frac{12.68 \text{ x } 14.85^4}{8\cdot 29{,}619{,}000\cdot 0.153}=0.125 \text{ m}$$

$$\eta_p = P_{ki}e_p'' = 11{,}658\cdot(-0.001088) = -12.68 \text{ kN/m}$$

$$\delta_{p,long\text{-}term} = \varphi(\infty,7d)\delta_{p,inst}\frac{\overline{P_{ki}}+\overline{P_\infty}}{2\cdot\overline{P_{ki}}} = 1.50\cdot 0.125\cdot\frac{11{,}680.0 + 9{,}806.9}{2\cdot 11{,}680} = 0.172\text{m}$$

$$\delta_{p,tot}=\delta_{p,inst}+\delta_{p,long\text{-}term}=0.125+0.172 = 0.297 \text{ m}$$

- Flexural ultimate limit state (ULS) in the worst section, arranging the necessary longitudinal passive reinforcements.

After verifying the SLS of cracking, the ULS of bending and shear should be checked in order to know if it is necessary to add passive reinforcement.

ULS bending with axial forces (pre-stressing force)

The compression block depth is first calculated to check if it is inside the flange; that is, if it is lower than 200 mm. If so, the ultimate bending moment can be calculated in a similar manner as that of a rectangular section.

$$y = \frac{A_p f_{pyd} d_p}{U_0} = 0.328\ \text{m} > 0.20\ \text{m} = h_f$$

where $U_0 = f_{cd} b d_p = 45{,}933$ kN, $d_p = 1.06$ m, $A_p = 2 \cdot 33 \cdot 140 = 9{,}240\text{mm}^2$,
$f_{pyd} = f_{pyk}/\gamma_p = 1{,}770/1.15$

Therefore, the verification at ULS should be done assuming a T-section. The width of the section is assumed as the web thickness, and then the flanges are assumed as a fictitious compression reinforcement whose capacity is equal to:

$$U_{s0} = f_{cd}(b - b_w)h_f = \frac{50}{1.5} \cdot 0.8 \cdot 0.2 \cdot 1{,}000 = 5{,}333.33\ \text{kN}$$

$$U_0 = f_{cd} b_w d_p = 17{,}666\ \text{kN}$$

$$y = \frac{A_p f_{pyd} d_p}{U_0} - \frac{U_{s0}}{U_0} d_p = 0.8532 - \frac{5{,}333}{17{,}666} 1.06 = 0.533\text{m}$$

$$M_u = (A_p f_{pyd} - U_{s0})(d_p - y/2) + U_{s0}(d_p - h_f/2) = (14{,}868 - 5{,}333.3)(1.06 - 0.533/2) +$$

$$+ 5{,}333.3\left(1.06 - \frac{0.2}{2}\right) = 12{,}684\ \text{kN.m}$$

$$M_d(x = 14.85\text{m}) = 10{,}855\ \text{kN.m} \leq M_u = 12{,}684\ \text{kN.m}$$

The design bending moment at ULS combination in the least favourable section is lower than the ultimate value given by the cross-section area considering only the pre-stressing area.

- ULS of Shear, calculating the necessary transverse reinforcements

The least favourable section is the connection with the support where the design shear force, due to the external loads, is 1,461.98 kN. Since the slope of the pre-stressing layout at the support is zero, the shear pre-stressing component is also zero, and the reduced shear design force is 1,461.98 kN.

The design shear force should be lower than the ultimate shear limited by crushing of diagonal struts, V_{u1}, and lower than the ultimate shear force due to a tensile failure in the web, V_{u2}.

$$V_{u1} = K f_{1cd} b_0 d \frac{\cot\theta + \cot\alpha}{1+\cot^2\theta} = 4{,}075.8\ \mathrm{kN}$$

being

$f_{1cd} = 20\mathrm{MPa};\ K = 1.25$

since

$\sigma'_{cd} = \frac{P_\infty(x=14.85)}{Ac} = 11.66 \leq 0.5 f_{cd};\ b_0 = b_w - \eta\varnothing = 0.50 - 0.5\cdot 2\cdot 0.12 = 0.38\mathrm{m},\ \cot\theta = 1.9606,$
$d = 1.06\ \mathrm{m}$

Assuming that the section is cracked at ULS:

$$V_{u2,woA90} = \left[\frac{0.18}{\gamma_c}\xi(100 f_{ck}\rho)^{1/3} + 0.15\sigma'_{cd}\right] b_0 d =$$

$$= [0.12\cdot 1.43\cdot(100\cdot 50\cdot 0.02)^{1/3} + 0.15\cdot 11.66]0.38\cdot 1.06 = 1{,}025.32\ \mathrm{kN}$$

where

$$\xi = 1+\sqrt{200/d} = 1.43 < 2;\ \rho = A_p/b_0 d = \frac{9{,}240}{380\cdot 1{,}060} = 0.0229 < 0.02$$

$$V_{u2,minwoA90} = \left[\frac{0.075}{\gamma_c}\xi^{3/2} f_{ck}^{1/2} + 0.15\sigma'_{cd}\right] b_0 d = 949.1\ \mathrm{kN}$$

since $V_d \geq V_{u2,woA90}$, passive transverse reinforcement is required:

$$V_{u2,wA90} = V_{cu} + V_{su}$$

$$V_{cu} = \left[\frac{0.15}{\gamma_c}\xi(100f_{ck}\rho)^{1/3} + 0.15\sigma'_{cd}\right]b_0 d =$$

$$= [0.10\cdot 1.43\cdot(100\cdot 50\cdot 0.02)^{1/3} + 0.15\cdot 11.66]0.38\cdot 1.06 = 971.85\text{kN}$$

$$V_{su} \geq V_d - V_{cu} = 1{,}461.98 - 971.85 = 490.12 \text{ kN}$$

$$V_{su} = z\sin\alpha(\cot\alpha + \cot\theta)A_{90}f_{y90d}$$

$$A_{90} = \frac{V_{su}}{z\sin\alpha(\cot\alpha + \cot\theta)f_{y90d}} = 0.655\text{mm}$$

where $z = 0.9\cdot d = 0.954$ m

The transverse reinforcement will be two closed stirrups ϕ12/0.30 ($2\cdot 753$ mm^2/mm)

- Anchorage devices, checking the stresses in the concrete under them, and defining the required passive reinforcement

According to the MK4 catalogue, the dimensions of the anchor plates are 444 mm $\times$ 444 mm. The layout in plan view should be modified to be able to implement the anchor plates, leaving a free space between them of 100 mm. Therefore, the spacing between the two tendons of each web should be 554 mm at the anchor area and 240 mm at the support connection.

- Drawings of the overall solution geometry and drawings of the passive and active reinforcements.

The proposed solution can be consulted in detail in *Annex XIV*.

C) Obtain the bill of quantities of the design project

As an example, the bill of quantities is provided for the slab and the concrete wall, considering only concrete, active and passive reinforcement, and the formwork; the final sum is 195,366.16 €. Detailed calculations can be found in *Annex XV*.

BILL OF QUANTITIES							
m^3	Concrete for pre-stressed elements with a maximum aggregate size of 20 mm						104.87 €
	Description	**A**	**B**	**C**	**D**	**Quantity**	**Amount**
	Deck	25.8	33.38	0.70769		609.47	63,914.85 €
	Intermediate Wall	1	25.8	1	6	154.80	16,233.88 €
					Total quantity	**764.27**	**80,148.73 €**
kg	Internal steel reinforcement B500S in the form of corrugated rebars with a yield strength ≥ 500 N/mm2						1.16 €
	Description	**A**	**B**	**C**	**D**	**Quantity**	**Amount**
	Deck	21.84	25.8	33.38		563.34	653.48 €
	Intermediate Wall	40.44	25.8	6		6260.12	7,261.74 €
					Total quantity	**6,823.47**	**7,915.22 €**
kg	Tendon made of strands for active reinforcement Y 1860 S7, till 37 strands of 15.2 mm of nominal diameter in ducts of less than 70 m length						1.39 €
	Description	**A**	**B**	**C**	**D**	**Quantity**	**Amount**
	Deck	25.8	50.77	33.38	1.099	48,051.21	66,791.18 €
				Total quantity		**48,051.21**	**66,791.18 €**
m^2	Assembly and disassembly of formwork with pine wood board for exposed concrete						34.25 €
	Description	**A**	**B**	**C**	**D**	**Quantity**	**Amount**
	Deck	25.8	33.38			861.204	29,496.24 €
		2	25.8			51.6	1,767.30 €
		2	33.38			66.76	2,286.53 €
	Wall	1	1	6	2	12	411.00 €
		1	25.8	6	2	309.6	10,603.80 €
				Total quantity		**1,182.804**	**40,511.04 €**
						TOTAL AMOUNT	**195,366.16 €**

Evaluation criteria

In order to evaluate this activity, a report will be requested from each group, in which the entire activity should be solved. The report should include index construction and justification and all calculations and schematic drawings associated to the solution proposed.

For the specific assessment of the report, we recommend using the rubric mentioned previously (see *Annex IX*), and specifically, the technical aspects identified within the rubric. Thus, the rubric represents a possible instrument to facilitate the evaluation of the proposed activities as a whole. As mentioned above, the professor is free to choose an alternative method.

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ANNEXES

I. Vall d'Hebron neighborhood data < A.I_Vall_Hebron.pdf >

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