POLITECNICO DI TORINO

Facoltà di Architettura / Architecture
MSc Program in Architecture for the Sustainability Design

Master's Degree Thesis

The evaluation of project economic sustainability in a life cycle perspective: the case of cycle infrastructures

Supervisor:
Prof. Elena Fregonara

Co-supervisor:
Prof. Diego Giuseppe Ferrando

Candidate:
Bianca Bettinardi

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"Le radici stanno dove siamo nati e cresciuti. Quelle radici non le tagli.
Sono elastici con un capo legato al campanile e l'altro intorno alla nostra vita.
Più ti allontani e più gli elastici si tirano, finchè diventano fini come corde di violino.
Ma non si rompono. Quando sono tirati al massimo,
passa il vento della memoria e questi elastici mandano i suoni dei ricordi.
A sentirli pensi al paese e diventi debole. Molla le mani da dove ti tenevi aggrappato
e gli elastici, con uno strappo, ti riportano a casa."

Mauro Corona

Contents

Abstract

This Master's Degree thesis is developed within the evaluation of project economic sustainability, with a focus on "slow" mobility and specifically cycle infrastructures. The main objective was to figure a suitable evaluation tool for assessing the total cost of a cycle network over its life cycle. The most appropriate approach resulted in the Life Cycle Costing (LCC) Analysis integrated with the Cost-Benefit Analysis (CBA). The central issue in the development of a theoretical LCC guideline adapted to the field of study was the integration a of a number of cost items that are usually neglected. In fact, the application of the traditional LCC approach is generally linked to private projects and focuses mainly on owner/investor total costs, without the involvement of other stakeholders. The study investigates the influence of the cost categories represented by user, environmental and social costs, that are declined and adapted to specific expenses related to cycle paths. As a result, a theoretical guideline for the construction of the LCC spreadsheet variation to evaluate cycle projects economic sustainability is developed. This opens the way to a switch towards a hybrid Life-Cycle Cost-Benefit Analysis (LCCBA), with the exploration of the resulting benefits and the definition of cash flows and a practical application of the operative modality to real case studies.

Introduction

In the construction sector, the importance of economic assessment tools for the evaluation of projects sustainability is a consolidated topic. Starting from the theories of Life Cycle Thinking and Circular Economy, developed respectively from the 1950s and the 1970s, the central issue has become to take into consideration the economic, social and environmental impact of projects through their whole life cycle, to ensure the overall sustainability of construction practices. Consequently, the theoretical approaches have been transposed into practical tools for quantifying in monetary terms positive and negative impacts. The two most popular and employed approaches are the Life Cycle Costing (LCC) and Cost-Benefit Analysis (CBA). The first, mainly used in the private sector, allows the calculation of the total cost of a project considering its entire life cycle, from the very early phase of planning and design, until the disposal of the system; the second methodology relies on a set of criteria to measure the economic value of one or more project solutions and it is generally applied to evaluate alternatives in the public sector. Despite the reliability of these tools, some variables which may be essential for a more accurate application to various construction fields and in the interest of all the stakeholders are neglected. On one hand, the LCC Analysis usually focuses on investor/owner costs, excluding the significative economic impact caused by user, social and environmental costs. On the other hand, the traditional CBA models also leave out these variables because their identification for major public projects is very complex and time expensive. Among the studies that in recent years have tried to implement these methodologies, those of PhD Professor Thoft-Christensen led to the development of an innovative Life-Cycle Cost-Benefit Analysis (LCCBA) methodology, that is basically and extended LCC Analysis including social and environmental externalities. Thoft-Christensen researches confirmed that a simple LCC based analysis is insufficient in the case of infrastructure life cycle evaluation, and further development of the traditional LCCBA formulation are more suitable to analyze this field. For this reason, this master's thesis focuses on "soft" mobility investments and particularly on cycle infrastructure projects. The decision to investigate this field was also given by todays' growing need of sustainable and "green" mobility and the potentiality and benefits of well-structured cycle networks, both in the cities and remote territories. Through the analysis of forward-looking projects, EU policies and national plans, the core of the work is the examination of cost implications throughout the whole life cycle of bike paths, based on the indications of Thoft-Christensen. The general categories of cost are represented by owner costs, user costs, environmental costs and social costs, that are declined in a series of detailed cost items. This operation allows the implementation of the traditional LCC approach generally applied to buildings construction and management that consider only owner/investor costs. The theoretic reformulation of the LCC spreadsheet towards a LCCBA-oriented approach enables a comprehensive analysis of the impacts on all the stakeholders directly and indirectly involved in the project development and management.

The work is developed in four main chapters addressing step by step the above-mentioned issues. In Chapter 1 the theoretical and methodological context is presented, with regard to the most reliable economic evaluation tools; in Chapter 2 the potential applicative framework is defined, with a first section dedicated to the infrastructure sector in general and a second part focusing on "soft" mobility investment perspectives and particularly on the benefits related to cycle networks development. Chapter 3 analyzes cycle paths cost implications with a detailed description of the cost items involved in this kind of investments. Chapter 4 presents the definition of a guideline and the theoretical adaptation of the traditional LCC spreadsheet to the field of cycle networks. Finally, some considerations on the implementation of this research are made. With the adaptation of real projects, the theoretical spreadsheet can be completed by quantifying costs and adding benefits, allowing the determination of cash flows and switching to a more suitable LCCBA hybrid formulation for the "slow" sustainable infrastructure field.

Chapter 1

Theoretical and methodological context

In this chapter we introduce the holistic concepts of Circular Economy and Life Cycle Thinking in the field of public infrastructure. A particular emphasis will be given to the fundamental issue of costs during the maintenance phase, which corresponds in fact to the most critical stage in terms of risks and variables. Two of the most consistent and currently used methodologies to examine the feasibility of projects will be analyzed to investigate the impact of maintenance planning and implementation. The methodologies presented will be the Life Cycle Costing (LCC) or Life Cycle Cost Analysis (LCCA) and the Cost-Benefit Analysis (CBA), focusing on their potential, but also on their current limits. This will be a starting point to introduce the least known methodology of Life-Cycle Cost-Benefit Analysis (LCCBA), through an alternative model which may prove more useful for the evaluation of infrastructure projects in the public sector.

1.1 Circular Economy

In the first section of this chapter we explore the nowadays widespread theoretical concept of Circular Economy, in opposition to the traditional Linear Economy system. First, an analysis of the damages and failures of the “take-make-dispose” model is pursued, followed by the presentation of the origins and development of the more sustainable circular model. Finally, we get deeper into the topic by investigating the level of awareness and the present criticalities of Circular Economy to be further explored in the construction sector.

1.1.1 The limits of Linear Economy

Even if we now live in the XI century, the prevailing part of our industrial economy is still stuck to the characteristic established in the early days of industrialization. From that time, companies and industries have been extracting and harvesting materials, processing and using them and finally discarding them when they no longer served their purpose properly. This is the traditional linear consumption pattern, based on the "take-make-dispose" principles.

The Linear Economy Model.

Source: Author's re-elaboration from https://www.supplychainschool.co.uk/topics/sustainability/waste-and-resource-efficiency/

According to the Ellen MacArthur Foundation[1], this economic design finds its roots in the historically uneven distribution of wealth by geographic regions. The western societies have experienced a massive resources and energy availability, adopting business models based on the overexploitation of resources and a total disregard for recycling and reusing products. Furthermore, the regulatory framework hasn't really opposed this way of operating until recent years, as it didn't charged producers for their negligence on the environmental impact of their work.

But while the linear economy has successfully generated material wealth in the western industrialized countries until the XX century, the new millennium is showing growing weakness and a likely future collapse of this model. In the past decades, the new challenges and issues of the global development lead the society to start questioning the linear economy success. The growing and increasingly

[1] EMF, *Towards the Circular Economy Vol.1: an economic and business rationale for an accelerated transition*, Ellen MacArthur Foundation, Cowes, UK, 2012. Available online: https://www.ellenmacarthurfoundation.org/publications

demanding population has been causing overexploitation of non-renewable resources, higher price levels and more volatility in markets. Companies started facing a higher exposure to risk and unpredictable prices in resource markets, while some individuals and associations began to worry about peoples' health and environment protection.

Already in 1966, the American economist Kenneth E. Boulding described the so-called "cowboy economy" [2] as a system in which the natural environment is perceived as limitless and exploited with no limitation on the energy and material flows, leading to both environmental and social dramatic impacts, such as pollution and exploitative and violent behaviors. He also introduced the idea that a circular economic system could be an effective alternative to preserve the sustainability of human life on Earth.

On these premises, a change in perspective has become a central need to address nowadays challenges to satisfy demand and production without compromising environment and human health. This change in perspective is represented by the development of the circular economy theories.

1.1.2 Circular Economy: origin and basic principles

The concept of a circular economy cannot be traced back to one single date or author, but more likely to different schools of thought that developed from the 1970s.

According to Wautelet[3], five main schools of thought have developed through the years, evolving and consolidating the concept of Circular Economy:

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[2] Boulding K., *The Economics of the Coming Spaceship Earth*, in *Jarrett H., Ed. Environmental Quality in a Growing Economy*, 1966, Baltimore, Resources for the Future/Johns Hopkins University Press, pp. 8-10.

[3] Wautelet T., *The Concept of Circular Economy: its Origins and its Evolution*, 2018, DOI: 10.13140/RG.2.2.17021.87523

• **Industrial Ecology** (IE) emerged to counteract the tendency of considering the industrial system as separate from the environment and with the aim to look upon the industrial society as a specific ecosystem within the biosphere.[4] This is accomplished by analyzing all the system's components and understanding how the flow of materials and energy work and interact with the environment. In order to move towards a more sustainable industrial society, Erkman described four key principles[5]:

1) Systematic valorization of waste and by-products;

2) Minimization of loss caused by dispersion;

3) Dematerialization of the economy to minimize the total material flows while ensuring equivalent or higher level of services;

4) Less reliability on fossil hydrocarbon for energy production.

• **Cradle to Cradle** (C2C) concept first arised in 2002 thanks to the contribution of the architect William McDonough and the chemist Dr Michael Braungart[6], claiming for a new way of designing material goods to reduce the harmful impact of human activities on the environment. The so-called eco-effective strategy focuses on the minimization of negative impacts in favor of a better quality of positive impacts and positive relationships between humans and environment. The goal is "not to minimize the cradle-to-grave flow of materials, but to generate cyclical, cradle-to-cradle "metabolisms" that enable materials to maintain their status as resources and accumulate intelligence over time (upcycling)".[7]

The C2C principles have been of crucial importance for the definition of the widespread and most known concepts of Circular Economy provided by the Ellen MacArthur Foundation.

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[4] Erkman S., *Industrial ecology: An historical view*, in *"Journal of Cleaner Production"*, 1997, Vol. 5, 1-2, pp. 1-10.

[5] Erkman S., *Industrial ecology: a new perspective on the future of the industrial system*, in *"Swiss medical weekly"*, 2001, Vol. 131, 37-38, pp. 531-538.

[6] McDonough W., and Braungart M., *Cradle to cradle: Remaking the way we make things*, New York, North Point Press, 2002.

[7] Braungart M., McDonough W.,Bollinger A., *Cradle-to-cradle design: Creating healthy emissions - A strategy for eco-effective product and system design*, in *"Journal of Cleaner Production"*, 2006, Vol. 15, 13-14, p. 1338.

• **Performance Economy** principles were developed by the architect Walter Stahel in a research report contracted by the European Commission.[8] The study analyzed the potential for substituting manpower for energy product-life extension in car manufacturing and building sector and it showed that product-life extension represented the best strategy to substitute manpower for energy. Stahel researches evolved through the years coming up with new outputs and definitions, such as the shift from "doing things right" to "doing the right things"[9], referring on focusing on problem-solving to reduce the environmental impact. The linear economy model, for which the manufacturer is not responsible for maintenance and end-of-life of the product, switches to a business model that imposes the assumption of responsibility for the product's entire lifetime.

• **Blue Economy** is a more recent movement mainly represented by the businessman Gunter Pauli, that promoted it as "the best and the cheapest solution for health and the environment where necessities of life are free due to local system of production that works only with already existing resources".[10] The goal is to inspire entrepreneurs to innovate their business models to respond to the basic needs of all by using locally available resources and increase competitiveness.
According to Pauli[11], the Blue Economy departs from the Red Economy, the traditional one based on a fast and cheap production and generating negative impacts, and the Green Economy, the emerging model based on green technologies, biomaterials and renewable resources and energies. The latter is criticized for its high costs and a lack of global systemic approach. In contrast with the Red and the Green Economies, the Blue Economy relies on restoring the environment, providing jobs places and high quality and cheap products.

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[8] Stahel W. R., Reday-Mulvey G., *Jobs for tomorrow: The potential for substituting manpower for energy*, Vantage Press, 1981.

[9] Stahel W. R., *The performance economy*, 2nd edition, Basingstoke, Palgrave Macmillan, 2010, p. 5.

[10] Pauli G. A., *The Blue Economy: 10 years, 100 innovations, 100 million jobs*, Taos NM, Paradigm Publications, 2010, p. 14.

[11] Pauli G. A., *The Blue Economy: A Report to the Club of Rome*, 2009. Available online: https://www.slideshare.net/mpoissonquinton/gunter-pauli-blue-economy-2009

• **Biomimicry** finds its origins back in 1997 thanks to Janine Benyus contribution *"Innovation inspired by Nature"*.[12] The core concept is to learn from the billions of years of development and changes in nature and living organisms to foster nature-inspired business models and designs, which naturally adapt to the environment on a long term. Nature represents a model, a measure and a mentor, but it needs to be analyzed in combination with innovation, with a deep understanding of the interactions between the elements of the ecosystem.

All these schools of thought have the same basic principles despite some specific divergences. The shared theory is that the traditional Linear Economy is not sustainable and there is the need to determine a respectful relationship with the environment.

Summing up all these literature inputs, the first official organization that globally spread the Circular Economy principles and started giving solid answers is the Ellen MacArthur Foundation, a UK registered charity founded in 2009 by the English sailor and environmentalist Ellen MacArthur. With its first series of reports *"Towards a Circular Economy"*[13], a shared inclusive definition of this model is given. The main goal is to broadcast Circular Economy as a powerful and lasting answer to the world's future growth and development. Through a solid framework and tangible case studies, the reports show that the concept of circular design works because it is adaptable to diverse scales and products regardless of length of their service life and offers the possibility to face successfully nowadays challenges from a different perspective. The robustness of the EMF's reliability is based on some undeniable trends:

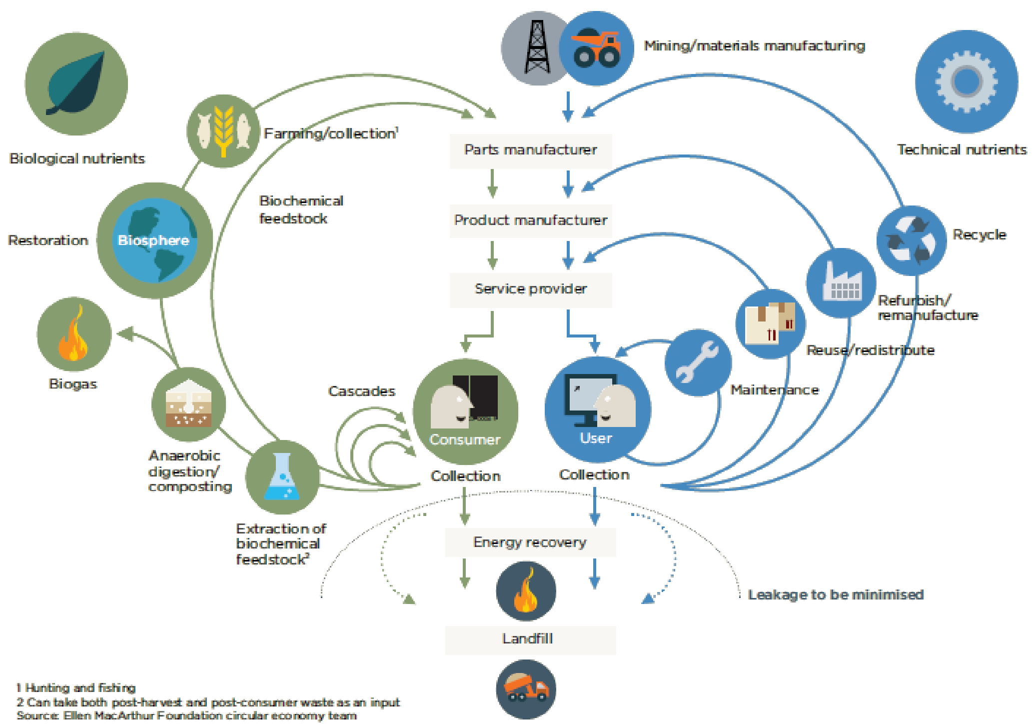
[12] Benyus J. M., *Biomimicry: Innovation inspired by nature*, New York, Morrow, 1997.

[13] EMF, *Towards the Circular Economy Vol.1: an economic and business rationale for an accelerated transition*, Ellen MacArthur Foundation, Cowes, UK, 2012. Available online: https://www.ellenmacarthurfoundation.org/publications
EMF, *Towards the Circular Economy Vol.2: Opportunities for the consumer goods sector*, Ellen MacArthur Foundation, Cowes, UK, 2013. Available online: https://www.ellenmacarthurfoundation.org/publications
EMF, *Towards the Circular Economy Vol.3: Accelerating the scale-up across global supply chains*, Ellen MacArthur Foundation, Cowes, UK, 2014. Available online: https://www.ellenmacarthurfoundation.org/publications

• Resource scarcity and stricter environmental standards are permanent and will possibly increase in the future;

• Technological innovation can become a powerful tool to trace materials and products supply and monitor their condition during use, but also to attract millions of customers in short terms;

• A shift in consumer behavior is globally occurring: new generations seem to prefer access over ownership and are developing greater responsibility towards the exploitation of products and resources.



The Circular Economy Model.

Source: EMF, *Towards the Circular Economy Vol.1: an economic and business rationale for an accelerated transition*, Ellen MacArthur Foundation, Cowes, UK, 2012, p. 25.

In 2012, the Foundation was claiming that towards 2025 there was a chance for Circular Economy to go mainstream, and for savings to raise above the 20% mark.[14] Actually, eight years later a lot of literature has been produced and the concept is theoretically well-established, but from a practical and legislative point of view the implementation of the Circular Economy principles is still not solid and further transformational changes are needed from the corporate sector and from government regulatory framework.

Therefore, the EMF and its partners are increasingly committing to support and motivate the pioneers of the Circular Economy, sharing their best practices and case study repository, and educating the next generations.

1.1.3 Circular Economy in the building sector

As the Linear Economy system is failing in the nowadays society, the urgency to change course involves of course and especially the building sector. As mentioned before, many material resources are likely to become scarier and more costly in the close future and a continuous exploitation of them will cause a complete loss for future uses. As an example, in 2016 WRAP (Waste Resources Action Programme) UK stated that an estimated 37% of the overall annual construction materials inputs, equivalent to 158 Mt is completely lost.[15]

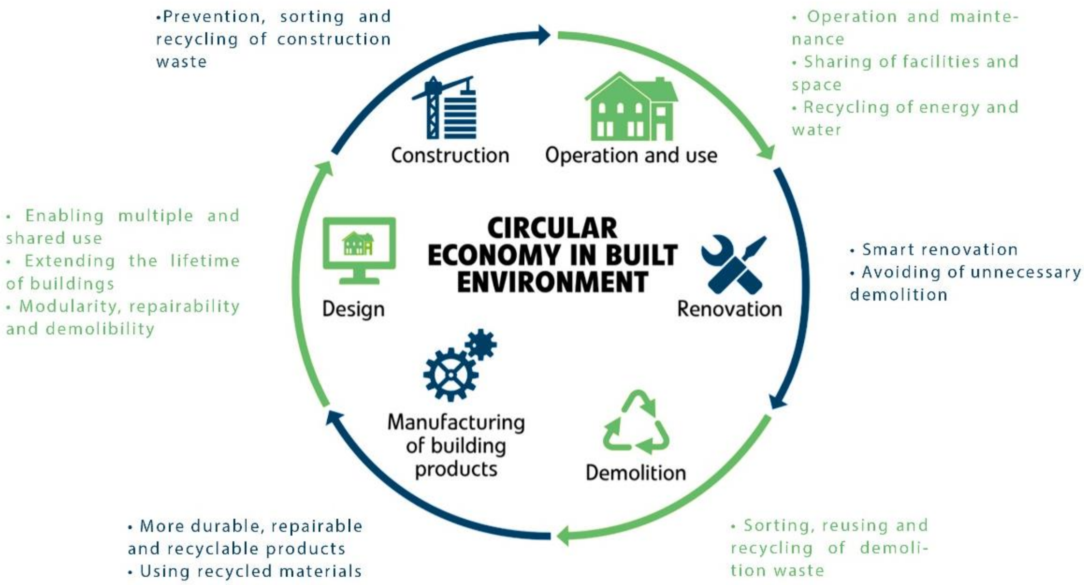
Therefore, the possibility to move towards a Circular Economy system has become a primary objective, in order to reduce the use of primary non-renewable materials, protect natural resources and limit the carbon footprint. According to Morgan and Mitchell[16], the switch to the Circular Economy would not only bring environmental benefits, but it would also lead to economic advantages, both for individuals and

[14] Ibid.

[15] WRAP (Waste Resources Action Programme), *WRAP and the Circular Economy. Waste Resources Action Programme*, 2016, Banbury, UK. Available online: http://www.wrap.org.uk/about-us/about/wrap-andcircular-economy.

[16] Mitchell P., Morgan J., *Employment and the circular economy Job creation in a more resource efficient Britain*, 2015, DOI: 10.13140/RG.2.1.1026.5049.

enterprises or productors. In fact, business benefits may include a growth in gross domestic product, new job opportunities, reduced risks in materials price volatility, as well as higher competitiveness and flexibility.



The Circular Economy Model in built environment and construction sector.
Source: Author's re-elaboration from
https://ec.europa.eu/transparency/regexpert/index.cfm?do=groupDetail.groupMeetingDoc&docid=35644

Considering that the built environment represents 5-13% of the total gross added value[17], its importance at a global economic level has been taken into consideration and many Polices have been developed in recent years at the European level to improve in a meaningful way the social, environmental and economic sustainability of the sector. In 2015, EMF estimated that with the application of a Circular Economy thinking to the European built environment by 2030, £300 billion could be saved from primary resource benefits, including energy.[18] But while research has largely

[17] Eurostat, *Construction Statistics - NACE Rev. 2.*, 2015, Eurostat, Luxembourg, Luxembourg. Available online: http://ec.europa.eu/eurostat/statistics-explained/index.php/Construction_statistics_-_NACE_Rev._2

[18] EMF, *Growth within: a Circular Economy Vision for a Competitive Europe*, Ellen MacArthur Foundation, Cowes, UK, 2015. Available online: https://www.ellenmacarthurfoundation.org/publications.

focused on recycling construction and demolition waste, a limited attention has been emphasized on the sustainability of the longer phase of service life and maintenance.

According to Adams and Osmani[19], there is a good level of awareness on the subject among producers and enterprises, but there is still a major need to articulate and regulate the benefits of the Circular Economy in a more solid and measurable way.

Levels of awareness of Circular Economy in the construction sector.

Source: Adams K. T., Osmani M., Thorpe T., Thornback J., *Circular economy in construction: current awareness, challenges and enablers*, in *"Proceedings of the Institution of Civil Engineers. Waste and resource management"*, 2017, vol. 170, issue WR1, p. 4.

The survey recognizes the success of circularity in the short term, but at the same time it underlines the importance of developing it in long term. The most significant challenge of our time is to apply further and further all the Circular Economy principles to a sector that is fragmented by nature and characterized by long lifespans, constraints and uncertainties.

19 Adams K. T., Osmani M., Thorpe T., Thornback J., *Circular economy in construction: current awareness, challenges and enablers*, in *"Proceedings of the Institution of Civil Engineers. Waste and resource management"*, 2017, Vol. 170, issue WR1, pp. 15-24.

1.2 Life Cycle Thinking

This second section takes a step back to the holistic theory of Life Cycle Thinking (LCT). This approach represents a pillar for the life cycle principles and the multiple and solid methodologies and models. Starting from a framework of LCT, its origins and its main guidelines, we will then introduce the theoretical features of two among the major operative techniques based on the LCT principles: Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) or Life Cycle Cost Analysis (LCCA).

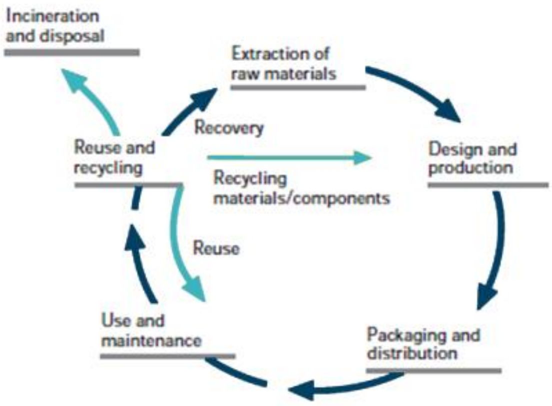
1.2.1 The holistic approach of Life Cycle Thinking

The development of Circular Economy notions that arose from the 1970s can be traced back to the holistic approach of Life Cycle Thinking (LCT), that finds its origins in the 1950s in the United States. In fact, the concept of circularity approached economics and business models after the awareness of a wider aim, the one to consider design and production as a process evolving continuously during its life cycle. As defined by Carnimeo et al.[20], from a general point of view LCT can be defined as a "cultural" attitude with as main objective the focus on all the aspects linked to the management of a product project or process through its life cycle. According to this vision, all the impacts, real or potential, generated during the life cycle must be considered from the very beginning.

In the past decades, many life-cycle-based environmental initiatives started taking place in the building sector. According to the Danish Ministry of the Environment[21], while at the beginning of this process enterprises primarily focused on environmental improvements to the production within their own perimeter fence, more recent initiatives involve products control and development "from cradle to grave", meaning from raw materials extraction, transport and manufacturing, to use and consumption and finally re-use or disposal.

[20] Carnimeo G., Frey M., Iraldo F., *Gestione del prodotto e della sostenibilità. Le imprese di fronte alle nuove prospettive delle politiche ambientali comunitarie e della Integrated Product Policy*. Milano, FrancoAngeli, 2002.

[21] Remmen A., *An introduction to Life-cycle Thinking and Management*, The Danish Ministry of the Environment, 2003.



The life cycle of a product - and closing the resource cycle.

Source: Remmen A., *An introduction to Life-cycle Thinking and Management*, The Danish Ministry of the Environment, 2003, p. 9.

This operating mode provides the opportunity to have a clear overview at any time of the process over the advantages and disadvantages associated with the specific choices taken, that can occur during the product's life cycle. Therefore, new initiatives can be developed in the making and a more detailed knowledge can lead to a more solid decision-making process.

More in detail, the LCT approach conceives the project as a process evolving along its entire life cycle at different scales, from the building materials and components, up to the territorial areas and infrastructures. Thanks to this philosophy, the integration between sustainability and life-cycle assessment has become the central issues spinning around the key concept of cost.

1.2.2 Concepts of Cost

Before moving on to illustrate the more robust approaches that have been developed on the LCT basis, some basic notions on the concepts of costs related to environmental sustainability need to be underlined, both in terms of definitions and regulatory framework.

Outlining costs in projects is of fundamental importance from the early briefing and planning phase, until the end of life and disposal of the work. This broadened concept is regulated in the Standard ISO 15686[22] and in the Standard EN 15459[23]. The former defines the Whole Life Cost (WLC) definition, referring to all initial and future cost typologies in the life cycle time scale, including also the ones related to external factors, not specifically linked to construction and the incomes, as negative costs. In the latter, the WLC viewpoint is circumscribed to Global Cost or Life Cycle Cost concept, that regards the costs of an asset or its component to meet the required performances during its life cycle. The environmental costs are considered in both cases, even if their assessment is very complicated. As shown in *Fig. 1* and *2*, the most relevant cost items are the ones occurring in phase 5 of WLC: *Use, Maintenance, Adaptation*.

In fact, about 50% of investments during a building or infrastructure life cycle, are carried out for maintenance management, minor and major repairs and replacements and failures [24].

In *Fig. 3*, the two cost concepts are schematized in a tree diagram.

[22] International Organization for Standardization, ISO 15686-5:2008, *Buildings and constructed assets - Service-life planning*, *Part 5: Life Cycle Costing*, ISO/TC 59/CS 14, International Organization for Standardization, Geneva, Switzerland, 2008.

[23] European Committee for Standardization (CEN), Standard EN 15459-1:2017, *Energy Performance of Buildings - Economic evaluation procedure for energy systems in buildings*., European Committee for Standardization, Brussels, Belgium, 2017.

[24] Fregonara E., *Evaluation Sustainability Design. Life Cycle Thinking and international orientations.*, Milano, FrancoAngeli, 2017.

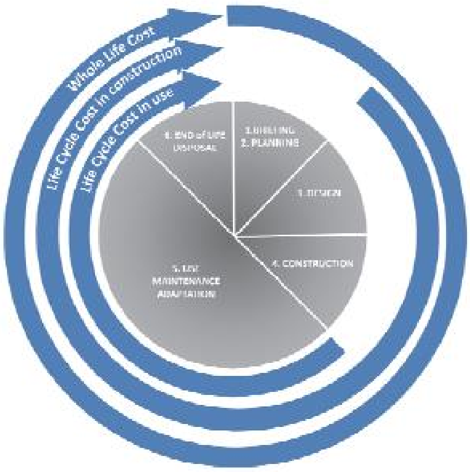


Fig. 1: Life cycle in construction and WLC and LCC (or Total LCC or Global Cost).

Source: Fregonara E., *Evaluation Sustainability Design. Life Cycle Thinking and international orientations.*, Milano, FrancoAngeli, 2017, p. 11.

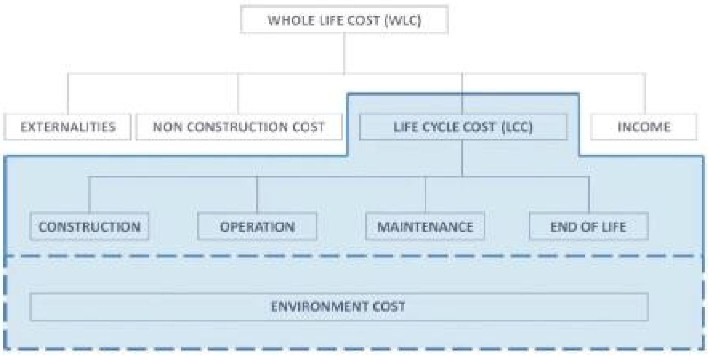


Fig. 2: Different components of the Whole Life Cost and Life Cycle Cost.

Source: Fregonara E., *Evaluation Sustainability Design. Life Cycle Thinking and international orientations.*, Milano, FrancoAngeli, 2017, p. 12.

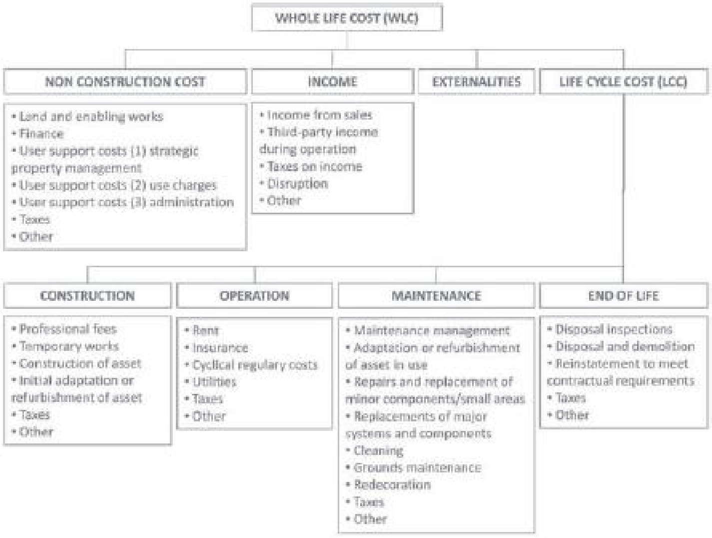


Fig. 3: Whole Life Cost (WLC): detailed items.

Source: Fregonara E., *Evaluation Sustainability Design. Life Cycle Thinking and international orientations.*, Milano, FrancoAngeli, 2017, p. 13.

The approach for the calculation of the Global Cost is particularly useful because it can be applied to all types of buildings and infrastructures. The EN 15459 provides two calculation methodologies:

• The more diffused **Global Cost Method** calculates the sum of the actual value of all cost items referred to the investment starting year. The cost items refer to every year from the starting year and they are linked to the calculation period. The Global Cost is evaluated with this formula:

$$C_G\ (\tau) = \ C_I + \sum_J \left[\sum_{i=1}^{\tau} \Big(C_{a,i}(j) * R_d(i) \Big) - V_{f,\tau}(j) \right]$$

Where:

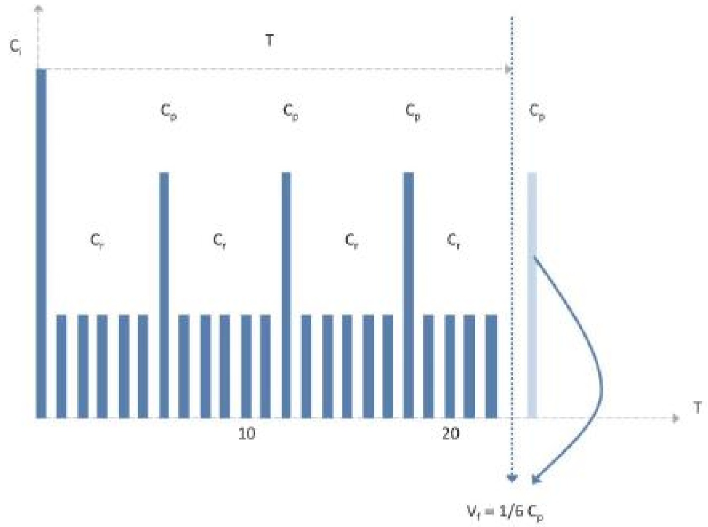
CG (τ) = Global Cost, referred to the initial year *τ0*;

CI = initial investment costs;

Ca,i (j) = annual cost at year *i*, for the *j* component (including running and periodic or replacement costs);

Rd (i) = discount factor at year *i*;

Vf,τ (j) = final value of the *j* component at the end of the calculation period.



Calculation of the Global Cost, highlighting the final value concept.

Source: Fregonara E., *Evaluation Sustainability Design. Life Cycle Thinking and international orientations.*, Milano, FrancoAngeli, 2017, p. 15.

• The **Annuity Method** or **Equivalent Annual Cost** (EAC) approach, less explored in literature, represents a valuable and possibly more effective alternative to support maintenance cost planning, by joining all the costs into a single annualized mean cost. According to the EN 15459, considering a calculation period τ, the Annuity Cost is given by summing up three components in the formula:

$$AC = C_r + \sum_i (a(i) * \sum_j V_0(j)) + \mathrm{a}(\tau_{Building}) * \left(\sum_j V_0(j)\right)$$

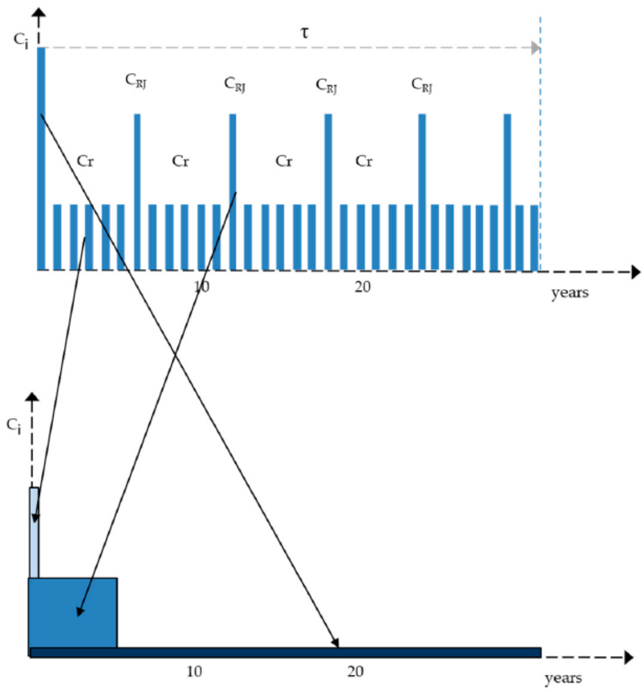
Where the 3 components are represented by:

1) Cr = annual running costs, usually constant over time;

2) $\sum_i (a(i) * \sum_j V_0(j))$ = total annualized costs related to j components or system replacements with lower service life than the building life cycle;

3) $a(\tau_{Building}) * (\sum_j V_0(j))$ = total annualized costs related to j components or system replacements with unchanged service life during the building life cycle, having a life cycle longer than the one of the building.

It is important to point out that the three components are summed and not discounted, since they are associated to annual periods. The Annuity Method can be specifically useful to select a preferable solution among different project possibilities, considering the lowest EAC as the more suitable and convenient option[25].



Annuity Cost graphic presentation.

Source: Fregonara E., Ferrando D. G., *The Stochastic Annuity Method for Supporting Maintenance Costs Planning and Durability in the Construction Sector: A Simulation on a Building Component*, in *"Sustainability"*, 2020, 12, 2909, p. 7.

[25] Fava J.A., Denison R., Jones B., Curran M.A., Vigon B., Selke S., Barnum J., *SETAC Workshop Report: A Technical Framework for Life-Cycle Assessment* (August 18–23, 1990), 1991, Smugglers Notch, Vermont, SETAC, Washington, DC.

1.2.3 Life Cycle Assessment (LCA)

Life Cycle Assessment is one of the more consolidated methodologies developed from LCT. It is a flexible technique that can be applied at various scales of a project to assess and quantify the impact of energy and environmental loads through its life cycle. In this case, the life cycle refers to the service life, that is usually shorter than the entire lifespan. LCA concepts started to spread in the mid-1980s to analyze the impact of chemicals under various environmental categories, to identify and remove them at their source. In 1991 the Society of Environmental Toxicology and Chemistry (SETAC) at Vermont, USA, published various guides and advices on LCA simplification and methods.[26]

Later in 1997, LCA was officially defined in the *International Organization for Standardization* in the ISO 14040/44 as "a technique for assessing the environmental aspects and potential impacts associated with a product" [27].

The environmental impact is evaluated on the basis of the macro areas of resources consumption, human health and environmental conservation and it is accomplished by carrying out four phases: goal and scope definition, inventory analysis of the most relevant inputs and outputs, potential impact assessment and finally interpretation of the results considering the objective of the analysis.

The 4 phases represent the various calculation stages of LCA and can be further detailed[28]:

• Phase 1 – **Goal and scope definition**: the aim of the analysis needs to be consistent with the final application of the system and therefore three elements must be identified: functional unit, system definition and system boundaries;

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[26] Ibid.

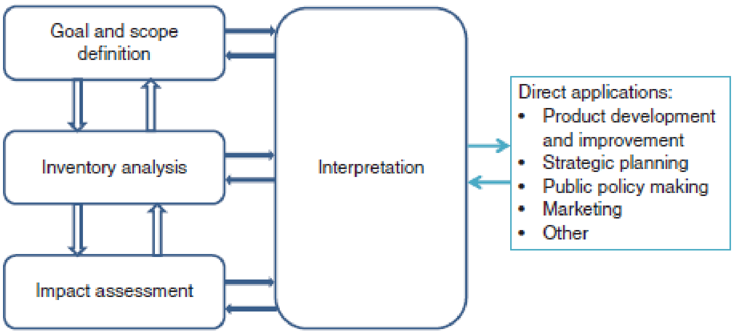
[27] International Organization for Standardization, ISO 14040:2006, *Environmental Management - Life Cycle Assessment - Principles and Framework*, ISO/TC 207/S05, International Organization for Standardization, Geneva, Switzerland, 2006.
International Organization for Standardization, ISO 14044:2006, *Environmental Management - Life Cycle Assessment - Requirements and Guidelines*, ISO/TC 207/S05, International Organization for Standardization, Geneva, Switzerland, 2006.

[28] Sadhukhan J., Ng K. S., Hernandez E. M., *Biorefineries and chemical processes: Design, integration and sustainability analysis*, 2014, Hoboken, Wiley, pp. 93-111.

• Phase 2 – **Inventory analysis**: it identifies stressors that cause environmental impacts at various scales, such as the global impacts, the regional impacts and the local impacts;

• Phase 3 – **Impact assessment**: the data collected in the inventory analysis are used to calculate the Global Warming Potential (GWP) of different environmental impacts by multiplying a flux of an inventory with an impact characterization factor;

• Phase 4 – **Interpretation of results**: the final phase gathers together the results of inventory analysis and impact assessment with the aim of analyzing the system performance and eventually suggest improvements and changes. Results are obtained in the form of numerical scores, allowing the comparison with other technological systems.



LCA study stages.

Source: Sadhukhan J., Ng K. S., Hernandez E. M., *Biorefineries and chemical processes: Design, integration and sustainability analysis*, 2014, Hoboken, Wiley, p. 97.

1.2.4 Life Cycle Costing (LCC)

Life Cycle Costing (LCC) or Life Cycle Cost Analysis (LCCA) is an economic evaluation that allows the calculation of the total cost of a project considering its entire life cycle, from the very early phase of planning and design, until the disposal of the system. The result of this calculation is indeed defined as the Life Cycle Cost.

1.2.4.1. Theoretical and historical overview

While in Europe in the 1960s there was an irregular and fragmented management of the "cost in use" of buildings, in those years the US developed the LCC shared approach as a support to the national Department of Defense for the supply of military equipment. After the energy crisis of 1973 the LCC technique is affirmed in a global way and recognized as the main tool for the technical and economic evaluation of alternatives in the construction sector.

According to the Pennsylvania State University[29], there are two main reasons to carry on an LCC analysis:

1) Different systems or options can be examined to compare the economic advantages/disadvantages;

2) After the analysis, the more convenient solution can be identified.

The methodology framework is illustrated in the ISO 15686[30], that is divided in 11 parts:

• ISO 15686-1 Buildings and constructed assets - Service life planning: Part 1, General principles and framework;

• ISO 15686-2 Buildings and constructed assets - Service life planning: Part 2, Service life prediction procedures;

• ISO 15686-3 Buildings and constructed assets - Service life planning: Part 3, Performance audits and reviews;

• ISO 15686-4 Buildings and constructed assets - Service life planning: Part 4, Service Life Planning using IFC based Building Information Modelling;

• ISO 15686-5.2 Buildings and constructed assets - Service life planning: Part 5, Life-cycle costing;

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[29] The Pennsylvania State University, *Life Cycle Cost Analysis*, in EGEE 102: Energy Conservation and Environmental Protection, 2017, PennState College of Earth and Mineral Sciences. Available online: https://www.eeducation.psu.edu/egee102/node/2036.

[30] International Organization for Standardization, ISO 15686-5:2008, *Buildings and constructed assets - Service-life planning*, *Part 5: Life Cycle Costing*, ISO/TC 59/CS 14, International Organization for Standardization, Geneva, Switzerland, 2008.

• ISO 15686-6 Buildings and constructed assets - Service life planning: Part 6, Procedures for considering environmental impacts;

• ISO 15686-7 Buildings and constructed assets - Service life planning: Part 7, Performance evaluation for feedback of service life data from practice;

• ISO 15686-8 Buildings and constructed assets - Service life planning: Part 8, Reference service-life estimation;

• ISO 15686-9 Buildings and constructed assets - Service life planning: Part 9, Guidance on assessment of service-life data;

• ISO 15686-10 Buildings and constructed assets - Service life planning: Part 10, When to assess functional performance;

• ISO 15686-11 Buildings and constructed assets - Service life planning: Part 11, Terminology.

According to these standards, the literature sums up the application fields in which the LCC calculation operates[31]:

• Decision-making and resources allocation to understand if a new construction or a restructuring activity is more convenient in terms of performance;

• Economic benefits evaluation by orienting the choice not only towards the initial capital invested for maintenance and management;

• Individual cases analysis when selecting qualitative parameters;

• Development of a verification process to check the project's feasibility and the budget schedules specifically concerning the intervention on an existing asset;

• Orientation of maintenance choices on global cost in a strategic way;

• Support of planning, construction and operational cost control activities during the building's life cycle;

[31] Langdon D., *Life Cycle Costing (LCC) as a contribution to sustainable construction: a common methodology – Final methodology*, 2007, Available online: http://ec.europa.eu/enterprise/sectors/construction/studies/life-cycle-costing_en.htm.

• Formulation of effective solutions related to the project services;

• Facilitated comparison between alternatives thanks to the "economic efficiency index", an indicator that calculates the economic performance of a specific project solution.

In the case of building or infrastructure projects, the mathematical model for the LCC can be expressed as follows, taking into consideration only the relevant costs in the sector[32]:

$$LCC = \sum_{t=0}^{N} \frac{C_t}{(1+r)^t}$$

Where:
Ct = sum of relevant costs;
N = n. of years of the period considered;
r = discount rate
The formula can be further detailed for the evaluation of building projects, in order to distinguish between investment, operational and maintenance costs[33]:

$$LCC = C_i + \sum_{t=0}^{N} \frac{C_o + C_m}{(1+r)^t} \pm V_r \left(\frac{1}{(1+r)^N}\right)$$

Where:
Ci = investment cost;
Co = operational cost;
Cm = maintenance cost;
t = year when the cost is incurred;
N = n. of years of the period considered;

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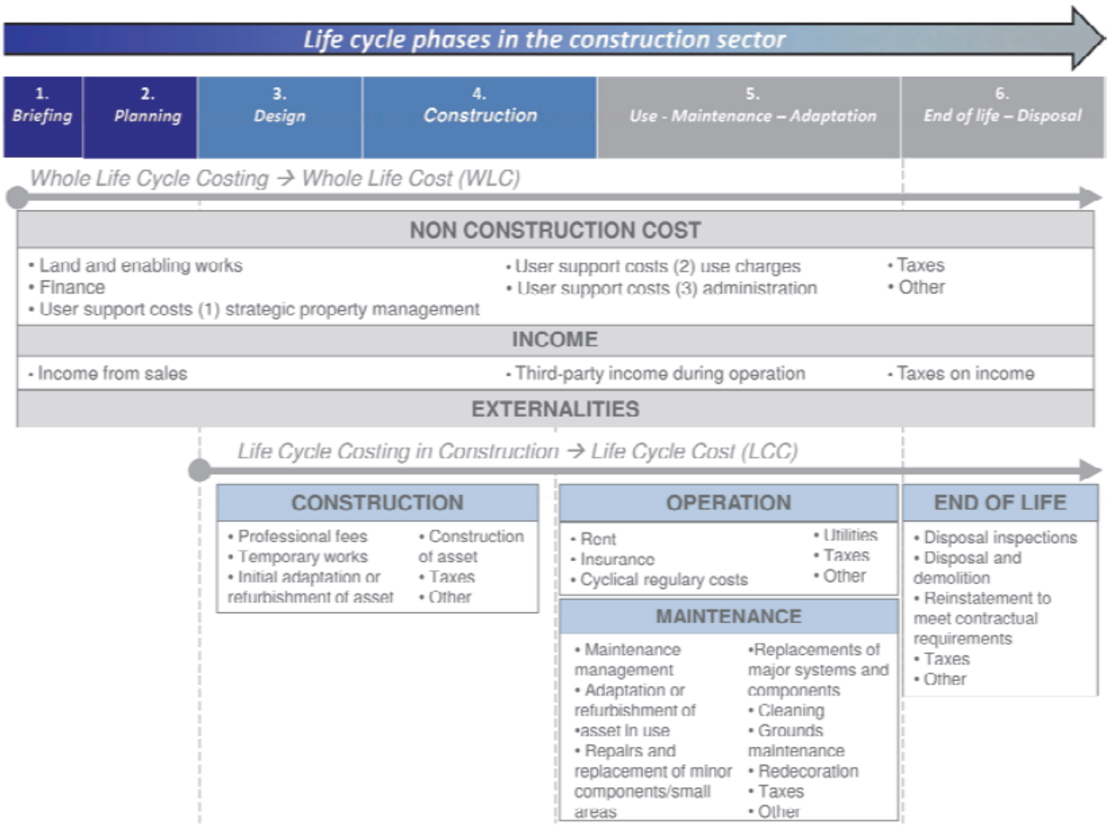
32 Fregonara, op. cit., p. 80

33 Fregonara, op. cit., p. 80

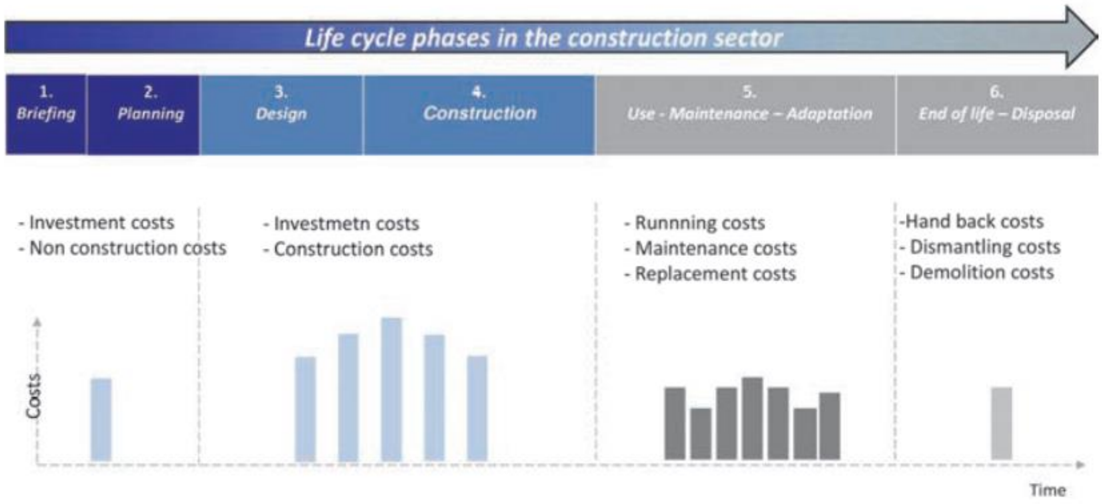
r = discount rate;

Vr = residual value of the asset, materials or components

The following images graphically represent the distribution of costs in the life cycle phases, from the briefing phase to the end of life and disposal. The relevant costs are made up of direct costs of construction, maintenance and dismantling and indirect costs such as non-construction costs, incomes and externalities.



Categories and cost entries for the LCC analysis and their distribution over the life cycle of a building. Source: Fregonara E., *Evaluation Sustainability Design. Life Cycle Thinking and international orientations.*, Milano, FrancoAngeli, 2017, p. 85.



Relevant Costs for LCC analysis and their distribution over the building's life cycle.

Source: Fregonara E., *Evaluation Sustainability Design. Life Cycle Thinking and international orientations.*, Milano, FrancoAngeli, 2017, p. 85.

1.2.4.2. Methodological aspects

The potentiality of LCC is today consolidated at an international level as a particularly useful tool in the early design phase, allowing a precocious choice between alternative products and solutions and limiting the cost of a possible redesigning.

The most valuable research project on LCC definition is the 2007 Report by Davis Langdon[34], that provides an analysis and evaluation of the different national approaches and elaborates in detail 15 operative steps for the estimation of LCC and related indicators. This practical guidance approaches the project evaluation from the initial appraisal up to the completion, until the disposal of the asset, supporting both private and public sectors.

The 15 steps represent some fundamental passages and they can be summed up as follows[35]:

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[34] Langdon, op. cit.

[35] Ibid.

Step 1: identification of the main purpose of LCC analysis;

Step 2: identification of the initial purpose;

Step 3: identification of the relationship between LCC and sustainability analysis;

Step 4: identification of the analysis period and economic evaluation methods: this allows to operate with cost-related amounts at different time frames; for example, when dealing with periods longer than one year, it is necessary to take into account the discount operation. By relying on the widespread literature, discount rates are usually selected in the range between 3-5%, but when it comes to construction assets with long service life, it is advisable to apply LCC with real costs and discount rates. The net discounted value of the asset is represented by the Net Present Value (NPV), calculated with the following formula:

$$NPV = \sum_{t=0}^{N} \frac{C_t}{(1+r)^t}$$

Where:
NPV = net discounted value;
Ct = total of relevant costs;
N = number of years considered in the life span;
r = discount rate

Step 5: identification of the necessary supplementary analysis: according to the complexity of the project, risks may be treated in a more careful way. They usually take the form of a surplus on the total predicted cost or a variance between the effective cost at a certain time compared to those forecasted. The classic activities to manage risk are:

- Risk identification;
- Risk estimate in terms of probability and potential impact;
- Measures to avoid or mitigate the risk.

There are a variety of operative techniques for the evaluation of risk and they are divided in two main categories:
1) Qualitative techniques that need subjective procedures sustained by knowledge and previous experiences; among these we recognize risk matrices, interviews, brainstorming, risk registers;
2) Quantitative techniques based on mathematical principles, among which we identify deterministic approaches (Sensitivity analysis, Scenarios analysis) and more precise probabilistic approaches (simulation models, numerical methods).

Step 6: identification of the requisites of the asset and project;

Step 7: identification of necessary options and cost items to include in the LCC analysis;

Step 8: cost and scheduled data collection to be used in the LCC analysis;

Step 9: verification of financial parameters and period of analysis;

Step 10 (optional): risk strategies review and production of a preliminary analysis of risk and uncertainty;

Step 11: economic evaluation plan: it is accomplished with the support of software tools referring to all previously collected data. It involves data entry activities, life cycle cost calculations and analysis of the results and it can be applied by using different parameters:
• Net Present Value (NPV) indicator to compare the results with a base case or support the different options;
• Payback Period (PBP) indicator, simple or discounted, that must be lower than the service life of the asset to note the option cost-effectiveness;

$$SPB = \frac{O_i}{R_{my}}$$

Where:
SPB = Simple Payback Period (non-discounted version);

Oi = initial outlays of the investment;

Rmy = mean yearly revenue

$$DPB = F + \frac{A}{NO}$$

Where:

DPB = Discounted Payback Period;

F = last period where the value of cumulative discounted cash flow is negative;

A = absolute value of the cumulative discounted cash flow;

NO = value of the non-cumulative cash flow;

• Net Savings (NS) and Net Benefits (NB) ratio, that must be positive to accept the selected option;

• Net Savings (NS) indicator to put in order of preference the alternatives;

$$NS = LCCBC - LCCA$$

Where:

LCCBC = LCC of a base case;

LCCA = LCC of a project alternative

• Savings to Investment Ratio (SIR) indicator based on options that can be put in order of preference and can be selected or rejected;

$$SIR = \frac{O_s}{A_i}$$

Where:

Os = operational savings;

Ai = additional investment costs;

• Adjusted Internal Rate of Return (AIRR) indicator based, as for the SIR, on options that can be put in order of preference and can be selected or rejected.

$$AIRR = (1+r)(SIR)^{\frac{1}{N}} - 1$$

Indicators	Aims	Acceptability conditions
NPV	To compare/select alternative options through the evaluation of Life Cycle Costs	The lowest cost possible
	Sort out alternatives on the basis of cost-effectiveness principles	The lowest possible
	To identify the best alternative (cost-effectiveness)	The lowest possible
	To check the acceptability of an alternative in economic terms based on relevant cost elements (LCC comparison of an option with a base case)	The lowest possible
NPC	To accept/reject project alternatives (eg. traditional orbital vents vs. bentatial fixtures)	The lowest possible
	To select more convenient systems/ installations (eg heating / cooling systems)	The lowest possible
	To select optimal or convenient combinations of independent systems (alternative packets involving wrap, implants, etc.)	The lowest possible
NS/ NB	To accept / reject design alternatives based on a cost-effective principle	Acceptable (cost-effectve) if > 0 Rejectable if < 0
NS	To evaluate a single option, to sort out preferences of alternative solutions based on the lowest lifecycle cost	The highest possible
	To select more convenient systems / installations	The highest possible
	To select optimal or convenient combinations of independent systems	The highest possible
PBP (SPB/DPB)	To accept / reject a design solution based on a somewhat effective principle	Lower than the service life of the asset
SIR	To accept / reject project solutions	> 1
	To order / select alternative options	Sorting for increasing SIR values
AIRR	To accept / reject project solutions	> r (discount rate applied)
	To order / select alternative options	Sorting for increasing AIRR values

Summary table of economic evaluation measures: synthetic indicators, relative aims and acceptability conditions.

Source: Fregonara E., *Evaluation Sustainability Design. Life Cycle Thinking and international orientations.*, Milano, FrancoAngeli, 2017, p. 94.

Step 12 (optional): application of the detailed risk/uncertainty analysis;

Step 13 (optional): application of the Sensitivity analysis;

Step 14: interpretation and presentation of initial results;

Step 15: presentation of the results in the final report.

1.3 Cost-Benefit Analysis (CBA): a consolidated model

In general, Cost-Benefit Analysis (CBA) is one of the most consolidated models to analyze a project or policy in order to establish, whether it is, or it will be, a good investment. By determining a set of simplified assumptions, CBA is a support tool for decision-making in the public sector. More specifically and as defined by Fregonara, "CBA is one of the evaluation techniques for testing the feasibility of intervention projects on public assets/resources (architectural, cultural, environmental). It is based on economic-quantitative criteria to measure the "economic value of a project" according to which to accept/exclude alternative project options." [36]

1.3.1 Theoretical and historical overview

To better understand how CBA works, it is useful to take a step back at its origins. An important number of literature surveys have been published in the past 40-50 years, including more and more health and environmental issues as fundamental aspects of the analysis.

In one of its research reports, Arler[37] presents the CBA historical background, from the roots until today's developments:

The earliest references date back to 1708, when the French Abbé de Saint Pierre studied in detail the importance of public roads improvement.

More methodological procedures were developed at the beginning of the XIX century by a group of engineers at the École Nationale des Ponts et Chaussées in France. In general, the XIX century marked a more systematic attitude of economists and philosophers towards the "welfare economics" definition, that would later become the Cost-Benefit Analysis.

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[36] Fregonara E., *A life cycle perspective for infrastructure management*, in *"Aestimum"*, 2020, DOI: 10.13128/aestim-8449, p. 3.

[37] Arler F., *Ethics and Cost-Benefit Analysis*, Denmark, Aalborg University, Technology, Environment and Society, Department of Development and Planning, 2006, research report, n. 4.

The first regulated application of CBA occurred in 1936 in the U.S. with the Flood Control Act, requiring that the expected benefits deriving from flood control project should exceed their realization costs. After this significant push, the standard for application of CBA in assessment of public investments, were summed up in 1950 in the so called "Green Book"[38].
Cost-benefit analysis was officially recognized as a basic tool in U.S. federal planning in 1981, when President Reagan signed the Executive Order 12291, requiring the federal regulatory agencies to use as an integral part of their procedures the CBA approach.
But within a few years, the credibility of CBA began to falter, due to the lack of attention given to the impact of both positive and negative externalities.

For this reason, in the last decades the U.S. EPA funded more than 450 studies to measure these impacts and particularly the environmental costs and benefits.
One can distinguish between private and public application of CBA. For the first one, the only significant perspectives are the ones of the private company or the consumer. Since we are dealing with infrastructure management issues, the meaningful point of view is public at large, for which all interests are relevant and different scales can be taken into consideration. Therefore, the transition from financial to economic analysis must be performed. The main difference between the analysis is that while in the financial one the focus is on the subject in charge of project realization and management, the economic one is carried out according to the community's needs.

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[38] Subcommittee on Benefits and Costs, *Proposed Practices for Economic Analysis of River Basin Projects*, report to the Federal Inter-Agency River Basin Committee, Washington D.C., 1950.

1.3.2 Methodological aspects

Before proceeding with the description of the main steps that make up the analysis, it is important to take a quick look at the most common contexts in which the CBA proves to be particularly useful, defined by Arler in His research report[39]:

• When the market is not able to provide a series of goods without public interference, as in the case of basic infrastructures;

• In case of economic regression, when public projects can give a boost to the market condition;

• When the market is not able to provide a series of goods without public interference, as in the case of basic infrastructures;

• When the externalities are not registered on the market, as in the case of future environmental and health consequences.

The basic principle for the application of the methodology is to compare a scenario including the realization of a project or policy, with a scenario without the project / policy or presenting an alternative. The chosen scenario will be the one which proves to be the most convenient from an economic point of view, by estimating present and future costs and benefits. The heart of the matter is that a project or policy must constitute a substantial improvement to the preexisting condition.
In the next lines the typical 8 steps of Cost-Benefit Analysis will be resumed; apart from minor variation, this is the widespread procedure accepted by the most important research projects on the topic[40]:

Step 1 – Identification of the market failure and solutions seeking: market failures basically represent the standard problem that justifies public actions; the next step

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[39] Arler, op. cit.

[40] Campen J.T., *Benefit, cost, and beyond: the political economy of benefit-cost analysis*, 1986, Cambridge, Massachusetts.
Boardman A.E., Greenberg D.H., Vining A.R., Weimer D.L., *Cost-Benefit Analysis: Concept and Practice*, 2006, 3rd edition, Prentice Hall, Upper Saddle River, New Jersey.

is to find the most convenient project or policy to solve the problem, and policies are usually preferable to projects due to their more comprehensive nature;

Step 2 – Definition and delimitation of impact analysis: in this step all significant impacts must be taken into consideration, and the critical aspect is to establish which are the most significant impacts to include in the analysis and how far in space and time they must be developed. Of course, there is no single answer to this issue and final choice is usually determined by interests with a greater impact and / or by an ethical question;

Step 3 – Description of the impact: impacts should, whenever possible, described as marketable goods, specifically in monetary terms. Otherwise, the assignment of a quantified value becomes difficult to assess and the reliability of the analysis can be damaged;

Step 4 – Setting of economic values to the selected impacts: as mentioned in the previous step, the best way to compare the various kinds of costs and benefits is to monetize their value. Luckily, many values can be directly measured on the market, such as labor costs, building materials, land, equipment, office facilities, etc., but of course inflation can have a decisive impact on price fluctuations. The most convenient way to measure costs and benefits is to conceive them as lost or gained consumer goods and let opportunity costs match marginal costs;

Step 5 – Discounting according to time to find present values: usually, CBA assumes that future costs and benefits will have a minor influence than present ones. For this reason, they are discounted or transformed in the so-called Net Present Value (NPV) by the Discount Factor (*Rd*):

$$R_d = \frac{1}{(1+r)^t}$$

Where:

r = discount rate

t = time index from project beginning

The choice of the discount rate is extremely important for the final output; the right value is usually defined as the interest rate of the best private investment. In the case of public investments, the discount rate is typically between 1-3 % per year, but it may vary significantly for each country and it can grow in periods of rapid economic growth or decrease in periods of recession.

Step 6 – Aggregation of costs and benefits: this passage is quite simple if all costs and benefits are valued in monetary terms, since once all the values are collected it is possible to understand the profitability of the various options. The aggregation becomes complex if there is not a unified monetary term for all the variables. In this case, mixing different tools in according with the standards is recommended.

Step 7 – Conduction of sensitivity tests: towards the end of the calculation, it is necessary to highlight the controversy and possible risks related to the options selected. A list of typical controversial issues is detailed below:

- Injuries, health problems and losses of human lives;
- Losses of non-human species or other non-marketed environmental goods;
- Discounting future impacts;
- Dealing with risks and uncertainty in order to quantify them;
- Including interests;
- Including alternative scenarios;
- Question of equity for impacts distribution.

Step 8 – Comparison and ranking of outcomes: at the end of the evaluation, projects and policies that present a positive NPV, meaning potential benefits, should be ranked in accordance to their benefit-cost ratio, and the ones with the highest ratio should be implemented.

1.4 Life Cycle Cost Benefit Analysis (LCCBA): a circular perspective

This section focuses on rethinking specific consolidated and well-known socio-economic evaluation tools, according to life cycle principles. The issue of public infrastructure maintenance is a complex challenge, that needs specific attention on costs and benefits of long-term investments: for this reason, it is assumed as a reasoning context.

To achieve this, the Life-Cycle Cost-Benefit Analysis (LCCBA) methodology is proposed. An innovative operating process is investigated, by integrating this little explored approach with the long-established CBA, focusing on the use-maintenance-adaptation phase of public infrastructures.

As detailed above, the two main approaches for the economic evaluation of projects sustainability in the construction sector are the Cost-Benefit Analysis (CBA) and the Life Cycle Cost Analysis (LCCA). These two methodologies are today applied with success and accuracy. While the LCCA is often limited to the private sector, the application field of the CBA is the public one. The LCC analysis mainly allows the assessment of infrastructure condition in the residual lifespan, including estimated maintenance and failure costs. Two essential variables remain excluded from this analysis: user costs and benefits and the environmental costs and benefits. The social and environmental factors represent indeed a significative impact on the final calculation output, but since their quantification is complex and characterized by uncertainty, they are usually neglected. On the other hand, due to the complexity given by the numerous variables and stakeholders involved in the management plans of public buildings and infrastructures, in most cases the traditional CBA models are not sufficiently precise since a number of influential factors are left out from the analysis. If all the factors are taken into consideration, the operative modality could manage to establish the optimal maintenance investment planning, but the process is very time expensive.

On this basis, at the Aalborg University in Denmark, the PhD Professor Thoft-Christensen, conducted a research on further developments and improvements of the existing calculation methodologies starting from 2004 until present days[41]. A synthesis of the assumptions is resumed by one of Fregonara's latest works[42]:

• **LC** – Life Cycle Analysis: simple assessment of the infrastructure condition in the residual lifespan;

• **LCC** – Life Cycle Costing or Life Cycle Cost Analysis: LC Analysis with estimated maintenance and failure costs in addition;

• **LCCBA** – Life Cycle Cost Benefit Analysis: LCC analysis taking into consideration also user and environmental costs and benefits;

What this synthesis reveals is that the LCCB Analysis is basically an "extended LCC analysis" that includes social and environmental externalities.

1.4.1 LCCBA methodological background

Life-Cycle Cost-Benefit Analysis (LCCBA) refers in general to an informal approach for decision-making that helps to appraise or assess the feasibility and convenience of projects or proposals. It is traditionally intended as a formulation that estimates expected advantages of a project or intervention, that are used as a decision tool. The traditional formulation is quite well-established thanks to its robust theoretical and scientific background, but it presents some criticalities related to its application on major public infrastructures. The revised LCCB analysis has so far been little explored in literature; the following sections are then a reworking of the pioneering studies of the above-mentioned PhD Professor Thoft-Christensen of the Aalborg University.

[41] Thoft-Christensen P., [2004, 2006, 2008, 2009, 2012].

[42] Fregonara E., *A life cycle perspective for infrastructure management*, in *"Aestimum"*, 2020, DOI: 10.13128/aestim-8449.

1.4.1.1 Basic notions of economics for LCCBA development

According to Thoft-Christensen[43], the LCCB analysis is based on the three basic disciplines of engineering knowledge, economic understanding and mathematical experience.

Going backwards to the origin of these disciplines, the fundamental work of three famous scientists must be presented.

• **Jules Dupuit** (1804-1866) was the first to scientifically apply the LC-CB analysis. After moving from Italy to France at the age of ten, Dupuit education started at Versailles and continued at the École Polytechnique of Paris, where he graduated as civil engineer. After some important works on the French road systems and flood management, he introduced in 1844 the so-called "demand curve". The model assumes that the consumer is originally in equilibrium when the price of water is at *p1* and the quantity taken is *q1*. Figuring that the price of water falls to *p2*, at the lower price for water the individual is in disequilibrium at point *c*. So, "the marginal utility of the last unit of the consumer's existing stock is greater than the now-lower marginal utility of water represented by the lower price. In terms of price, what the consumer would pay for *q1* of water is greater than the price he must pay for quantity *q1*. The same quantity of water (*q1*) could be bought at a lower total expenditure, but Dupuit assumes that the consumer would not do this."[44]

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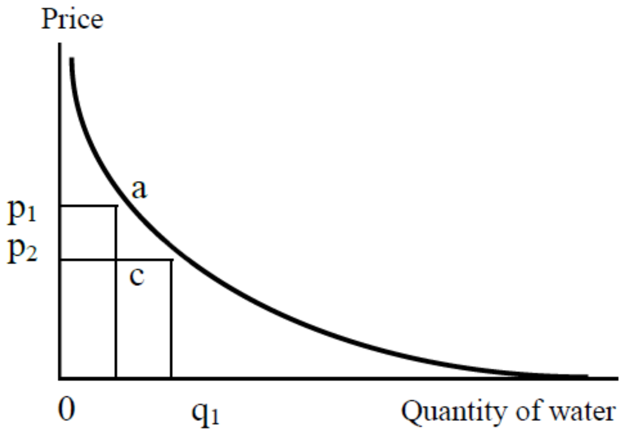
[43] Thoft-Christensen P., *Life-Cycle Cost-Benefit Analysis. Present and in the future.*, in *"ISRERM 2010. Reliability Engineering and Risk Management: Proceedings of the International Symposium on Reliability Engineering and Risk Management",* 2010, pp. 57-67.

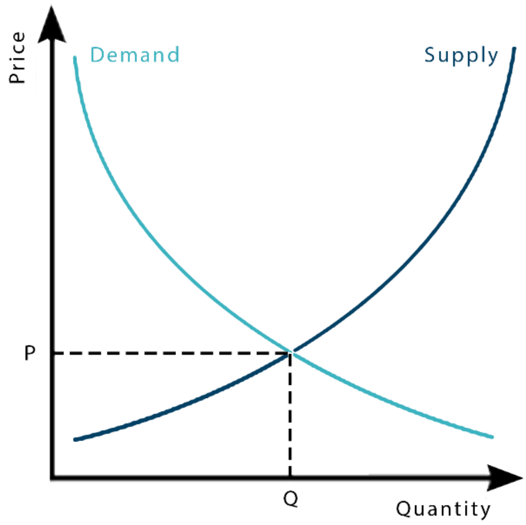
[44] Ibid., p. 58.



Demand curve by Jules Dupuit.

Source: Thoft-Christensen P., *Life-Cycle Cost-Benefit Analysis. Present and in the future.*, in *"ISRERM 2010. Reliability Engineering and Risk Management: Proceedings of the International Symposium on Reliability Engineering and Risk Management"*, 2010, p. 58.

• The second essential contribution to the LCCBA development is illustrated in **Alfred Marshall**'s masterpiece *"The Principles of Economics"*[45], published in 1890. Born in London and founder of the Cambridge School of Economics, Marshall specialized in the Microeconomics field. In his main book he introduced the concept that the price and output of a good are defined by supply and demand. Graphically, the two curves are like scissor blades that intersect at the equilibrium point.



Marshall's supply and demand curve.

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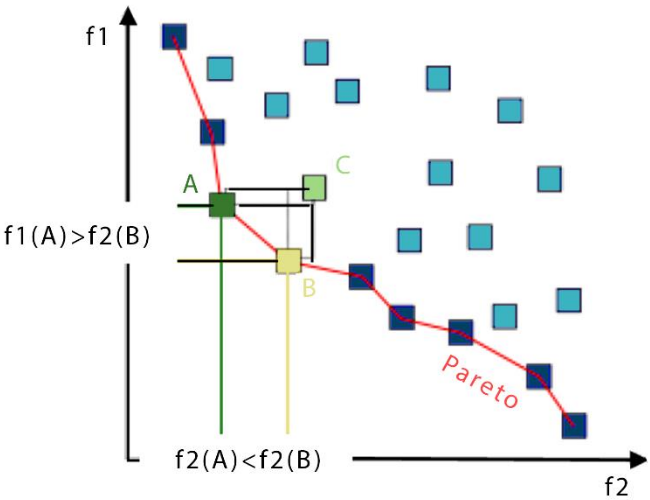
[45] Marshall A., *The Principles of Economics*, 2004, Digireads.com Publishing.

Source: Author's re-elaboration from https://en.wikipedia.org/wiki/ Supply_and_demand

• Later, the Italian industrialist, economist, philosopher and sociologist **Vilfredo Pareto**, conducted extensive studies on income distribution contribution to economics and on examining individual's choices. The so-called "Pareto optimization" shows that "the allocation of resources is achieved when it is not possible to make anyone better off without making someone else worse off"[46]. Given a set of options, the Pareto frontier or Pareto set represents the set of choices that are "Pareto efficient". In the figure below the Pareto frontier is shown, as well as the feasible choices represented by boxed points. Points A and B both lie on the frontier, while point C is dominated by point A and B and therefore it falls outside the Pareto set.



Pareto optimization.

Source: Thoft-Christensen P., *Life-Cycle Cost-Benefit Analysis. Present and in the future.*, in *"ISRERM 2010. Reliability Engineering and Risk Management: Proceedings of the International Symposium on Reliability Engineering and Risk Management"*, 2010, p. 59.

With these premises, the LCCB analysis represents a process that weights the total expected costs against the total expected benefits of one or more actions, in order to

[46] Thoft-Christensen, op. cit., p. 59.

allow the choice of the most convenient alternative. Costs and benefits are usually expressed in monetary terms and adjusted referring to their "present value".

1.4.1.2 Traditional formulation uses and limitations

Developed on this solid scientific basis, the traditional LCCBA formulation is summed up by Thoft-Christensen[47] as:

Expected Advantage = Expected Benefits – Expected Costs

This simple model can be applied to a series of cases:

- To compare a small number of bridges/small infrastructures proposals;
- To decide whether there is the need of replacements or reparations;
- To plan a maintenance strategy for a set of bridges/small infrastructures;
- When reliable data are not available.

In the basic formulation, expected benefits and expected costs are calculated considering the whole life cycle of the project and they are expressed as follows:

Expected Benefits (LCCB) = Bowner + Buser + Bsociety + Benvironment

Expected Costs (LCC) = Cowner + Cuser + Csociety + Cenvironment

Of course, these four components are represented by expected values that present a certain level of uncertainty. The main limitation of this traditional formulation is that, as specified before, environmental and user costs/benefits are particularly difficult to assess, but they can completely dominate the total cost and therefore they can't be neglected. On one hand environmental costs/benefits are increasingly considered through some defined aspects:

- CO_2 or other emissions released in the environment;

[47] Thoft-Christensen, op. cit., p. 59.

• Waste production, consumption, recycling and disposal;• Other impactful items such as traffic delays, time lost, disruptions, etc.

On the other hand, the issue of user costs and benefits represents a more insidious and complex topic.

1.4.1.3 The relevance of user costs and benefits in infrastructure management

As Thoft-Christensen continues to underline in His research[48], user costs and benefits are often mentioned in literature, but they are usually not included in optimal maintenance strategies. This causes a disregard towards the long-term effects of decisions and a lack of acceptance of political decisions by the community. The complexity of this topic is evident, mainly because user costs should be modelled by stochastic variables. However, a deterministic model based on statistic data could be a good starting point for approaching the subject.

In the same research by Thoft-Christensen, a number of cases from previously published reports demonstrate the importance of estimating user costs when infrastructure maintenance is planned. All these cases prove the strong impact of this cost category, that can may come to be ten times higher than the total repair costs.

• Technical report *"Corrosion cost and preventive strategies in the USA"*[49]: in this case, user costs are estimated on the basis of traffic delays and lost productivity, that cause losses in terms of money ten times higher than the estimated direct cost of maintenance, repair and rehabilitation of the infrastructure.

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[48] Thoft-Christensen P., *Life-Cycle Cost-Benefit Analysis of Bridges from a User and Social point of view*, in *"Structure and Infrastructure Engineering"*, 2009, Vol. 5, pp. 39-47.

[49] Kock, H.K., Brongers, M.P.H., Thompson, N.G., Virmani, Y.P., Payer, J.H., *Corrosion Cost and Preventive Strategies in the United States*, 2001, Report R315-01, CC Technologies Laboratories, Dublin, OH, USA and NACE Int., Houston, TX, USA. Available online: www.corrosioncost.com.

• Technical report *"Development of road user cost methods"*[50]: the project, sponsored by the Texas Department of Transportation, defines the "Road User Cost" (RUC) as the estimated daily cost to the public caused by the construction work of a road being performed. This means higher travel time due to rerouting, reduced road capacity and delays in the new facility. The RUC is expressed through the sum of three variables:

$$RUC = VOC + AC + VOT$$

Where:

VOC = Vehicle Operating Costs (fuel, engine oil, tires, maintenance and depreciation);

AC = Accidental Costs (fatal accidents, non-fatal accidents, property damage accidents);

VOT = Value of Time, function of the hourly wage rate. In most cases it represents the most influential component and it can be quite variable due to inflation.

• Technical report *"Development of user cost data for Florida's bridge management system"*[51]: the study states that "An analysis of the Pontis user cost model found that it was overly sensitive to extremes of roadway width, yielding unrealistic high benefit estimates. A new model was developed using Florida data on bridge characteristics and traffic accidents. The new model has superior behavior and statistical characteristics on a full inventory of state highway bridges. The user cost model developed in this study is an important part of the system's ability to measure the economic benefits of bridge investments."

[50] Daniels, P.E., Ellis, D.R., Stockton, W.R., *Techniques for Manual Estimation Road User Costs Associated with Construction Projects*, 1999, Texas Transportation Institute, Texas, USA, p. 602.

[51] Thompson, P.D., Najafi, F.T, Soares, R., Choung, H.J., *Development of User Cost Data for Florida's Bridge Management System*, 1999, Report 4910-4505-606-12, University of Florida, USA.

• Research report *"The cost of Construction delays and Traffic Control for Life-Cycle Cost Analysis of Pavements"*[52]: here it is specified that the Vehicle Operating Costs (VOC) vary with speed causing a difference also in typical fatality ranges.

• Research report *"Strategic review of bridge maintenance costs"*[53]: this review emphasizes the consequences for the society of delaying important maintenance of bridges, showing that the cumulated effects of underfunding infrastructures will become unacceptable from a social and economic point of view.

The main conclusion is a reconfirmation that an LCC based analysis is insufficient in the case of infrastructure management. Therefore, a further development of the traditional LCCBA formulation is necessary and more suitable to analyze the complex field of user cost in a satisfactory manner.

1.4.2 Towards a LCCBA hybrid formulation

With these premises, the traditional LCCBA and any implementation of the model, may be performed by three main different approaches, as illustrated by Thoft-Christensen[54]:

Level 3 – Scientific level: it is the most advanced approach, based on consistent scientific basis; it is very expensive and for this reason it is typically used in the design of new major infrastructures;

Level 2 – Engineering level: it is the average level, based on engineering simplifications on material deterioration and maintenance; it is mainly used for the design of new infrastructures or to estimate the deterioration of existing ones;

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52 Rister, B.W., Graves, C., *The Cost of Construction Delays and Traffic Control for Life-Cycle Cost Analysis of Pavements*, 2002, Research report KTC-02-07/SPR197-99 & SPR218-00-1F, Kentucky Transportation Center, University of Kentucky, Lexington, Kentucky.

53 Maunsell Ltd., *Strategic Review of Bridge Maintenance Costs*, 1999, Report on 1998 review, HA project 980532/10.

54 Thoft-Christensen, op.cit.

Level 1 – Technical level: it is the most simplified level, based on existing experience and direct observation; the limitation is that it can be applied to a restricted number of parameters.

According to Thoft-Christensen[55], the EU sponsored LCCB infrastructure management system is typically based on the level 2 mode.

Circular Economy and Life Cycle Thinking principles allow to treat the impact of projects over time, and this is a fundamental aspect of the LCCBA. Relying on these preconceptions, Fregonara rewrites the traditional LCCBA equation transforming the model into a "hybrid procedure"[56]. Let's proceed by grade:

The traditional formula (as presented in Thoft-Christensen research[57]):

$$LCCBA = LCCB - LCC$$

Can be rewritten as:

$$LCCBA = \left(B_{society} + B_{owner} + B_{user} + B_{environment}\right) - \left(C_{society} + C_{owner} + C_{user} + C_{environment}\right)$$

As detailed before, the fundamental difference that must be taken into consideration between an LCCA and the extended methodology of LCCBA is the presence of positive and negative impacts on users and environment. Following this principle and the formula above, in the LCCBA the Net Present Value (NPV) equation can be rewritten as:

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[55] Thoft-Christensen P., *Life-Cycle Cost-Benefit Analysis of Bridges from a User and Social point of view*, in *"Structure and Infrastructure Engineering"*, 2009, Vol. 5, pp. 39-47.

[56] Fregonara E., *A life cycle perspective for infrastructure management*, in *"Aestimum"*, 2020, DOI: 10.13128/aestim-8449, p. 8.

[57] Thoft-Christensen, op.cit.

$$NPV = \left(\sum_{t=0}^{N} \frac{B_{p\ society} + B_{p\ owner} + B_{p\ user} + B_{p\ environment}}{(1+r)^t} - \sum_{t=0}^{N} \frac{C_{p\ society} + C_{p\ owner} + C_{p\ user} + C_{p\ environment}}{(1+r)^t} \right) - \left(\sum_{t=0}^{N} \frac{B_{wp\ society} + B_{wp\ owner} + B_{wp\ user} + B_{wp\ environment}}{(1+r)^t} - \sum_{t=0}^{N} \frac{C_{wp\ society} + C_{wp\ owner} + C_{wp\ user} + C_{wp\ environment}}{(1+r)^t} \right)$$

This last formula can be summed up into:

$$NPV = C_i + \sum_J \left(\sum_{t=0}^{N} NB_{souep} \cdot \frac{1}{(1+r)^t} \right) - \sum_J \left(\sum_{t=0}^{N} NB_{souewp} \cdot \frac{1}{(1+r)^t} \right) - V_{fT}(J)$$

This final formula represents the "hybrid procedure" that integrates the original NPV formula with CBA and LCC analysis. Once the positivity of NPV is verified, the preferability of the alternatives is ranked from the highest NPV value to the lowest one. Since this kind of evaluation aims at analyzing the use-maintenance-adaptation phase, the initial investment costs are discarded from the formula and substituted with a repair investment at some point in the asset lifetime.

This procedure provides minor changes to the traditional LCCBA formulation, but it introduces new potentialities for a correct and convenient infrastructure management.

Chapter 2

Potential applicative framework

After an introduction on the theoretical and methodological context of this research, this chapter focuses on a potential applicative framework of the previously described approaches. The following sections will focus on their management through the years and particular attention will be given to their social value and impact. Afterwards, the research will arrive to the core of the financial methodologies application context, the development of a "soft" mobility, related to the need of a shift towards a more sustainable mobility. The EU situation in terms of policies will be presented, mentioning high-profile examples and the Italian degree of awareness and involvement. The benefits of "soft" mobility systems based on cycle infrastructures will be stressed, displaying their importance not only in the cities but also for the development of cycle tourism and for the rediscovery of remote territories. This set of information will conclude the theoretical application framework to give space to the presentation of the evaluation of cycle paths' economic sustainability.

2.1 Focus: The Case of Infrastructures

After the Second World War, a consistent part of buildings and infrastructures in Europe were destroyed or severely damaged, and countries faced the challenge to rebuild the society and respond to its basic needs, from agriculture and factories, to infrastructures and homes[58]. The greatest peak of this construction boom occurred between the 1960s and the 1970s and still today those buildings and infrastructures are a part of our cities network.

[58] Hertogh, M. J. C. M., *Connect and Renew*, Inaugural Speech, Delft University of Technology, 2013.

2.1.1 The issue of public infrastructure management in Europe and Italy

In the forthcoming years, many of both major and minor infrastructures in Europe will reach the end of their "technical, economical or functional lifespan"[59]. Therefore, the main challenge for asset managers is to determine replacement and renovation budgets in order to ensure the current functionalities and allow the opportunity to improve or adapt the existing network to users' evolving demand. This means that there is the need to invest in an efficient way on strategies and management plans, dealing with both the technical and functional aspects of infrastructures can give added value not only to asset managers, but also to users, enterprises, stakeholders and of course to the whole society.

The Italian situation is aligned with most of the other European countries, with half of the infrastructure stock built before the 1960s and a weak maintenance culture. Strategic maintenance activities are assuming growing importance in investment choices in the current economic context.[60] For this reason, the multidisciplinary approach of "optimal maintenance planning" needs to be deeply explored and applied to our infrastructure networks. Of course, a correct management of infrastructures requires balanced considerations of both the structure performance and safety and the total cost during its life cycle. The main issue is that maintenance systems are often developed aiming at life-cycle cost minimization and the result is that the solutions are usually not acceptable in the long term. Another problem is that the condition state of infrastructures is commonly checked by means of visual inspection, neglecting the real safety level[61].

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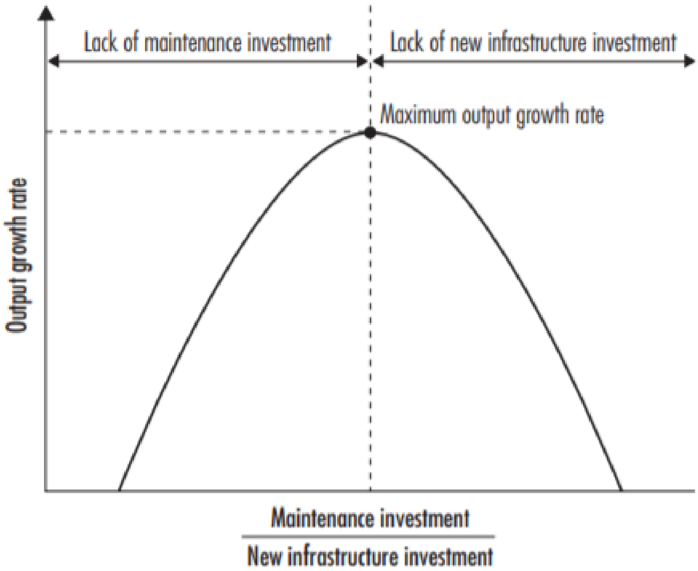
[59] Hertogh M. J.C.M., Jaap D. B., Van der Vlist M. J., Barneveld A. S., *Organization, Technology and Management in Construction*, 2018, Zagreb, vol. 10, fasc. 1., DOI: 10.2478/otmcj-2018-0005.

[60] Ibid.

[61] Frangopol D.M., Liu M., *Maintenance and Management of Civil Infrastructure based on Condition, Safety, Optimization and Life-Cycle Cost*, in *"Structure and Infrastructure Engineering"*, 2007, 3:1, pp. 29-41. DOI: 10.1080/15732470500253164.

The economist Rioja[62] showed in one of its surveys several aspects of infrastructure maintenance. First, its main role within standard growth models by reducing the depreciation of infrastructures, demonstrating that an optimal expenditures management can increase a country's growth rate.



Relationship Between Growth and the Ratio of Maintenance to New Investment.
Source: Rioja F., *What is the value of Infrastructure Maintenance? A survey*, in *"Infrastructure and Land Policies"*, 2013, Lincoln Institute of Land Policy, Cambridge, MA, USA, Vol. 13, pp. 347-365.

Then, the rates of return for maintenance were found evenly high, after a survey of the economic rates of return (ERR) of different countries. Finally, empirical studies stated that maintenance can have an influential and positive impact on productivity and economic growth of a country.

2.1.2 Technical, economic and functional lifespan

When referring to infrastructure lifespan, it is necessary to make a distinction between different kinds of lifespan. The reason for this distinction is that in the post-war period, investors and decision-makers focused on a mono-disciplinary

[62] Rioja F., *What is the value of Infrastructure Maintenance? A survey*, in *"Infrastructure and Land Policies"*, 2013, Lincoln Institute of Land Policy, Cambridge, MA, USA, Vol. 13, pp. 347-365.

approach in the construction sector, emphasizing only one of these aspects, without a deeper attention to externalities.

The differentiation is represented by technical, economic and functional lifespan[63].

• **Technical lifespan** comes to its end because of the structure's degradation and technical failure;

• **Economic lifespan** ends when it's not anymore economically worth investing in maintenance and renovation, because it would be more expensive than investing in a total replacement;

• **Functional lifespan**'s end is finally determined by negative externalities such as a more intensive use, heavier loads, climate change or new regulations.

Still today, as it can be imagined, the three lifespan typologies occur at different times and for different reasons. Therefore, a single-purpose solution can't satisfy nowadays demand and there is the need to activate a multi-disciplinary process, taking into consideration all the positive and negative impacts on the project's different lifespans.
The aim must be to consider all lifespan typologies and work on their maintenance and improvement through four main challenges:
• Thinking in terms of a network approach as an opportunity for projects redesign;
• Developing innovating techniques to satisfy the increasing requirements and budget restrictions;
• Conceiving adapting networks that will be able to face future changes;
• Combining different functionalities to add value to the assets.

To deal with complex technical and functional issues more inclusive investment strategies are needed. To move in this direction, existing structures must no longer be seen as a burden, but as elements with potential for economic growth and technological innovation.

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[63] Frangopol, op. cit.

2.1.3 The social value of infrastructures

When dealing with the impact of public infrastructures, two essential factors must be considered: the social and environmental value. In the end, when conceiving an infrastructure, the objective is to maximize the proper development of society without compromising the surrounding environment. The interaction among different stakeholders is a crucial step and all the actors should be involved in the decision-making process, from asset managers, investors and service providers, up to the final users.

The frenzy of today's society requires a network adaptation just as fast as our changing habits and a slow adjustment of infrastructures would cause a barrier to economic growth and people's welfare.

As underlined by Frischmann[64], a specific focus on projects impact on the perspective of commons must be deepened. Users often do not appreciate the social value provided by infrastructures or they simply can't take advantage of them.

Frischmann defines three economic criteria to infrastructural resources, stating that:

- They are non-rivalrous in consumption until an influent demand arises;
- They drive social demand;
- They offer goods and services.

Starting from these criteria, he classifies different types of infrastructures based upon their function and separating private and public assets. While the private strategy focuses on developing cooperation with competitors and maximizing the economic value of infrastructure, the public approach aims at improving social welfare by diffusing political and market pressure and by giving decision-making power to users.

[64] Frischmann B.M., *Infrastructure - The Social Value of Shared Resources*, 2012, Oxford University Press, New York.

That being said, it is essential that asset managers start to deal with programs of renovation that meet users and society's present and future needs, in order to increase opportunities for the stakeholders involved.

2.2 "Soft" mobility investment perspectives

It is by now clear to the eyes, that being our planet home to more than 7 billion people that use 1,5 times more resources than earth can provide[65], there is the need to radically reduce resources consumption and emissions.

Mobility and infrastructures are key elements for the modern economies, but they also represent a threat to the environment and to our health. According to the World Health Organization[66], the contribution of the transportation sector in Europe and North America contributes in a percentage of 24% to total greenhouse gas emission. This section introduces the cycle mobility system as an alternative with high potential in many cases, and a good starting point to improve life and environmental quality, as well as allowing the creation of more sustainable jobs[67]. Current European policies are presented, with some examples concerning the leading countries in the cycle mobility sector and the Italian situation. Then, particular attention is devoted to the potential benefits of various nature related to the creation of solid cycle networks. In addition to the social, environmental and economic benefits that big cities and congested areas can obtain, some important benefits and results can be achieved through the development of cycle tourism and consequently the rediscovery of remote territories in our countries. The implementation of these strategies can substantially improve national economies and quality of life. But to provide consistent pictures for future investments in this sense, specific studies and clear legislations must become part of national policies. The objective is to underline the advantages for the individual and for the whole community of investments in "soft" mobility infrastructures and specifically the cycle ones.

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[65] World Wide Fund For Nature, *Biodiversity, biocapacity and better choices*, Living Planet Report, 2012, p.42.

[66] Skinner I., Wu D., Schweizer F., Racioppi F., Tsutsumi R., *Unlockingnew opportunities: Jobs in green and healthy transport*, Copenhagen, World Health Organization, 2014

[67] Gausemeier P., Seidel J., Riedelsheimer T., Seliger G., *Pathways for Sustainable Technology Development: the case of bicycle mobility in Berlin*, in *"Procedia CIRP"*, Vol. 26, pp. 202-207.

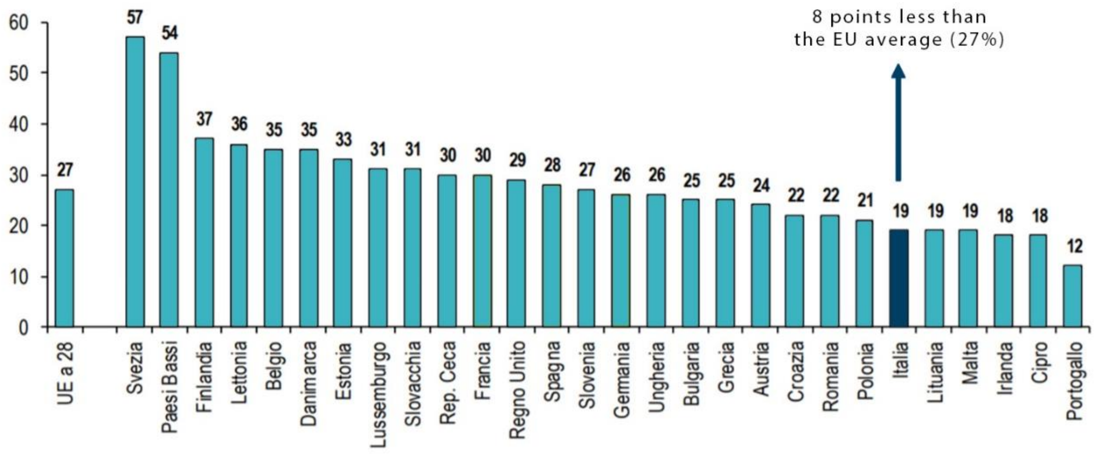
2.2.1 The challenge of sustainable mobility

As previously said, the uncontrolled growth and exploitation of natural resources have been leading in the past decades to the serious problems of atmospheric pollution, global warming, cities overpopulation and consequently environmental, socio-economic and health threats for the global population. The goal of a more sustainably way of living must represent today a vital aim for the development of present and future policies.

The constantly growing urbanization led to the issue of a chaotic traffic, with all its serious implications. These implications of environmental, social economic, and health nature, make the mobility and infrastructure sector a key player in the development of a more sustainable network.

To understand how important the impact of this sector is, we can take the example of Rome, the Italian capital. According to the Global INRIX Traffic Scorecard[68], in 2019 the citizens of Rome have spent 166 hours driving in congestion, meaning around 15-20% of their entire day. This simple numerical example clearly states the urgent need of new policies to reverse course in favor of a more positive impact of mobility. This positive impact can be represented by different options, such as the use of public transport to the detriment of private car transport, the electric mobility, but above all the cycle mobility. The awareness regarding this subject is now widely shared among European countries, but in practice only few countries are at the forefront in investing on well-functioning networks based on "soft" mobility. The image below shows the EU citizens attitude with respect to the environment by choosing a more sustainable way of travelling in the second half of 2019, including cycling, walking, using public transports or electric vehicles.

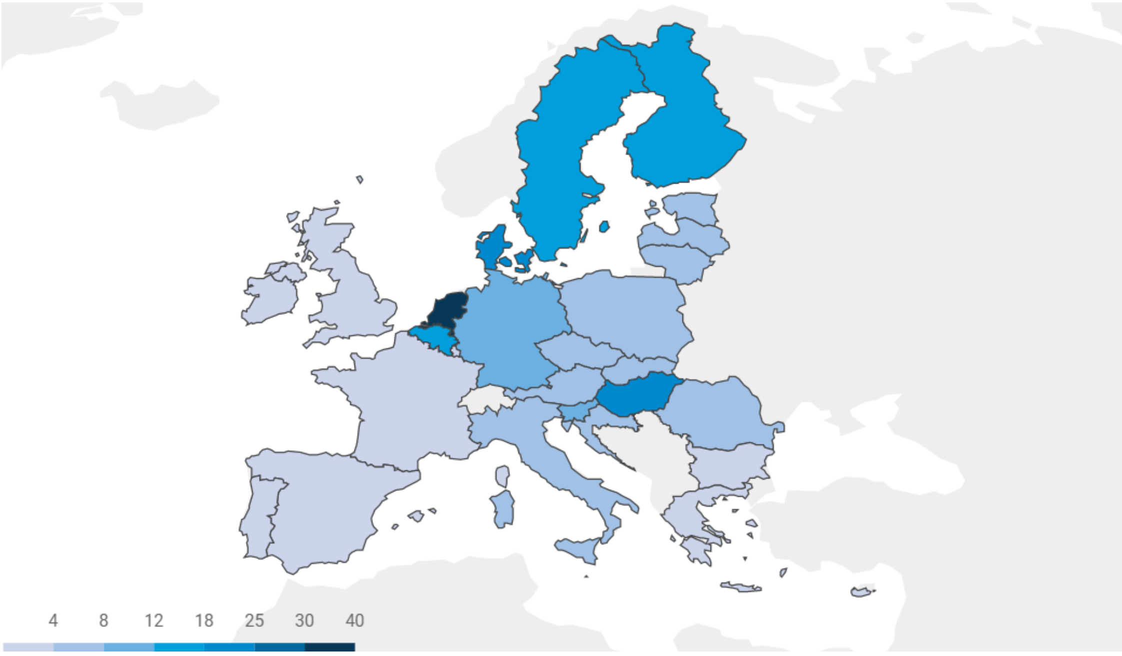
[68] https://inrix.com/scorecard-city/?city=Rome&index=6



EU countries percentage of sustainable ways of travelling in the second half of 2019, including cycling, walking, using public transports or electric vehicles.
Source: Elaboration of Ufficio Studi Confartigianato on data by the European Commission – Special EB n. 501 of March 2020, *Rapporto Artibici 2020. Artigianato e filiera della bicicletta*, 2020, p. 3.

Focusing on cycle transport, from the data of the Eurobarometer[69], the North European counties are the most advanced, Amsterdam and Copenhagen in particular, where respectively the 58% and 53% of the population uses the bike on daily basis. On the other hand, Rome is the worst in this sense among European capitals, with a percentage of only 1% of people using the bike as usual mean of transport. In the map below by the Eurobarometer, a comparison among all EU countries can be identified.

69 https://www.europarl.europa.eu/at-your-service/it/be-heard/eurobarometer



European and daily use of bike in percentage.

Source: https://ec.europa.eu/commfrontoffice/publicopinion/archives/ebs/ebs_422a_en.pdf

In order to raise awareness of the importance of sustainable mobility, especially in the least developed countries, the European Cyclists' Federation delivered in 2009 a list of "Global Goals"[70], among which there are 11 goals strictly related to cycle mobility:

• Goal #1 - End all forms of poverty: there is a high potential for economic growth through cycling-related jobs, that could influence the poverty-reduction strategies at all levels. Furthermore, a bicycle is often the only affordable mean of transport to access education services, jobs, markets and social activities.

• Goal #2 – End hunger, improve nutrition and develop sustainable agriculture: cycle paths can provide secure and equal access to land, and ensure a better access to food markets and communities.

• Goal #3 – Promote health and well-being: the physical activity, as well as the better air quality and road safety reduce the possibility of diseases and other negative impacts on human bodies.

[70] ECF, *Cycling Delivers on the Global Goals*, 2009, European Cyclists' Federation. Available online: https://ecf.com/resources/reports.

• Goal #5 – Achieve gender equality and women empowerment: a safe and well-conceived infrastructure for cycling can provide access for women and girls to education, markets and jobs.

• Goal #7 – Ensure access to affordable energy for all: the energy efficiency of transport systems can be improved by cycling as it uses renewable human power.

• Goal #8 – Promote sustainable economic growth and employment for all: sustainable tourism and healthy leisure activities contribute to the development of the cycling industry sector, improving its economic performance and work conditions.

• Goal #9 – Build resilient infrastructure and promote inclusive industrialization: the focus on equitable access for all makes it easier for governments to build resilient infrastructures.

• Goal #11 – Make cities inclusive, safe and sustainable: as cycling is safe, non-polluting, healthy and promotes a sustainable economy.

• Goal #12 – Ensure sustainable production and consumption patterns: in many urban areas, 50% of goods can be delivered by bicycle and commuters, consumers and tourists have the opportunity to easily move around.

• Goal #13 – Take action to fight climate change: climate action can be taken by using the bicycle, since its use helps in the decarbonization of transports and societies. A cycling education should be integrated in the climate action policies.

• Goal #17: Revitalize the global partnership for sustainable development: promoting cycling worldwide in both public and private sectors can support successfully a conscious global development.

2.2.2 EU policies for cycle infrastructure

Today, the European situation in terms of cycle infrastructure is very heterogeneous. Obviously, this is determined by government policies, that in some countries have been strongly promoting cycling in the last years. This happens in countries like Denmark, The Netherlands and Germany; the case of Copenhagen, one of the most advanced cities in this field, will be presented. Other countries such as Greece, Italy, Spain, UK and the area of Eastern Europe are still strongly dependent on traditional means of transportation and bicycles are mainly used for recreational purposes. Anyways, also in these countries some realities are changing and becoming a model, as in the case of the city of Bolzano, in Italy.

2.2.2.1 Forward-looking policies in Denmark, The Netherlands and Germany

It is common knowledge that technologically advanced countries like Denmark, The Netherlands and Germany, have managed in the last decades to make cycling a widespread mean of transport, obtaining cycling levels up to ten times higher than the other European countries. Pucher and Buehler[71] analyzed the fundamental strategies of these countries already in 2007, and in the following years their national and local policies have continued to improve in favor of cycle mobility. According to their studies, Dutch, German and Danish cities have focused in the past 50 years on serving people, more than the other countries do, by making their cities people-friendly rather than car-friendly. This process started in the mid-1970s with a quite extreme reversal in transport and urban planning policies at national, regional and local levels. The trump cards for the promotion of cycling for daily travels have been ensured on one hand by safer and improved cycle infrastructures, and on the other one by the imposition of restrictions on car use and higher expenses for this kind of mobility.

It is obvious that The Netherlands, Denmark and Germany are quite affluent countries with very developed economies and therefore, their high levels of cycling are not due to the impossibility to afford more expensive, technological or faster transport modes. The proof lies in the fact that the levels of car ownership in these three countries are among the highest in the world, especially in the case of

[71] Pucher J., Buehler R., *At the frontiers of cycling: Policy innovations in the Netherlands, Denmark, and Germany*, in *"World Transport Policy and Practice"*, 2007, Vol. 13, pp. 8-57.

Germany. People here freely chose a “soft” mobility network, because they are encouraged by national and local policies, that are able to ensure safety, savings and health and environmental protection.

2.2.2.1.1 A case study: Copenhagen (DK)

Copenhagen, the capital of Denmark, is often considered one of the most bicycle-friendly cities in the world, attracting the attention of other countries that want to follow its successful model.

Traditionally, Copenhagen has always had a high cycling share that reached its peak in the 1930s, with a share of about 60%, that severely fell after World War II, with the rise of the automobile era. As in many other European cities, the cycling mode share began to increase again in the 1970s, with the oil and economic crisis, but unlike most other cities, the share here reached 45% of all trips to work or education by 2014[72].

According to Zhao et al.[73], Copenhagen, together with the cities with extensive cycling experience, base their bicycle infrastructure planning on the so-called CROW principles. CROW is a non-profit organization established in 1987 that gathers information on cyclists’ preferences and behaviors, allowing an ever deeper understanding of this field. For what concerns the Dutch bicycle infrastructure system, CROW published its first set of guidelines in 1993, improving it over the years with more and more specific information. These guidelines led to the definition of five basic principles for constructing bicycle-friendly infrastructure. These principles are listed below, together with the feedback of Copenhagen planners, showing the tangible progresses of the city in this sense.

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[72] Carstensen T.A., Olafsson A.S., Bech N.M., Poulsen T.S., Zhao C., *The spatio temporal development of Copenhagen's bicycle infrastructure 1912–2013*, in *“Geografisk Tidsskrift - Danish Journal of Geography: Transformation of Cities”,* 2015, Vol. 115 (2), pp. 142-156.

[73] Zhao C., Carstensen T. A., Nielsen T. A. S., Olafsson A. S., *Bicycle-friendly infrastructure planning in Beijing and Copenhagen - Between adapting design solutions and learning local planning cultures*, in *“Journal of transport geography”,* 2018, Vol. 68, pp.149-159.

1) **Cohesion**: according to Groot[74], the meaning of cohesion is related to the ability of the cycling infrastructure plan to form a road network that guarantees people the possibility to move from their departure point to their destination. To ensure this, planners must take into consideration three fundamental aspects:

• Coverage and connectivity of the bicycle road network
• Removal of obstacles and barriers
• Resolution of conflicts concerning the infrastructure usage

Since cycling in Copenhagen is prioritized, these aspects are placed at the center of the matter, enhancing clear spaces devoted to cycling and decreasing the space for car parking.

2) **Safety**: it is the indispensable and guiding principle for bicycle infrastructure planning, provided by a clear separation of bicycle paths and motorized traffic and where this is not possible ensured speed control of vehicles. Apart from this essential aspect of "actual" safety, also the "perceived" safety must be considered. Danish planners emphasized the importance of listening to citizens opinions and perplexities regarding the places where they feel at risk or diffident in the traffic environment. One planner stated: "When people get up in the morning, they do not care about the statistical safety... They care about how they perceive it. […] Even if an area or section in statistically safe, if it is not seen as safe people may stop cycling suddenly."[75]

3) **Directness**: it is related to the reduction of travel time to the minimum. If one wants to make competitive the cycle infrastructure sector, this aspect must be guaranteed. Since the early 2000s, a series of measures has been introduced in Copenhagen, such as various cycling bridges and connections, traffic signals synchronized in order to prioritize cycling and "green routes" to increase speed and reduce travel time.

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[74] Groot R.D., *Design Manual for Bicycle Traffic*, 2007, Vol. 25.

[75] Zhao, op. cit., p. 155.

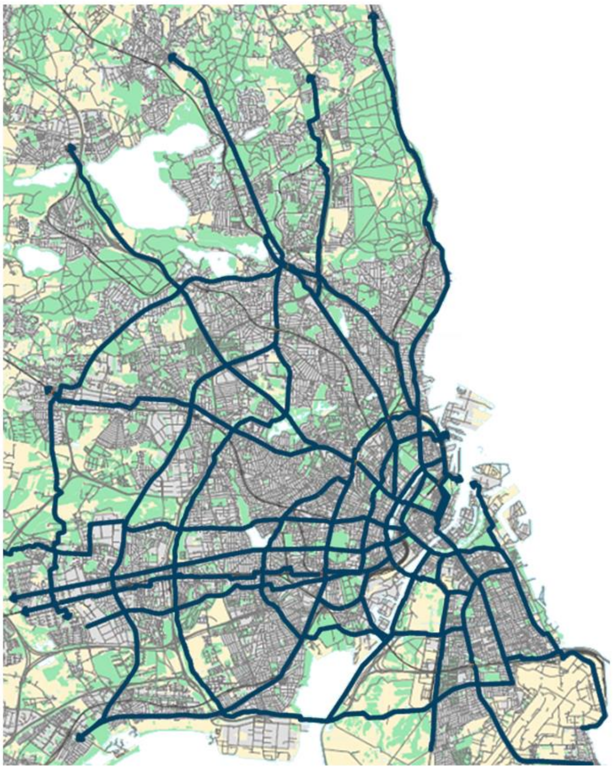
4) **Attractiveness**: the concept of attractiveness is strictly related to the "perceived" safety, because a safe and well-maintained environment stimulates the interaction of users with the urban space. This principle also includes small interventions that can be greatly appreciated by the citizens and that can make them feel like they are doing the right thing for themselves and for the whole society by cycling. Therefore, according to the planners, some facilities in Copenhagen weren't installed because they were necessary, but to increase the attractiveness and curiosity of the public. Some examples of these small interventions are:

• Footrests at intersections
• Signalized green waves
• Advertising campaigns to thank citizens for cycling in the city
• Increased space for bike parking
• Social cycling programs

5) **Comfort**: This principle is based on the need to develop cycling infrastructure systems that can reduce as far as possible the physical effort when people are cycling. This kind of comfort is strictly related to the quality of the infrastructure, meaning smooth surfaces, snow clearing and integration of cycling with public transport.

In addition to these five principles, Zhao et al.[76] also state that Copenhagen citizens show a strong personal preference for cycling, because this activity is linked to civic pride and consequently to a sort of environmental and social friendly status. According to the interviews results, a series of informants even appeared embarrassed to announce that they were also car-owners.

[76] Ibid.



Map of the cycle “super highways” in Copenhagen.

Source: Cycling Embassy of Denmark. Available online: http://www.cycling-embassy.dk/2011/02/02/super-cycle-highways-in-greater-copenhagen-area-2/

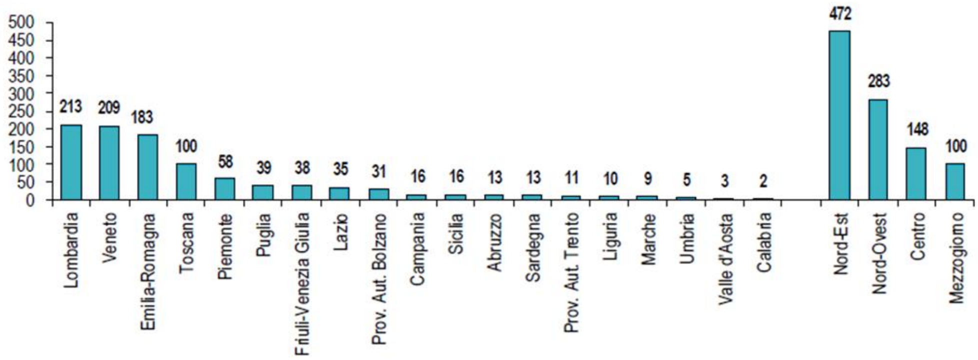
2.2.2.2 The Italian situation

The development of cycle infrastructure networks in Italy is evidently behind with respect to the above-mentioned countries. The Italian situation is in general fragmented and characterized by local initiatives which are rarely extended to a regional or national level through a structured and well-regulated process. Despite this, according to the National Information Agency ANSA[77], ISTAT (Istituto Nazionale di Statistica) data processing shows that between 2011 and 2016 Italian cycle paths have increased by 21,7%, reaching in the Municipalities a global length of 4.370,1 km. The highest surfaces of these cycle paths are mostly located in the

[77] https://www.ansa.it/canale_motori/notizie/analisi_commenti/2018/07/18/bici-in-5-anni-207-piste-ciclabili-in-italia_9d2f8caf-b122-4230-ad90-d43f1800683d.html

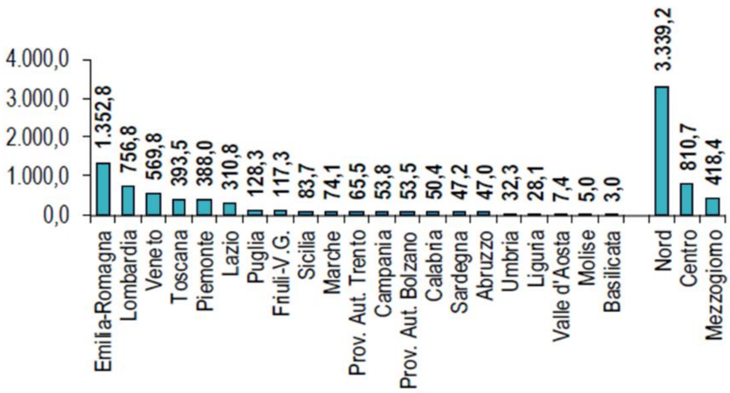
northern Regions of the country, demonstrating a significant imbalance between North and Center-South of Italy.

In the 2020 ARTIBICI Report[78], the Italian organization Confartigianato processed a set of ISTAT data on bike usage, length and density of cycle paths in Italy, referring to the years 2018-2019 and outlining a detailed comparison among regions.



Values in thousands of people cycling to work or school in the year 2019 in the Italian Regions, referring to workers aged ≥ 15 and students aged ≤ 34.

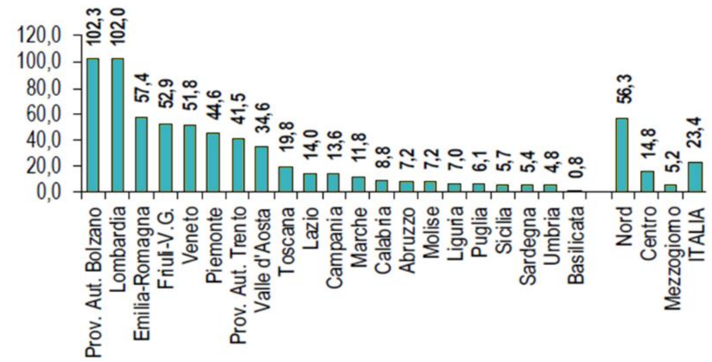
Source: Elaboration of Ufficio Studi Confartigianato of ISTAT data, *Rapporto Artibici 2020. Artigianato e filiera della bicicletta*, 2020, p. 38.



Cycle paths length in kilometers in the Italian Regions, referring to the year 2018.

Source: Elaboration of Ufficio Studi Confartigianato of ISTAT data, *Rapporto Artibici 2020. Artigianato e filiera della bicicletta*, 2020, p. 45.

[78] Ufficio Studi Confartigianato, *Rapporto Artibici 2020. Artigianato e filiera della bicicletta*, 2020.

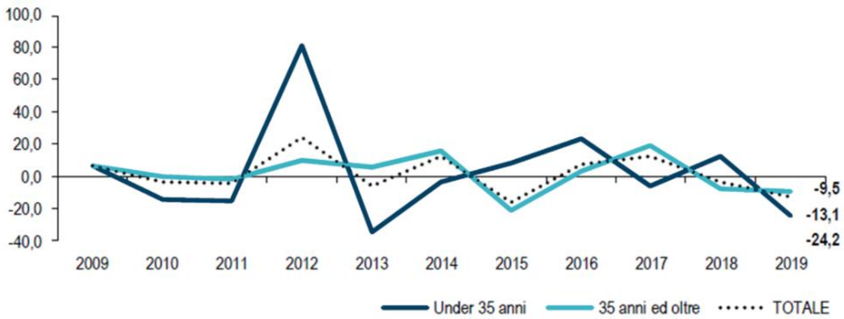


Km per 100 km^2 of cycle path density in the Italian Regions, referring to the year 2018.

Source: Elaboration of Ufficio Studi Confartigianato of ISTAT data, *Rapporto Artibici 2020. Artigianato e filiera della bicicletta*, 2020, p. 47.

As it can be inferred from the graphs above, the most advanced Regions in cycle transport from several perspectives are Lombardia, Emilia-Romagna and Veneto, with an important outdistance especially from the southern Regions.

Analyzing these data from the point of view of age groups, we can see the different involvement of people aged under and over 35 through the past ten years, with a slightly descending curve in the past two years.



Annual dynamics of workers traveling by bike in 5 years: comparison of people under and over 35, referring to the years 2009-2019.

Source: Elaboration of Ufficio Studi Confartigianato of ISTAT data, *Rapporto Artibici 2020. Artigianato e filiera della bicicletta*, 2020, p. 43.

With these premises, the Italian legislation has been taking actions to detect the problems related to safety and lack of connections, in order to develop solutions and homogenization at a national level. In 2018, with the Legge Quadro per la Mobilità Ciclistica[79] (Framework Law for Cycle Mobility), an allocation of 14,8 million of funds has been earmarked for the Regions to secure 70 cycle paths. Following this law, Regions, Provinces and Municipalities will have the duty to work together in drafting plans for interconnected cycle infrastructures harmonized at a regional level with "cycle highways". These cycle highways will be then linked to the ten National Touristic Cycle Paths designed by the Ministry of Transport. In section 2.2.3.2.2 we will further detail this ambitious project, that together with the program Bicitalia[80], is willing to contribute over the coming years to the development of cycle tourism in Italy.

2.2.2.2.1 A case study: Bolzano (IT)

The Municipality of Bolzano, located in South Tyrol, is one of the most bike-friendly in the country, with a share of around 30% of daily rides. As explained on the website of the Municipality of Bolzano[81], the city started developing the first bicycle paths already in the '80s, coming to define in 2002 the four pillars of a coherent bike system described by Morandini[82]:

1) **Demand analysis** for bicycle mobility: such study allows to understand the mobility habits of citizens, sketching a picture of who is movement through the city, from where to where, when, why and how. This sort of "mobility diary" represents an essential tool for decision-making;

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[79] Law 11 January 2018, n. 2, *Disposizioni per lo sviluppo della mobilità in bicicletta e la realizzazione della rete nazionale di percorribilità ciclistica*, entry into force from 15/02/2018. Available online: https://www.normattiva.it/uri-res/N2Ls?urn:nir:stato:legge:2018-01-11;2

[80] See section 2.2.3.2.1

[81] https://www.comune.bolzano.it/mobilita_context02.jsp?ID_LINK=1199&area=123

[82] Morandini M., *Cycling Management: the success story of the city of Bolzano Bozen*, in *"Transportation and Development 2008: Innovative Best Practices"*, 2008, American Society of Civil Engineers.

2) **Supply analysis** of bicycle mobility: this study must be based on citizens real needs. To do so, a set of priorities is highlighted, that is able to guarantee a high-quality network:

• Points of interest in the city
• Main axes for significant investments
• Non-expressed bike mobility (short term)
• Potential bike mobility (medium term);

3) **Communication**: the communication system is based on a corporate identity, promoting cycle mobility in the city through a strategic design. The funding element of this identity is the logo “Bici Bolzano - Fahrrad Bozen”. Furthermore, pocket-sized maps that clearly illustrate the whole cycle network are distributed;

Bici Bolzano
Fahrrad Bozen

Logo Bici Bolzano / Fahrrad Bozen.
Source: https://www.comune.bolzano.it/mobilita_context02.jsp?ID_LINK=4695&area=123

4) **Marketing**: working on a promotion linked to cultural rather than technical factors leads to the so-called “emotional marketing”. This kind of input gives dignity and importance to this transportation system, relying on citizens emotions and sensations. This is accomplished through big prints, postcards, cinema and TV spots.

In addition to these four pillars, the Plan for Cycle Mobility in 2002 identifies some other guidelines to increase cycle mobility in the city:

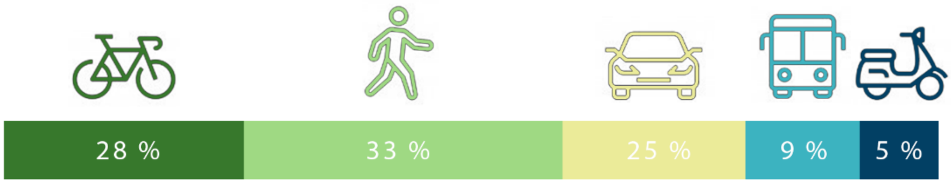
• Completion and extension of the city’s cycle network;

• Elaboration of clear and specific signs for a correct visibility and use of cycle paths;

• Awareness-raising projects is schools and workplaces;

• Displacement monitoring through a “Bicycle Barometer”.

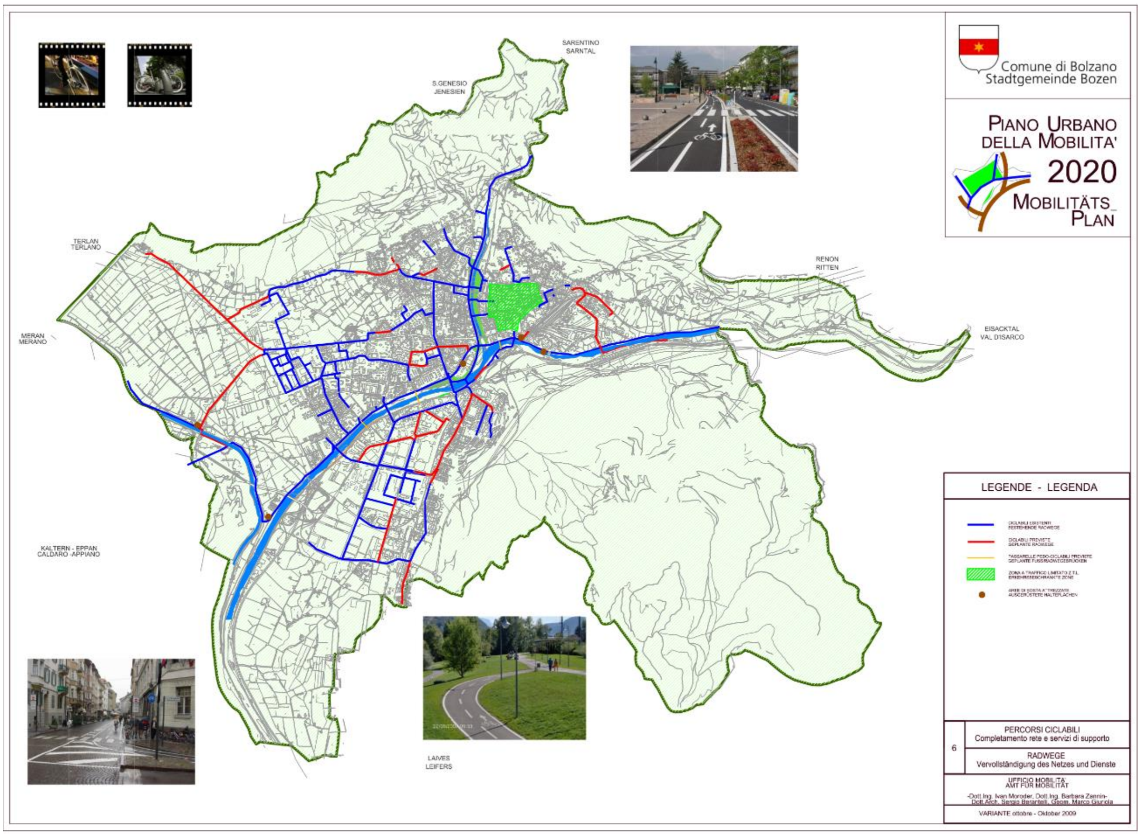
After few years, in 2009, the results of the planned activities appear extremely satisfactory. The cycle network has been widely extended, bike parking has increased and has been placed in strategic positions and the rental service has been updated. In practice, the share of annual rides switched from 17,5% in 2002 to 29% in 2009, reaching more than 30% at present times. Now, the goal is to reach a share of 34%, achieving at least 118.000 daily rides.



Percentage of travel type in Bolzano in 2012.
Source: Author's re-elaboration from
https://www.comune.bolzano.it/UploadDocs/14079_In_bici_a_Bolzano_it.pdf

The primary aim of the city to increase this activity, is to ensure citizens' safety and protection. As part of the security project promoted by the Department of Mobility, called "Insieme attraverso la città" ("Together across the city"), a number of panels are frequently installed on cycle paths and near some critical points shared by both cyclists and pedestrians, in order to raise awareness of respect for public spaces and call for safe behaviors.

Moreover, the PUM 2020 (Piano Urbano Mobilità / Urban Mobility Plan) contains new guidelines for further interventions in the field of sustainable mobility and in particular cycling.



Piano Urbano Mobilità / Urban Mobility Plan (PUM) 2020 of the Municipality of Bolzano.

Source: https://www.comune.bolzano.it/UploadDocs/9793_PUM_ciclabili.pdf

2.2.3 Potentiality and benefits related to cycle infrastructure

The bicycle, since its invention, has always been a cheap mean of transportation, that does not need specific maintenance or fuel to operate. The benefits associated with cycling clearly overcome the few disadvantages and impediments and this explains why, with the economic and energetic crisis in the '70s, there is a return to this practice that from the '50s had been left behind.

In general, the main advantages related to a good cycle network, and therefore the spread of cycling, are[83]:

[83] Serra M., *Valutazione di modelli economici-gestionali di progetti di sviluppo del modulo abitativo MAACC, per la valorizzazione architettonica e territoriale del Piemonte orientale, attraverso la mobilità lenta e lo sviluppo turistico sostenibile*, Tesi di laurea, Rel. Occelli C., Mondini G., Palma R., Politecnico di Torino, 2020, p. 32.

• Reduction of urban and suburban air pollution;

• Reduction of traffic congestion and of the resulting psycho-physical stress;

• Reduction of greenhouse gases emissions, CO_2 in particular;

• Reduction of accidents and consequently mortality;

• Reduction of the travel time due to the possibility to avoid traffic and find a parking spot quickly;

• Reduction of fossil fuels extraction and pollution derived from their production and transportation;

• Reduction of user costs for the management of private motor vehicles;

• Increase of the physical well-being and reduction of the percentage of contracting diseases;

In 2010, the European Cyclists' Federation developed a calculation to monetize all these kinds of benefits related to the level of cycling in the EU in that year[84]. The calculation analyzes six categories, that are considered the most influential and that combined together give a specific value in terms of monetary benefits:

1) **Health improvement and protection**: in addition to preventing obesity and a range of other diseases, such as cardiovascular diseases, it is proved that the cycling leads to a reduction in mortality. Thanks to the Health Economic Assessing Tool for Cycling (HEAT) created by the World Health Organization, is it possible to evaluate the reduction in premature mortality among adult cyclists (age category 20-64), for a volume of cycling of 77 billion km/year. Translated into monetary terms the health benefits are the most influential in the final result, reaching a saving of € 114-121 billion/year.

[84] Küster F., Blondel B., *Calculating the economic benefits of cycling in EU 27*, 2013, Economic report of the European Cyclists' Federation (ECF), Brussels. Available online: http://www.ecf.com/sites/ecf.com/files/Fabians%20ECF_Economic-benefits-of-cycling-in-EU-27-3.pdf

2) **Congestion-easing**: according to Botma et al.[85], a road can accommodate in an hour around 14.000 bicycles compared to only 2.000 cars. Since the European GDP is influenced for 1% by congestion costs (about € 130 bn), as stated by the European Commission[86], as the census of 2010 the saving was of € 24,2 billion/year.

3) **Fuel saving**: traditional transport relies on the availability of oil and petroleum, that in Europe are imported for 84,1% by other countries, for a cost of around € 1 bn per day, of which about 50% due to transport expenses[87]. This explains the savings due to cycling activity for € 2,7-5,8 billion/year.

4) **Reduced CO_2 emissions**: it is a fact that cycling is a low-carbon mode of transport, that saves, for a volume of cycling of 94 billion km/year, 11 to 24 million tonnes of CO_2. Translated into monetary terms, savings amount to € 1,4-3,0 billion/year.

5) **Reduced air pollution**: for passenger cars, air pollution depends on the size of engine, type of fuel type, road type and emission standards. These data, analyzed in the *"Handbook on estimation of external costs in the transport sector"*[88], demonstrate a monetary saving due to cycling activity for € 0,9 billion/year.

6) **Reduced noise pollution**: always according to the *"Handbook on estimation of external costs in the transport sector"*, the noise reduction induced by the cycle transport amounted in 2010 to savings for € 0,3 billion/year.

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[85] Botma H., Papendrecht H., *Traffic operation of bicycle traffic*, 1991, TU-Delft. Available online: http://onlinepubs.trb.org/Onlinepubs/trr/1991/1320/1320-009.pdf

[86] https://ec.europa.eu/transport/strategies/

[87] Commission Staff Working Paper, Accompanying document to the White Paper *Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system*, 2011, Impact Assessment, European Commission, Brussels.

[88] Maibach M., Schreyer C., Sutter D., Van Essen H.P., Boon B.H., Smokers R., Schroten A., Doll C., Pawlowska B., Bak M., *Handbook on estimation of external costs in the transport sector*, 2008, Internalisation Measures and Policies for All external Cost of Transport (IMPACT) Version 1.1, CE Delft. Available online: https://ec.europa.eu/transport/sites/transport/files/themes/sustainable/doc/2008_costs_handbook.pdf

Type of benefit	In € for 2010
1) Health benefits: reduced mortality	€ 114-121 bn
2) Congestion-easing	€ 24,2 bn
3) Fuel savings at US$ 100/ barrel	€ 2,7-5,8 bn
4) Reduced CO_2 emissions	€ 1,4-3,0 bn
5) Reduced air pollution	€ 0,9 bn
6) Reduced noise pollution	€ 0,3 bn
Total	**€ 143,2-155,2 bn**

Internal and external economic benefits of cycling at 7.4 % cycling mode share in EU-27 (2010).
Source: Author's re-elaboration from Küster F., Blondel B., *Calculating the economic benefits of cycling in EU 27*, 2013, Economic report of the European Cyclists' Federation (ECF), Brussels, p. 3.

This kind of calculation basically suggests that investing in cycling is usually good value

for money. After a first approach to this methodology, a report for the UK Department of Health concluded at the time that "the economic justification for investments to facilitate cycling and walking has been undervalued or not even considered in public policy decision-making. Yet, almost all the studies report economic benefits which are highly significant, with benefit to cost ratios averaging 13:1 (UK and non-UK)."[89]

The ECF's report[90] also specifies that additional economic benefits are of course provided by the bicycle industry and the development cycle tourism, an issue that will be discussed in section 2.2.3.2.

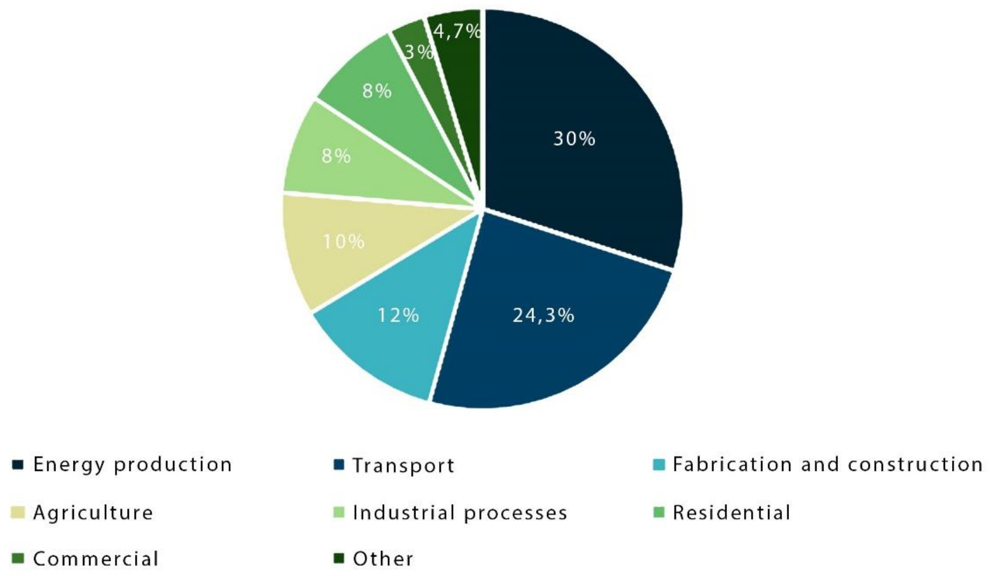
89
https://webarchive.nationalarchives.gov.uk/20050304041634/http://www.dft.gov.uk/stellent/groups/dft_econappr/ documents/pdf/dft_econappr_pdf_022512.pdf

90 Küster F., Blondel B., *Calculating the economic benefits of cycling in EU 27*, 2013, Economic report of the European Cyclists' Federation (ECF), Brussels. Available online: http://www.ecf.com/sites/ecf.com/files/Fabians%20ECF_Economic-benefits-of-cycling-in-EU-27-3.pdf

2.2.3.1 Environmental, social and economic benefits

The above-mentioned benefits can be linked to specific categories concerning economic, environmental and social benefits. These are the three fundamental principles that must be taken into consideration when assessing costs and benefits for any kind of analysis field.

Environmental benefits include all the positive impacts determined by cycling. The primary benefit in this field is represented by the reduction of CO_2 emissions. According to an ECF report published in 2011[91], the production of CO_2 is subdivided as follows in the various sectors:



Pie chart with the subdivision of CO_2 emissions in the various sectors.

Source: Author's elaboration from ECF data: Blondel B., Mispelon C., Ferguson J., *Cycle more often 2 cool down the planet! Quantifying CO_2 savings of cycling*, 2011, European Cyclists' Federation, Brussels, p. 5.

The same study shows an increase in CO_2 emissions caused by the transport sector of 36% between 1990 and 2007. In the face of these serious issues, the ECF analyzes the main characteristics and use of an average bicycle, together with the calorie consumption and therefore the diet of bike travelers. As a result, the total CO_2

[91] Blondel B., Mispelon C., Ferguson J., *Cycle more often 2 cool down the planet! Quantifying CO_2 savings of cycling*, 2011, European Cyclists' Federation, Brussels, p. 5.

production of an adult who uses the bike daily is of 21 gr CO_2e/km, in comparison to the 271 gr CO_2e/km produced by a car traveler. There are other environmental benefits related to cycling, such as noise reduction and an improved aesthetic quality of the environment. This benefit is related to the possibility of having less congested roadways in favor of green avenues and parks, which are better suited to cycling.

Social benefits relate to the social value of “slow” mobility in terms of physical and psychological positive influence. The slow speed movement allows to connect and harmonize with nature, as well as encouraging a healthy and sustainable lifestyle. According to the World Health Organization[92], in 2014 physical inactivity was the fourth cause of mortality globally, since it is strictly related to the onset of diseases associated with obesity, cardiovascular problems, diabetes and depression. Several studies in the past years underline how dedicating a percentage of weekly time to cycling or physical activity in general can significantly reduce the risk of developing certain diseases. Already in 2000, a study by Andersen et al.[93] demonstrated that cycling for about three hours per week can decrease the risk of mortality by 28%. Another research made in 2012 in Barcelona[94] analyzes the changes relating to mortality reducing vehicle mobility in favor of cycling. In the scenario that replaces 40% of car trips with bicycle trips, the result of 66,12 fewer deaths per year are estimated.

Economic benefits are a consequence of the positive impact of all other factors. According to an ECF study made in 2016[95], the main economic benefits derive from improved health and therefore better health management and optimization of time and space, followed by economic and social affairs and mobility systems.

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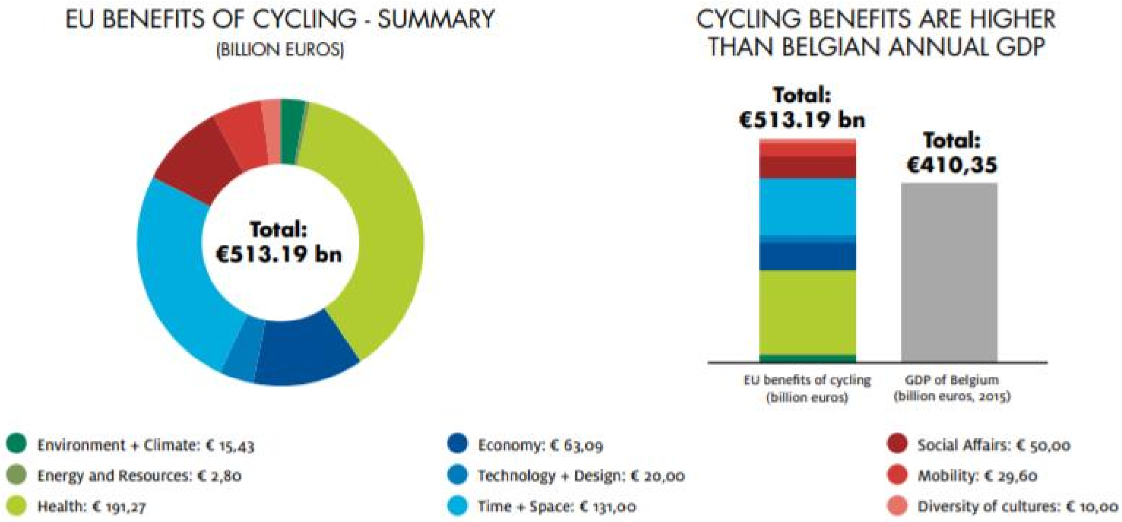
92 https://www.who.int/

93 Andersen L. B., Schnohr P., Schroll M., Hein H. O., (2000), *All-cause mortality associated with physical activity during leisure time, work, sports, and cycling to work.*, 2000, Archives of internal medicine, Vol. 160(11), pp. 1621-1628.

94 Rojas-Rueda D., De Nazelle A., Teixidó O., Nieuwenhuijsen M. J., *Replacing car trips by increasing bike and public transport in the greater Barcelona metropolitan area: a health impact assessment study*, in *“Environment international”,* 2012, Vol. 49, pp. 100-109.

95 ECF, *The EU Cycling Economy*, 2016, European Cyclists’ Federation. Available online: https://ecf.com/resources/reports.

A less significant, but not negligible impact on the society economic benefits is represented by a good quality of life, guaranteed by a healthy environment and good climate, energy resources, technological innovation and cultural dissemination.
In the face of these information, the following graphs by the ECF quantify the EU economic benefits of cycling. To understand to economic impact of cycle mobility, it is enough to consider that the total sum amounts to € 513,19 billion, that is more than the Gross Domestic Product of Belgium.



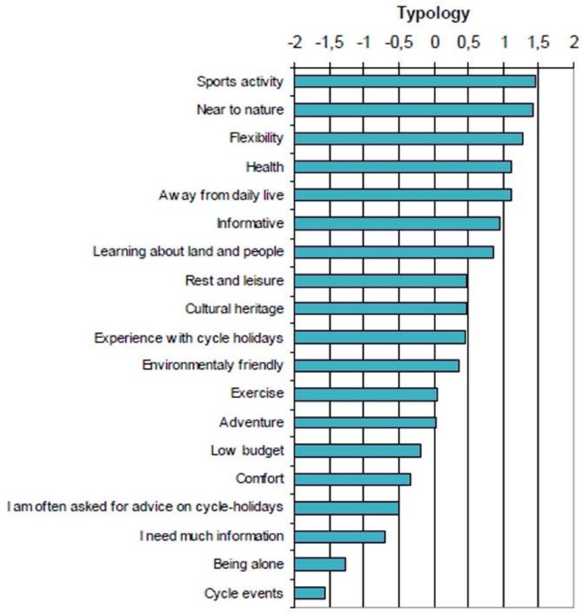
EU economic benefits of cycling and comparison with the Belgian annual GDP.
Source: ECF, *The EU Cycling Economy*, 2016, European Cyclists' Federation, p. 7.

2.2.3.2 Cycle tourism development

In addition to the focus on cycle infrastructure and networks in the cities, also the development of cycle tourism must be taken into consideration, for it has a significant impact on the above-mentioned benefits. According to the ECF, cycle tourism consists of "recreational visits, either overnight or day visits away from home, which involve leisure cycling as a fundamental and significant part of the visit."[96] Cycle tourism can be considered a sustainable tourism by nature, but also

[96] https://ecf.com/what-we-do/cycling-tourism

thanks to the attitude of cycle tourists, which are usually united by a deep sensitivity towards environmental preservation and sustainability.



Motivations given by cycle-holidaymakers, where -2 is the lowest score (not a motive at all) and 2 is the highest score (clear motive).

Source: European Parliament, *The European Cycle Route Network Eurovelo*, 2012, Directorate-General for Internal Policies, p. 38.

The UK transport charity Sustrans[97], subdivides the market for cycle tourism as follows:

• **Cycling holidays**: cycling is the main purpose of the holiday, that can be organized as a tour or center-based;

• **Holiday cycling**: cycling is part of the holiday experience, but it's not the main purpose. This kind of holiday involves cycle rides to move from one place to the other;

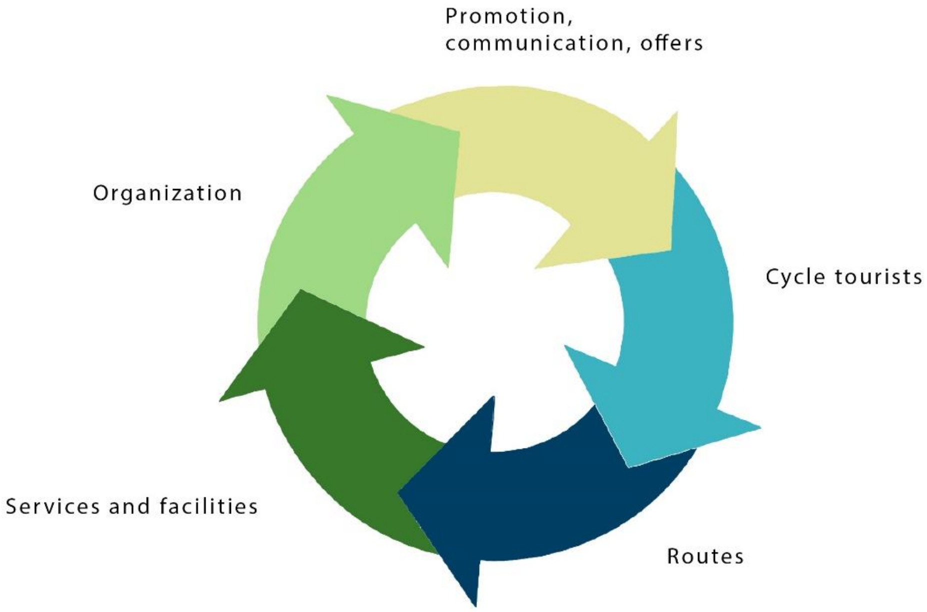
• **Cycle day excursions**: cycle daytrips of at least 3 hours made for leisure.

[97] https://www.sustrans.org.uk/

An ECF research of 2018[98] states that in Europe there are 2.3 billion trips related to cycle tourism, with a consequent economic revenue of around € 44 billion. The benefits of this kind of sustainable tourism include:

- Local SMEs (small-to mid-size enterprises) development
- Local employment
- Local tax incomes
- CO_2 emission reduction
- Tourism flow devolution

This system leads to the creation of a circular evolution of cycle tourism, based on promotion and communication, new routes, services and facilities and a structured organization.



Development circle of cycle tourism.

Source: Author's re-elaboration from ECF, *Cycling tourism in Europe a success story, a booming business and a gateway to urban cycling*, 2018, European Cyclists' Federation, p. 10.

[98] ECF, *Cycling tourism in Europe a success story, a booming business and a gateway to urban cycling*, 2018, European Cyclists' Federation. Available online: https://ecf.com/sites/ecf.com/files/Bodor_A._Cycling_tourism_in_Europe.pdf

2.2.3.2.1 The project Bicitalia

The first project under development for cycle tourism in Italy is the network Bicitalia, strongly desired by FIAB (Federazione Italiana Ambiente e Bicicletta). This project includes the realization of 16.850 km of cycle paths connecting Italy from north to south and from east to west and reaching the main cultural and natural touristic destinations. The network is divided in 20 cycle paths, called "ciclovie"[99]. Four of them, number 1, 2, 3 and 6, are linked to the European cycle network EuroVelo, broadening the vision at an international level.

BI1 **Ciclovia del Sole**: 1.600 km, crossing the map of Italy vertically from San Candido (BZ) to Palermo;

BI2 **Ciclovia del Po**: 1.300 km, from the source to the delta of the Po river;

BI3 **Ciclovia Francigena**: 2.000 km, crossing the map of Italy vertically from Como to Brindisi;

BI4 **Ciclovia Dolomiti – Venezia**: 350 km, from Brennero (BZ) to Venezia;

BI5 **Ciclovia Romea Tiberina**: 800 km, from Tarvisio (UD) to Roma;

BI6 **Ciclovia Adriatica**: 1.300 km, crossing the map of Italy vertically on the east side from Trieste to Santa Maria di Leuca (LE);

BI7 **Ciclovia Tibur Valeria**: 300 km, from Roma to Pescara;

BI8 **Ciclovia degli Appennini**: 1.500 km, along the mountain range of the Apennines from the Colle di Cadibona (SV) to Madonie (PA);

BI9 **Ciclovia Salaria**: 300 km, from Ostia (RO) to San Benedetto del Tronto (AP);

BI10 **Ciclovia dei Borbone**: 400 km, crossing the south from Bari to Napoli;

BI11 **Ciclovia dell'Acquedotto Pugliese**: 500 km, from Caposele (AV) to Santa Maria di Leuca (LE);

[99] http://www.bicitalia.org/it/bicitalia/il-progetto

BI12 **Ciclovia Pedemontana Alpina**: 1.100 km, in the foothills of the Alps from Trieste to Savona;

BI13 **Ciclovia Claudia Augusta**: 350 km, from Passo di Resia (BO) to Ostiglia (MN);

BI14 **Ciclovia Magna Grecia**: 600 km, from Taranto to Reggio Calabria;

BI15 **Ciclovia Svizzera – Mare**: 500 km, from Locarno (Switzerland) to Ventimiglia (IM);

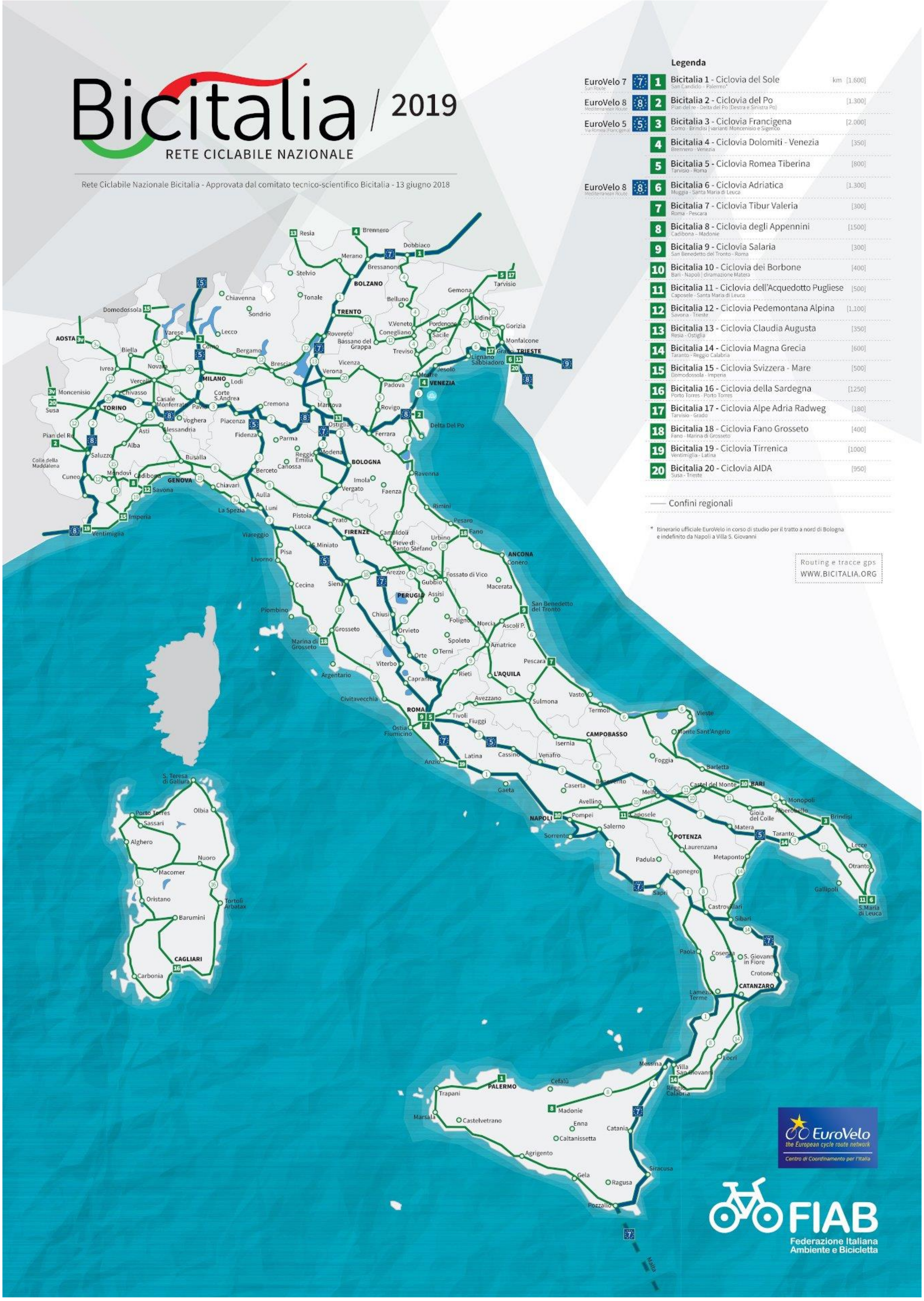
BI16 **Ciclovia della Sardegna**: 1.250 km, on the coast of the island with departure and arrival at Porto Torres (SS);

BI17 **Ciclovia Alpe Adria Radweg**: 180 km, from Tarvisio (UD) to Grado (GO);

BI18 **Ciclovia Fano Grosseto**: 400 km, crossing the center of Italy from Fano (PU) to Grosseto;

BI19 **Ciclovia Tirrenica**: 1.000 km, in the lands of the Etruscans from Ventimiglia (IM) to Latina;

BI20 **Ciclovia AIDA**: 950 km, from Susa (TO) to Trieste.



The Bicitalia network.

Source: http://www.bicitalia.org/it/bicitalia/la-rete-ciclabile-nazionale-bicitalia

The reasons which led to the approval of this project are linked to a national interest and expressed on Bicitalia[100] website:

- **Transport**: a national network based on "soft" mobility would represent an innovation and a breath of fresh air in the vision of a more sustainable EU;
- **Tourism**: a tourism that must be increasingly constructive and avoid pollution and environmental damages, expanding at the same time the economic benefits;
- **Environmental conservation**: the development of a cycle network is mainly based on existing minor infrastructure and paths, which only need to be reclaimed and recovered.
- **Local economies**: the territories crossed by cycle paths can sustainably develop their economies based on hospitality, refreshment, technical assistance and a specialized publishing for maps and guides.
- **Intermodality**: the network would contribute to the enhancement of intermodality of transport, by creating formulas that facilitate the use of bike + train, bike + bus or bike + boat.

In summary, the creation of a national cycle network such Bicitalia represents a qualified tourist attraction that can set up a chain reaction bringing benefits to all sectors and individuals.

2.2.3.2.2 The National Touristic cycle paths

Another project to implement cycle tourism in Italy is the one of the National Touristic cycle paths proposed by the Ministry of Infrastructure and Transport (MIT) and the Ministry of Arts, Culture and Tourism (Mibact) between 2015 and 2018[101]. Their proposal is inspired by the EU EuroVelo network and offers 10 national cycle paths strategically designed to enhance historical, cultural and

[100] Ibid.

[101] https://www.mit.gov.it/

environmental itineraries. Some of these paths are already existing and viable and the MIT is working to complete them. Through the Leggi di Bilancio of 2016 and 2017 this project has received funding for € 372 million from 2016 to 2024, that combined with the other co-financing reach a total of € 750 million.
Once they will be upgraded and finished, the 10 National Touristic cycle paths will follow these paths[102]:

1) **Ciclovia del Sole**: 300 km, it is part of the Ciclovia del Sole conceived by FIAB in the Bicitalia network[103]. The section already concluded connects Verona to Firenze, and it will reach Roma in the future;

2) **Ciclovia del Garda**: 140 km, a circular itinerary along the shores of the lake Garda, passing through the Provincia Autonoma di Trento, Veneto e Lombardia;

3) **Ciclovia Ven-To**: 680 km, running along the Po river and connecting Venezia and Torino;

4) **Ciclovia Venezia-Lignano Sabbiadoro-Trieste**: 150 km, it is the access to the country for central European tourists, connecting Trieste to Venezia;

5) **Ciclovia Adriatica**: 700 km, along the east coast of Italy, connecting Lignano Sabbiadoro (UD) to Gargano (FG);

6) **Ciclovia Tirrenica**: 1.200 km, along the west coast of Italy, of which more than 700 are already accessible, from Ventimiglia (IM) to Rome;

7) **Ciclovia GRAB (Grande Raccordo Anulare delle Bici)**: 44 km, a circular itinerary inside the city of Rome;

8) **Ciclovia dell'Acqua**: 500 km, requalification of an existing service road running along the main canal of the Apulian Acqueduct, from Caposele (AV) to Santa Maria di Leuca (LE);

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[102] Ibid.

[103] See section 2.2.3.2.1

9) **Ciclovia della Magna Grecia**: 1.000 km, connecting Lagonegro (PZ) to Pachino (SR) to visit the southern regions of Basilicata, Calabria and Sicilia;

10) **Ciclovia della Sardegna**: 1.230 km, across the island from S. Teresa di Gallura (OT) to Sassari.

The National Touristic cycle paths.

Source: https://www.mit.gov.it/

2.2.3.3 An opportunity for the rediscovery of remote territories

The development of cycle tourism and the growing demand for sustainable and experiential holidays, has become an opportunity to switch from mass tourism in favor of more remote or "slow" territories. According to Chafe and Honey[104], tourists

[104] Chafe Z., Honey M., *Consumer Demand and Operator Support for Socially and Environmentally Responsible Tourism*, 2005, Center on Ecotourism and Sustainable Development, Washington, DC. Available online: http://efti.hhp.ufl.edu/wp-content%5Cuploads/Consumer-Demand-for-Responsible-Tourism-2005.pdf

are looking more and more for profound experiences to appreciate local identities of unique and often forgotten territories. For this type of tourism, little-known or remote destinations can be pull factors to combine relaxation and learning.
Remote destinations are usually defined as "slow" territories, referring to their development approach, lifestyle and services. In addition to this, what makes them unique and touristically attractive is their cultural, environmental or historical heritage made of tangible and intangible resources. The condition for ensuring a sustainable development of these "slow" territories is a synergic and systemic combination of local actors and environmental, social and economic activities. In this case, strategic policies can be adopted to enhance the attractiveness potential. According to Caffyn[105], these localities may seek to achieve these results through some measures:

- Highlight slow ways to arrive and shared means of transport;
- Encourage longer stays by suggesting itineraries and scheduled visits;
- Minimize car use by proposing visitors attractive activities in short distances;
- Deliver paths for slow activities like walking and cycling;
- Provide quiet spots for relaxing and enjoy the environment;
- Highlight local heritage and culture by involving tourists in local traditions and festivals;
- Support local producers by promoting their works and products;
- Encourage companies to facilitate slow mobility, in order to overcome infrastructural issues.

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[105] Caffyn A., *Advocating and implementing slow tourism*, in *"Tourism Recreation Research"*, 2012, Vol. 37, pp. 77-80.

Through these adaptations, time, travel and place become key dimensions for an authentic, sustainable, healthy and meaningful experience, with several beneficial effects on "slow" territories economies and preservation.

2.2.4 Obstacles and challenges

In the present day, cycling can be considered a daily mean of transport in the cities or a form of slow tourism to both enjoy and preserve environment and traditions. This phenomenon as the main form of "slow" and sustainable mobility has been at the center of attention in recent years. On one hand, it still has many gaps and shortcuts mainly in eastern and southern EU countries, where there is a need of change in policy making and investment prospects. On the other hand, in northern EU countries where such investments are analyzed and put in place, the economic, environmental and social benefits are tangible. According to Gazzola et al.[106], crucial to determine these results is the definition of planning teams made up of both public and private stakeholders to define strategic tasks and goals, including:

• Highlight success factors and critical issues, that in monetary terms are translated into economic benefits and costs;

• Create a long-term strategy based on the resources of a specific territory;

• Develop an action plan divided into steps, taking into consideration maintenance, failures and external changes.

Within this framework, it has become necessary to introduce tools for the economic evaluation, as the ones examines in the first chapter, to harmonize and clarify the implications of investments in "slow" infrastructure and specifically cycle paths and related services.

[106] Gazzola P., Pavione E., Grechi D., Ossola P., *Cycle Tourism as a Driver for the Sustainable Development of Little-Known or Remote Territories: The Experience of the Apennine Regions of Northern Italy*, in *"Sustainability"*, 2018, 2071-1050, Vol. 10 (6).

Chapter 3

From LCC towards LCCBA for evaluating “slow” mobility projects

When dealing with urban transport systems of all kinds, a series of factors must be considered, that can be directly or indirectly linked to the mobility network. According to Deffner et al.[107], urban mobility system must be considered as cultural processes in continuous evolution, highly dependent on places circumstances and socio-economic conditions. In the case of “slow” mobility and in particular cycle paths, there is not a systematic application of a single customized methodology for the assessment of costs and benefits during the object’s whole life cycle. As outlined in section 1.4, the LCC Analysis is usually limited to the costs affecting the owner / investor, meaning initial investment costs and maintenance and failure costs. This approach rules out the other three essential variables for an accurate evaluation: user costs, social costs and environmental costs.

Instead, these variables are taken into consideration in the LCCB Analysis, as anticipated in section 1.4.2. The traditional formulation, reviewed by the PhD Professor Thoft-Christensen[108], is expressed as:

$$LCCBA = LCCB - LCC$$

The aim of this 3rd chapter is to introduce a passage from the consolidated LCC model towards the development of a LCCBA formulation, starting from the analysis of the full range of costs. This transition is therefore characterized by an implementation of the common LCC cost items with the costs that are more difficult to assess, but not less influential on the final evaluation. In this preliminary LCC-to-LCCBA model switch, only the costs will be considered, leaving the benefits analysis to further developments.

[107] Deffner J., Schubert S., Potting C., Stete G., Tschann A., Loose W., *Entwicklung eines integrierten Konzepts der Planung, Kommunikation und Implementierung einer nachhaltigen, multioptionalen Mobilitätskultur*, Frankfurt Am Main, Institut Für Sozial-Ökologische Forschung. 2006.

[108] Thoft-Christensen, op. cit., p. 59.

3.1 Cycle paths investments and cost implications

Cycle paths investments must be considered as a form of sustainable mobility development, that operates thanks to improved infrastructure and facilities for both cycle tourists and locals[109]. To ensure the correct functioning of this complex system, it is necessary to understand and conceptualize all the cost dynamics that must be faced by the different stakeholders during the system's life cycle. In the LCC-to-LCCBA model switch, the integration of all the required cost items details the sum of the LCC elements in the following way:

$$\textit{Expected Costs (LCC)} = C_{owner} + C_{user} + C_{society} + C_{environment}$$

These four subtotals, represented by owner costs, user costs, social costs and environmental costs, are the four cost macro-categories that must be taken into consideration when assessing the life cycle cost of a bicycle infrastructure.
Of course, to examine the overall economic efficiency of a cycle path, the financial outflows determined by the cost items must be then balanced by direct and indirect inflows produced by different types of benefits. Furthermore, all the flows must be adjusted according to:

- Fiscal corrections;
- Prices conversion from market to "shadow" values;
- Non-market impacts and externalities
- Discount rates (usually ranging between 3-5%).[110]

In the following sections, the four general cost items will be analyzed in detail, presenting the sub-categories involved and their economic influence. Some of the following sub-categories are well-known and taken into consideration in traditional LCC Analysis of various building elements; some others, strictly linked to the life

[109] Nilsson J. H., *Urban bicycle tourism: path dependencies and innovation in Greater Copenhagen*, in *"Journal of Sustainable Tourism"*, 2019, Vol. 27 (11), pp. 1648-1662, DOI: 10.1080/09669582.2019.1650749.

[110] Hromádka V., Shashko M., *Risk and Efficiency of Bicycle Paths*, in *"Procedia Computer Science"*, 2015, Vol. 64, pp. 758-763.

cycle of bicycle paths, will be added after the examination of international projects and existing infrastructures.

3.1.1 Owner costs

In general, owner costs include all the costs that the owner, that can be either a private or public institution, must face over the entire life of the project. According to Hromádka et al.[111], the recent experiences prove that the composition of initial investment costs cycle path projects seem to be very similar to the ones of road and highway infrastructures. In the 2018 EUPAVE (European Concrete Paving Association) guide[112], the typical costs for pavements are represented by all the initial investment costs, that usually range from 50 to 90% of the owner's total costs and the management costs, including the process of end of life. Initial owner costs must be divided into non-construction and construction costs, that in this case can be defined as non-pavement and pavement costs.

Non-construction costs are not directly linked to the physical realization of the structure, but they affect considerably the overall cost of the project. They include:

• **Cycle path design** at all stages, from the preliminary phase to the final executive project, regarding the type of cycle path, its structure and materials and the expected initial design life;

• **Related services design**, thinking of bike parking, bike sharing stations, hostels, restaurants, maintenance structures for bikes and rest equipped and non-equipped areas;

• **Construction fees**;

• **Administrative costs**;

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[111] Ibid.

[112] Diependaele M., *A guide on the basic principles of Life-Cycle Cost Analysis (LCCA) of pavements*, EUPAVE, Brussels, 2018.

• **Promotion costs** for the creation of tools to publicize the project, meaning a website, a smartphone app, paper and digital maps, events and workshops to involve citizens and tourists.

More specifically, the details of a bike plan process costs from the point of view of the owner are summarized by the NSV Government of UK into a 3 phases process divided into a series of steps[113]:

Phase	**Step**
A: Preliminaries	1. Budget, staff and timing
	2. Management team set up
	3. Review of existing planning and delivery documents
	4. Review of the land use planning context
	5. Goals setting
	6. Preparation of a project brief
	7. Determination of the bike plan's structure
	8. Work with the communications team
B: Preparation of the bike plan	1. Data collection to understand cycling in the area
	2. Existing routes and infrastructures assessing
	3. Proposed routes identification
	4. Routes network mapping
	5. Cyclists' requirements planning and design
	6. Network priorities setting
	7. Bicycle program's costs estimate
	8. Cycling promotion in the area
	9. Promotion of road awareness and safety
	10. Employer programs encouragement
	11. Funding streams identification

[113] NSV Government, *How to prepare a bike plan*, Roads and Maritime Services, 2012. Available online: https://www.rms.nsw.gov.au/business-industry/partners-suppliers/lgr/downloads/programs/documents/bikeplan.pdf

	12. Establishment of an implementation plan
	13. Bike plan development review
C. Bike plan finalization	1. Public exhibition of the bike plan draft
	2. Bike plan finalization
	3. Launch of the bike plan

Summary of a typical bike plan process.

Source: Author's re-elaboration from: Taylor I., Hiblin B., *Typical costs of cycling interventions: Interim analysis of Cycle City Ambition schemes*, 2017, Report to the Department of Transport, UK, p. 4.

As in the case of building or highways projects, pavement costs basically include labour and works supervision, materials, equipment and transport. In the case of cycle paths, some fixed elements must be considered, such as the subgrade and base preparation, surface making and signs installation. Another set of variables can be taken into consideration to obtain a complete picture of different options and additional benefits:

• **Construction or installation of related services**, such as: bike parking, bike sharing stations, hostels, restaurants, maintenance structures for bikes and rest equipped and non-equipped areas;

• Continuous **balustrades** in the case of proximity to rivers and lakes or other elements of possible danger;

• **Vehicles traffic barriers** in the cities, which depending on the degree of safety required can be designed as light or heavy segregation[114];

• **Cycle bridges** in the case of waterways crossing, that can be new or upgraded, made of non-slip surfacing material and equipped with ramps at comfortable gradients for cyclists[115];

[114] Taylor I., Hiblin B., *Typical costs of cycling interventions: Interim analysis of Cycle City Ambition schemes*, 2017, Report to the Department of Transport, UK. Available online: http://www.transportforqualityoflife.com

[115] NSV Government, op. cit.

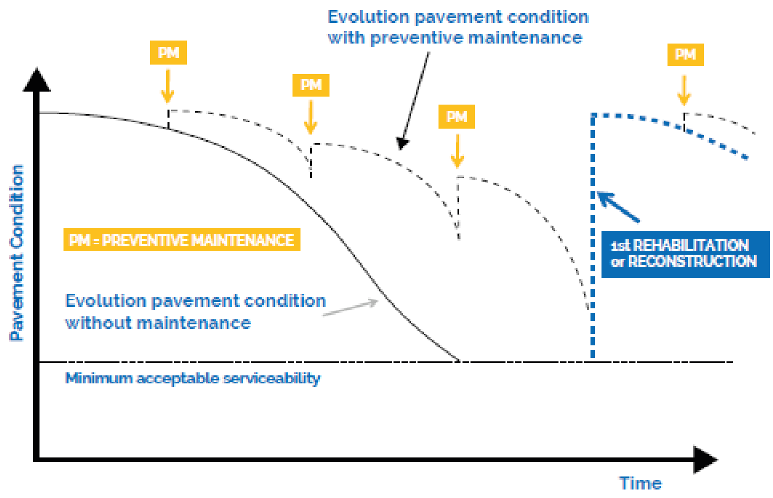
• **Safety cameras** to guarantee protection and safety for users;

• **Night electric power** to allow the use of the cycle path at all hours.

The initial investment costs are followed by the management costs, that start from the first day of service life of the system, until its end of life with its implications. The elements that must be considered in this long phase are:

• **Maintenance costs**, that can be of two types, with a significant difference in terms of final costs. On one hand, ordinary and preventive maintenance can be previously programmed, with the allocation of a budget to face the costs, that are usually low-impact and regular. In the case of cycle paths, some necessary ordinary maintenance intervention can be represented by resurfacing, signs and barriers substitution, vegetation containment, equipment replacement and so on. On the other hand, the extraordinary and emergency maintenance is characterized by unexpected events, such as natural disasters or other external events that cause damages to the system. This kind of maintenance is usually unplanned and involves significant costs that should be included in the maintenance budget despite the uncertainty that characterizes them.
It is essential to underline that even if routine maintenance costs are usually not excessively high, their role in keeping high performance and accessibility levels cannot be underestimated, since it can affect significantly the NPV[116];

[116] http://www.pavementrenewal.org/docs/LifeCycleCosts.pdf



Evolution in time of a pavement's condition, when taking into consideration the maintenance processes.

Source: Diependaele M., *A guide on the basic principles of Life-Cycle Cost Analysis (LCCA) of pavements*, EUPAVE, Brussels, 2018, p. 10.

• **Operation costs**, that involve the management and promotion costs of the cycle path itself and all the related services, incorporating organization expenses of connection to other means of transport, hostels and restaurant and public spaces cleaning. Operation costs are represented also by the continuous cost of an alleged night lighting system and the owner's insurance in presence of damages or accidents;

• **End of life costs** must not be neglected, since dismantling and disposal can be often expensive. In this phase, the possibility of structure's rehabilitation, change of use of materials recycling can be good options to reduce costs and waste.

3.1.2 User costs

The importance and criticality of user costs has already been introduced in section 1.4.1.3; this topic is complex and presents many variables, which, if ignored, could lead to a non-acceptance of the project by the community and therefore to its social and economic failure.

User costs are represented by the costs incurred by the cycle path user over the life of the system and they are the direct consequence of the owner long-term decisions and the related management implications.

The **Road Used Cost (RUC)** formula is based on highway projects, but it can be adapted to the case of cycle paths by slightly revising the cost items[117]. The original formula of the Texas Department of Transportation[118]:

$$RUC = VOC + AC + VOT$$

Where:

VOC = Vehicle Operating Costs must not consider the expenses related to motor vehicles, but still there are costs of maintenance and depreciation, even if they are of course less significant than in the original case;

AC = Accidental Costs remain in the formula, even if the risk of fatal accidents and non-fatal accidents should be significantly reduced in the case of a cycle path. The formula for Accidental Costs proposed by Daniels et al.[119] is the following:

$$AC = FA + NFA + (PDO)\ x$$

Where:

FA = Fatal accidents;

NFA = Non-fatal injury accidents;

PDO = Property damage only accidents:

x = Adjustment factor for unreported PDO accidents.

VOT = Value of Time, function of the hourly wage rate, remains a crucial element, but in the case of cycle infrastructure it is not conditioned by the traffic variable, as in the case of roads and highways.

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117 Zhu Y., Ahmad I., Wang L., *Estimating Work Zone Road User Cost for Alternative Contracting Methods in Highway Construction Projects*, in *"Journal of Construction Engineering and Management"*, 2009, Vol. 135 (7), pp. 601-608.

118 Daniels, op. cit., p. 602.

119 Daniels, op. cit., p. 604.

The RUC formula can be classified into quantifiable and non-quantifiable effects. The three elements taken into consideration here are the monetary factors VOC, AC and VOT, while the non-monetary Quantifiable effects include monetary and nonmonetary factors should include in the analysis environmental impact and comfort.

Another element that must be taken into consideration are the user costs related to maintenance operations. According to the 2018 EUPAVE guide[120], these types of costs can be divided into two categories:

• User costs caused by **ordinary maintenance operations**, that in the case of cycle paths are nearly null, since the problem of traffic due to reduced space hardly arises;

• User costs caused by the so-called **"work zone operations"**. This category must be taken into consideration for extraordinary maintenance operations or major rehabilitation that can cause the interruption of the entire service or its partial operation for a period of time. Work zones for roadways and highways usually result in "congestion and traffic delays, leading to increased driver frustration, traffic accident, and road user delay cost."[121] In the case of cycle paths, this process involves the use of another means of transport and therefore additional charges, the possibility of delays and accidents and the user's frustration.

In a 2013 case study involving a road network in Portugal[122], the authors demonstrated through the Pareto optimization[123] that for this type of infrastructure the owner or agency costs weight value corresponds to 4% of the entire life cycle, while the user cost weight value can reach 96% at the end of the process. Of course, the costs for highways and vehicular roads cannot be compared with those of a cycle

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[120] Diependaele, op. cit.

[121] Jiang X., Adeli H., *Freeway Work Zone Traffic Delay and Cost Optimization Model*, in *"Journal of Transportation Engineering"*, 2003, Vol. 129 (3), pp. 230.

[122] Meneses S., Ferreira A., *Pavement Maintenance Programming considering Two Objectives: Maintenance Costs and User Costs*, in *"The International Journal of Pavement Engineering"*, 2013, Vol. 14 (2), pp. 206-221.

[123] For the Pareto optimization, see section 1.4.1.1

path, but once again this demonstrates how user costs can dominate the decision process.

3.1.3 Environmental costs

The construction and management of a new road network implies environmental impacts that can be quantified into environmental costs. The three main elements that must be taken into consideration as substantial impact variables are:

• The **embodied energy of materials**, which is "the total energy required for the extraction, processing, manufacturing, and delivery of buildings. Unlike the life cycle assessment, which evaluates all of the impacts over the whole life of a material or element, embodied energy only considers the front-end aspect of the impact of a building material. It does not include the operation or disposal of materials"[124];

• The **embodied carbon of materials**, meaning the global quantity of CO_2 emitted for the production of a specific material, from the extraction phase to transport and manufacturing[125];

• The **greenhouse gas (GHG) emissions** involved in the construction phase and in a lower quantity in the management phase of the system.

A 2020 research made at the Indian Institute of Technology Tirupati[126], provided a systematic methodology to quantify the total energy consumption and greenhouse gas emissions caused by the construction of pavements. This recent study is a starting point to introduce the same kind of process for cycle paths, with lower costs and emissions than roads and highways.

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[124] https://ec.europa.eu/energy/eu-buildings-factsheets-topics-tree/embodied-energy_en

[125] https://www.ucl.ac.uk/engineering-exchange/sites/engineering-exchange/files/fact-sheet-embodied-carbon-social-housing.pdf

[126] Singh A., Vaddy P., and Biligiri K. P., *Quantification of Embodied Energy and Carbon Footprint of Pervious Concrete Pavements through a Methodical Lifecycle Assessment Framework*, in *"Resources, Conservation and Recycling"*, 2020, Vol. 161.

According to the research, “while energy consumption and emissions in transportation sector are often related to burning of gasoline through vehicles, construction and maintenance of pavements is also causative for substantial energy consumption and greenhouse gas (GHG) emissions.”[127]

For example, in the case of cement and concrete pavements, the process from-cradle-to-grave[128] is energy-and-carbon-intensive. Starting from cement, which is one of the materials with the highest environmental footprint, the necessary energy for the production of 1 ton of concrete is 1.4 GJ, mostly generated by fossil fuels burning[129] and its embodied CO_2 is approximately 5-13% of its total weight[130].

Even if more than 50% of emissions occur during the material production and the construction of pavements, it is important to be aware that the environmental impacts and cost must be quantified also during maintenance and rehabilitation phases over the entire life of the system.

The research by Singh et al.[131] developed two equations for the quantification of total embodied energy and total CO_2 emissions for pavement systems:

$$Total\ embodied\ energy\ \left(\frac{MJ}{km}\right) = \sum\Big(1000\ x\ W\ x\ (T\ x\ Dn\ x\big(Pe + Me + (Te\ x\ Di)\big) + Ce\Big)$$

$$Total\ kg\ CO2\ eq./km = \sum\Big(1000\ x\ W\ x\ (T\ x\ Dn\ x\big(Pg + Mg + (Tg\ x\ Di)\big) + Cg\Big)$$

Where:

W = width of the road in m;

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[127] Ibid., p. 1.

[128] https://circularecology.com/glossary-of-terms-and-definitions.html

[129] National Ready Mixed Concrete Association (NRMCA), *Concrete CO2 Fact Sheet*, Virginia, USA, 2008. Available online: http://www.nrmca.org/greenconcrete/concrete%20co2%20fact%20sheet%20june%202008.pdf

[130] Chappat M., Bilal J., *The environmental road of the future: life cycle analysis. Energy Consumption and Greenhouse Gas Emissions*, 2003. Available online: http://www.colas.com/sites/default/files/publications/route-future-english_1.pdf

[131] Singh, op. cit., p. 4.

T = thickness of layer in m;

Dn = density of pavement material in kg/m^3;

Pe = material production value in MJ/kg;

Pg = material production value in kg CO_2 eq./kg;

Me = material mixing value in MJ/kg;

Mg = material mixing value in kg CO_2 eq./kg;

Te = transport from production site to application site in MJ/kg-km;

Tg = transport from production site to application site, kg CO2 eq./kg-km;

Di = distance from material production site to application site in km;

Ce = material compaction value in MJ/m^2;

Cg = material compaction value in kg CO2 eq./m^2.

All the material values refer to the two distinct equations for the energy consumed (total embodied energy formula) and the GHG emissions produced (total kg CO_2 formula). The material production values *Pe* and *Pg* are related to the production of a unit quantity of the pavement material, the material mixing values *Me* and *Mg* refer to the mixing phase of a unit quantity of the pavement material and the material compaction values *Ce* and *Cg* the energy relate to the compaction phase.
Whereas the costs will be significantly lower than the ones for vehicular roads, these equations can be adapted to the field of cycle infrastructure to assess their environmental impact, by simply quantifying the values expressed in the equations for a selected cycle project.

3.1.4 Social costs

In addition to the costs listed in the sections above, another essential factor that must be considered in a LCCB Analysis is the relationship between costs and benefits in the social field. Since this study analyzes the costs, all the benefits related to cycle networks and the practice of cycling listed in section 2.2.3 are at this moment neglected. However, it is important to underline that in the case of a cycle network project the social costs to be taken into consideration, unlike the case of a road or highway, are almost null. In fact, invasive and vehicular road network produce a set of serious social issues and costs as described by Surahyo et al.[132]:

• Human health costs caused by toxic vehicular emissions;

• Human comfort costs caused by "construction disturbance" and long-term noise pollution, leading to elevated stress levels and behavioral effects;

• Property value reduction due to noise and visual pollution, reflecting on adjacent private properties, cultural heritage and recreational public spaces;

All these issues are minimized in the case of cycle networks and the only factors that can have a significant impact, even if less relevant than the other cost categories, are:

• The **"construction disturbance"** issue, given by the negative social impacts of noise pollution and toxic emissions during the construction phase and the social discontent over the use of economic resources;

• The **social discontent over the use of economic resources**, which is a more subjective factor referring to the society disagreement on the allocation of economic funds for a cycle path at the expense of other necessary services.

[132] Surahyo M., El-Diraby T. E., *Schema for Interoperable Representation of Environmental and Social Costs in Highway Construction*, in *"Journal of Construction Engineering and Management"*, 2009, Vol. 135 (4), pp. 254-266.

Chapter 4

Simulation and final considerations

At this stage of the study, the work aims at defining a sort of guideline by summarizing in more technical and quantifiable terms the cost items described in the previous chapter. By modifying an LCC model-based spreadsheet for buildings construction and management it is possible to define in detail and systematize all the cost items that characterize the construction and management of a cycle network. The process is structured in two parts; in stage one the cost items involved in the construction and development of a cycle paths are summarized and described in a generic spreadsheet. At a later stage, these outflows are substituted in a traditional LCC approach generally applied to building development.

4.1 Reformulation of cost items

As first step for the elaboration of the classic LCC approach, the costs presented in chapter 3 have been summarized in a generic spreadsheet, together with a synthetic description and/or specification of each cost item. In such way, all the stakeholders are included in the cost analysis taking into consideration many different variables related to the project features. Each basic expense has been analyzed and branched to detailed expenses according to the essential, but also optional characteristics of a cycle network. Starting from this descriptive spreadsheet, it is possible to adapt the cost items to a specific project design and create the conditions for the LCC model variation with the subsequent quantification and cash flows identification.

Cost type	Cost description/specification
OWNER COSTS	
Initial investment cost (50-90% of total cost)	All owner costs required to start and put into operation the project
Non construction costs	All owner costs, other than construction costs, occurring for the project realization
Administrative costs	Administrative and bureaucratic expenses and salaries for non-technical works
Construction fees	Expenses for the payment of consultants and the use and development of soil
Cycle path design	Design of pavement type, structure and expected initial design life
Related services design	Design of rest equipped areas, bike parkings, bike sharing stations, bike rental, repair shops, etc.
Promotion costs	Creation of a website, smartphone apps, digital and printed maps, workshops and events
Construction costs	All owner costs for the construction of the cycle path and related services (subgrade preparation, base, surface, signs, related services and public areas, balustrade, light or heavy vehicle traffic barriers, cycle bridges, safety cameras, etc.)
Labour and supervision	Technical labour, excavations, subgrade and base preparation, equipments installation, etc.
Materials	Building materials according to the project specifications
Equipment	Signs, balustrades, vehicle traffic barriers, cycle bridges, safety cameras, related services and public areas, etc.
Transports	Materials and equipment transport from production to construction site
Management costs	All owner costs required for the administration and operability of the project
Operation costs	Expenses related to the day-by-day project operation
Management and promotion costs	Promotion tools management and related services organization (connections to other means of transport, hostels, restaurants, etc.)
Electric power	Night lighting, bridges signalling
Insurances	For the legal protection of the owner throughout the life and operation of the project
Maintenance costs	Costs to keep the asset in acceptable working conditions
Ordinary preservative maintenance	Vegetation containment, public spaces cleaning, replacement and adjustment of cycle path's elements
Extraordinary maintenance	Rehabilitation, damages caused by external events
End of life	Expenses related to the disposal, demolition or change of inteded use of the asset at the end of its service life
Dismantling costs	Removal of plant and equipment
Disposal costs	Discard of the asset

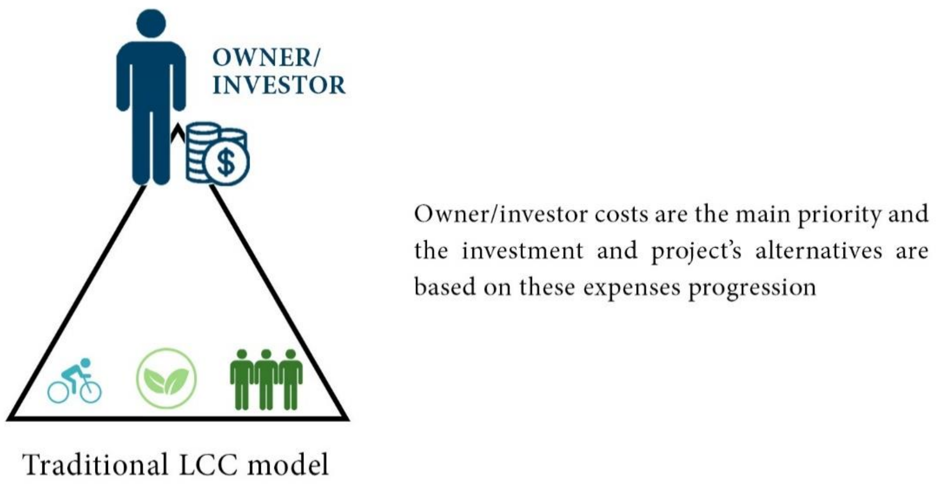
USER COSTS	
VOC - Vehicle operating costs	Costs associated with a correct functioning of the means of transport
AC - Accidental costs	Fatal and non-fatal accidents
VOT - Value of Time	Equivalent amount of money that users would pay to reduce travel time (function of the hourly wage rate)
Delay costs due to ordinary maintenance	Monetization of the user delay caused by ordinary maintenance operations (cleaning, substitutions, etc.)
Delay costs due to extraordinary maintenance	Monetization of the user delay caused by extraordinary maintenance operations, defined as "work zone operation costs"
ENVIRONMENTAL COSTS	
Embodied energy of materials	Energy required from the extraction to the delivery of building materials
Embodied carbon of materials	CO_2 emitted for the production of building materials
GHG emissions	GHG emitted during the construction and management phases
SOCIAL COSTS	
Construction disturbance costs	Impact of noise, visual pollution and toxic emissions during the construction phase
Discontent over the use of economic resources	Allocation of economic resources at the expense of other necessary services

Descriptive spreadsheet for cost items in cycle path LCC operative modality variation.

Source: Author’s elaboration

4.2 Features of the new operative modality

The descriptive Excel spreadsheet shown above is the fundamental starting point for the re-elaboration of the traditional LCC approach. Once the cost items have been analyzed and defined, they can be included in a basic LCC spreadsheet for buildings construction and management, by replacing the cost items related to the field of study of this research. Some costs will remain the same, although at a quantitative level there will certainly be substantial differences between the expenses for buildings construction and management and the ones for cycle paths development. As specified above, other expenses will be added in their entirety to the model, since they represent the outflows that are usually not considered in traditional LCC Analysis: user costs, environmental costs and social costs. The main difference between the two spreadsheet is represented by the attention given to these additional cost items, which constitute the point of view of all the stakeholders without giving importance exclusively to the costs incurred by the owner/investor.



Graphic representation of costs breakdown in the traditional model and the new formulation adapted to cycle paths.

Source: Author's elaboration

costs quantification (numeric data)

costs are spread in a timeline subdivided into yearly periods according to the entity of the project

		Quantity	Unit cost	Total	%	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year n	Year n+1	
						works starting + work finishing at a specified time											
OWNER COSTS																	
Non construction costs																	
Administrative costs	%					%	%	%	%	%	%	%	%	%	%	%	*100%*
Construction fees	%					%	%	%	%	%	%	%	%	%	%	%	*100%*
Cycle path design	m^2					%	%	%	%	%	%	%	%	%	%	%	*100%*
Related services design	m^2					%	%	%	%	%	%	%	%	%	%	%	*100%*
Promotion costs	€					%	%	%	%	%	%	%	%	%	%	%	*100%*
Total 1																	
Construction costs																	
Labour and superivison	€/m^2					%	%	%	%	%	%	%	%	%	%	%	*100%*
Materials	€/m^2					%	%	%	%	%	%	%	%	%	%	%	*100%*
Equipment	€/m^2					%	%	%	%	%	%	%	%	%	%	%	*100%*
Transports	€/m^2					%	%	%	%	%	%	%	%	%	%	%	*100%*
Total 2																	
				Yearly total		**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Year 7**	**Year 8**	**Year 9**	**Year n**	**Year n+1**	
Management costs																	
Operation costs																	
Management and promotion costs	%					%	%	%	%	%	%	%	%	%	%	%	*100%*
Electric power	%					%	%	%	%	%	%	%	%	%	%	%	*100%*
Insurances	%					%	%	%	%	%	%	%	%	%	%	%	*100%*
Maintenance costs																	
Ordinary preservative maintenance	%					%	%	%	%	%	%	%	%	%	%	%	*100%*
Extraordinary maintenance	%					%	%	%	%	%	%	%	%	%	%	%	*100%*
End of life																	
Dismantling costs	€/m^2					%	%	%	%	%	%	%	%	%	%	%	*100%*
Disposal costs	€/m^2					%	%	%	%	%	%	%	%	%	%	%	*100%*
Total 3																	
Total owner costs																	
Inflation	%		year														

total owner costs quantification

				Yearly total		Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year n	Year n+1	
USER COSTS																	
VOC - Vehicle Operating Costs	€					%	%	%	%	%	%	%	%	%	%	%	*100%*
AC - Accidental Costs	€					%	%	%	%	%	%	%	%	%	%	%	*100%*
VOT - Value of Time	€					%	%	%	%	%	%	%	%	%	%	%	*100%*
Delay costs due to ordinary maintenance	€					%	%	%	%	%	%	%	%	%	%	%	*100%*
Delay costs due to extraordinary mainten:	€					%	%	%	%	%	%	%	%	%	%	%	*100%*
Total user costs																	
				Yearly total		Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year n	Year n+1	
ENVIRONMENTAL COSTS																	
Embodied energy of materials	MJ/kg					%	%	%	%	%	%	%	%	%	%	%	*100%*
Embodied carbon of materials	kg CO_2e					%	%	%	%	%	%	%	%	%	%	%	*100%*
GHG emissions	kg CO_2e					%	%	%	%	%	%	%	%	%	%	%	*100%*
Total environmental costs																	
SOCIAL COSTS																	
Construction disturbance costs	€					%	%	%	%	%	%	%	%	%	%	%	*100%*
Discontent over the use of economic resources	€					%	%	%	%	%	%	%	%	%	%	%	*100%*
Total social costs																	
TOTAL COSTS																	

quantification of the sum of owner + user + environmental + social costs

LCC spreadsheet re-elaboration with reference to cycle path projects. Source: Author's elaboration

The LCC variation is obviously not complete, since the benefits that can be achieved in the life cycle of a cycle network are not introduced. In fact, the work focuses on the elaboration of outflows, neglecting in this first phase of the research the life cycle financial incomes. It was decided to strictly concentrate on the issue of costs in order to deepen in detail all the variables which may occur in a cycle path project. This way, the study opens the way to the subsequent development of a complete LCCBA model, including the definition and quantification of owner, user, environmental and social benefits. Once the inflows and outflows are defined and quantified, it is possible to define the trend of cash flows through the years and calculate the Net Present Value (NPV), obtaining specific information on a project's economic preferability. In any case, already at this stage of the process, a project evaluation based on total costs can be made. With the definition a specific project and quantifiable data, the LCC variation spreadsheet can be completed to examine the economic sustainability of that particular case and to compare more or less preferable alternatives.

Conclusions and development scenarios

The objective of this study was to select an appropriate tool for the economic evaluation of “slow” mobility projects through their life cycle, focusing particularly on the case of cycle networks. First, an analysis of solid existing methodologies for projects’ economic evaluation has been made and in turned out that the most suitable one for this research field is the Life Cycle Costing (LCC) Analysis integrated with a Cost-Benefit Analysis (CBA). It has emerged over the years that the two methodologies, with their strength and some deficiencies, can be incorporated to give life to Life-Cycle Cost-Benefit Analysis (LCCBA) model, that operates on the LCC approach with the inclusion of benefits for a more coherent and comprehensive evaluation.

The importance of the recently developed LCCBA model is linked to the involvement of cost items that are usually neglected in traditional LCC analysis. As PhD Professor Thoft-Christensen anticipated, the impact on total costs of a project is influenced not only by the typically analyzed owner/investor costs, but also by user, environmental and social costs.

A deepening on the application framework introduced the case of public infrastructure management, first in a general context and then focusing on “slow” mobility and cycle networks. A survey on European policies and cutting-edge case studies allowed a better understanding of cycle paths investments. This led to the definition of significant cost items in this field, including the expenses generally ignored. As a result, owner costs, user costs, social costs and environmental costs, represent the four cost macro-categories that must be taken into consideration when assessing the life cycle cost of a bicycle infrastructure. These four cost groups are detailed in sub-categories, among which some are well-known and taken into consideration traditional LCC Analysis of building elements, while some others, strictly linked to cycle paths construction and management, have been added after the examination of the literature about international projects and existing networks. The definition of these cost items opens the way to the variation of the traditional LCC model covered by the last part of the research. A new LCC spreadsheet is proposed for cycle infrastructures at a theoretical and methodological level, with the scope of defining a guideline adaptable to a large number of cycle projects.

The study presented aims at opening the door to further developments of the LCC variation. Further researches could lead to the definition of owner, user, environmental and social benefits over the life cycle of a bicycle path to be able to define cash flows over the years and examine the sustainability indicators.

This first step towards a complete LCCBA model for cycle infrastructure construction and management already allows the adaptation of the spreadsheet to projects with quantified data. This way, the economic sustainability of an investment can be evaluated with only the use of simple spreadsheets, taking into consideration the stakeholders directly or indirectly involved in the process and offering the possibility to compare different alternatives and select the more suitable in terms of cost.

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