

Article

Sustainability Analysis of the M-30 Madrid Tunnels and Madrid Río after 14 years of Service Life

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Abstract: In 2007, the excavation of the M-30 ring road located in Madrid and the creation of a green corridor either side of the Manzanares river brought significant change to the metropolitan area. The corridor and linear park which it provided were designed to contribute to the regeneration of the fluvial ecosystem, establish links among residents on each side of the river and promote cultural and leisure activities. This paper provides a sustainability analysis of the excavation of the M-30 (involving the socio-economic and environmental impact) 14 years after its construction. In order to show such an impact, an analysis of the area both prior to the project and after completion, as well as a hypothetical solution that uses improved materials, has been performed. This entails use of the multi-criteria decision-making model named MIVES (initials in Spanish, modelo integrado de valor para una evaluación sostenible). The MIVES method is based on the application of value functions of sustainability indicators selected by socio-economic and environmental criteria, chosen by experts. Results from analysis showed that the excavation of the M-30 considerably improved the sustainability of the area (sustainable index 3.43 and 6.26 both before and after the excavation works). However, use of improved materials in contrast with the application of conventional materials slightly improved the sustainability of the work (Sustainability Index 6.26 and 6.74, respectively, of the conventional materials).

Keywords: sustainability; MIVES method; tunnels; construction materials; M-30

1. Introduction

The city of Madrid holds about 3.5 million of inhabitants and its metropolitan area is over 6 million [1]. These factors make Madrid the largest city in Spain and the fourth largest city in the European Union [2].

Madrid has worked on enhancing the sustainability of the city by improving transport infrastructure (such as urban ring roads and high occupancy vehicle lanes), green areas (such as Madrid Río linear park), the recycling system and supporting green business, among others [3]. As it is known that the improvement of transport infrastructures is vital for the socio-economic development, and also to improve mobility and safety [4–6], infrastructure investments play a major role on the sustainability of the cities. Additionally, sustainable transport entails a significant contribution on reaching urban sustainable development [7].

Madrid is surrounded by three ring roads (M-30, M-40, and M-50), Figure 1. The M-30 is the busiest one and that which passes closest to the city center, contributing 24.2% of the metropolitan area daily traffic and 9.4% of that of the greater Madrid region, with an average annual daily traffic about

200,000 vehicles/day [8]. Its total length is about 32 km, with a generic configuration of 3 + 3 lanes except on the north part where it is an urban boulevard [1].

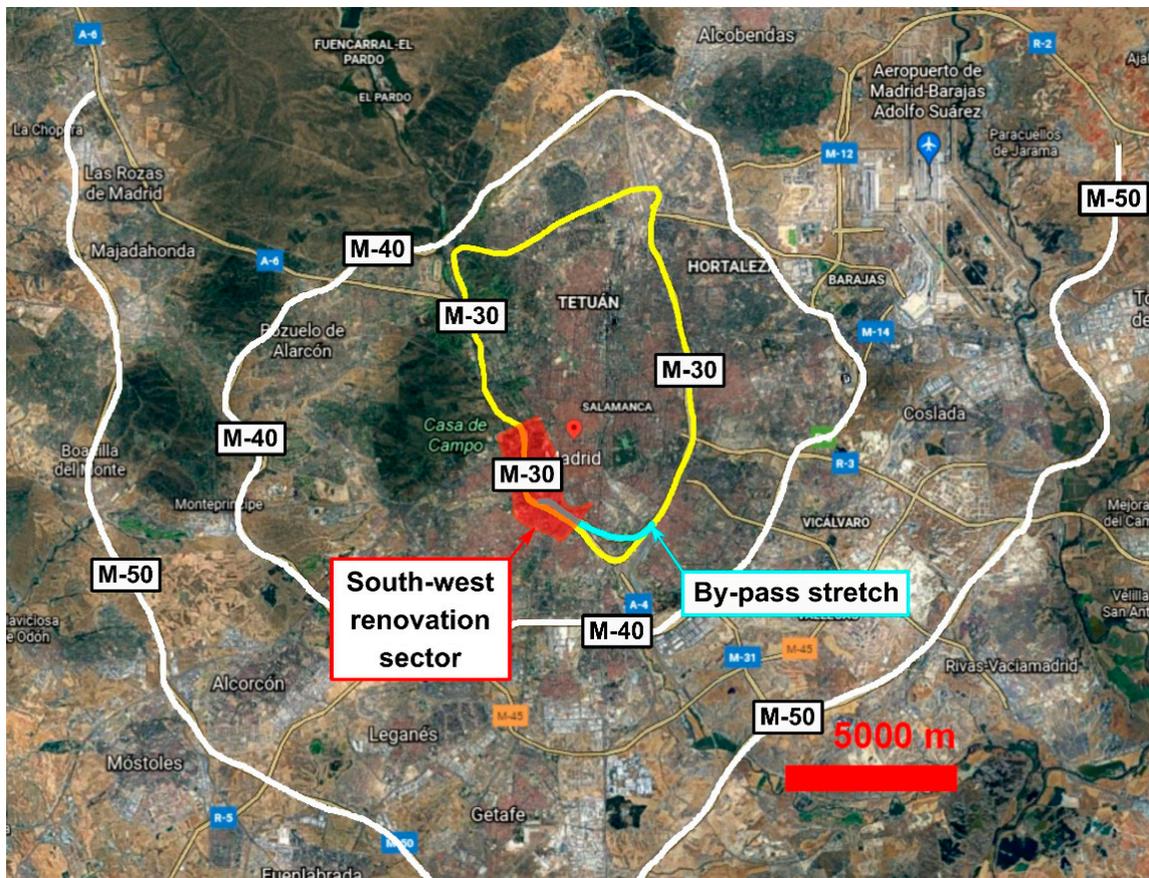


Figure 1. Location of the M-30 ring-road and surrounding districts. South-west area renovated in 2004–2007 to build the tunnels and Madrid Río park is highlighted in red.

It was built during the 1970s and 1990s with a heterogeneous design, combining sections with highway and urban characteristics regulated by traffic lights. Although this diversity of sections still exists, during its first years the M-30 encountered issues which concurrently compromised road safety in the area (an average 600 accidents and eight deaths per year from 1998 to 2002, [9]). One of the main reasons was an excessive amount of entrances and exits from the main stem and several (and too short) transfer sections between side and central lanes [9]. Furthermore, the M-30 is located in close proximity to the city center and crosses built-up areas, which has caused several environmental problems such as noise and air pollution [10]. These issues were especially severe on the west sector where the highway flowed over an extremely developed area, causing a significant barrier effect [9]. Therefore, a renovation of layout was needed to improve socio-economic and environmental conditions.

In such a way, renovation (carried out from 2004 to 2007) sought to increase the road service level and improve comfort and environmental conditions both of the road and the surrounding areas. Road service level was improved by homogenizing and relocating part of the road underground (with 8.8 km of tunnels being constructed [8]), reducing the accident rate and traffic congestion in the area. Such comfort and environmental conditions were improved by creating a new green corridor located in the south-west part of the city, Figure 1 [10]. This corridor aimed to decrease the environmental impact and fluency problems caused by the barrier effect of the road in nearby neighborhoods [8–10].

In this study, the sustainability analysis of the M-30 focuses on the works performed in its south-west stretch. This area was that most influenced by the new road design due to the burial of the layout and creation of a new green corridor, and public open space, named Madrid Río. The tunnels of this section were built through use of two typologies: an opencast tunnel with screen walls and a false ceiling (next to the Manzanares river) and a tunnel built by using two tunnel boring machines (TBMs) (a by-pass stretch, as shown in Figure 1) [11]. The tunnels offer high safety measures, such as accident and fire prevention, as well as several units and devices to control and ensure a suitable air quality. Indeed, they are fitted with a high amount of ventilation stations with ventilation areas about 600 m long to dilute the pollutant concentration inside of the tunnels [12]. Madrid Río is a linear park with 429 hectares of new green areas distributed along the banks of the Manzanares river with the aim of integrating the river environment into the urban landscape of Madrid [13]. Thus, the park offered not only an improvement of the environmental conditions but also eliminated the previous road barrier, linking the south with central Madrid, thus producing extensive urban regeneration of the area [14]. The materials used to build the tunnels should also be taken into account, as it is known that cement production contributes to global warming with 7–8% of global CO₂ emissions [15]. The most effective ways to reduce emissions caused by such production entail incorporating by-products or waste materials as aggregates or reducing the amount of cement used and thus substituting part of the cement with by-products such as, among others, fly ash [15,16]. In this case, the tunnels were built by using conventional concrete. Such concrete types are those with a compression resistance of 20–30 MPa, reaching 35–45 MPa when used in pre-stressed concrete. Improved concretes are used when specific characteristics are required, such as self-compacting, high-strength, or lightweight types [17]. Considering use of improved concretes, such as the high-strength ones (compressive strength higher than 50 MPa [18]), it should be noted that dosage would differ from that of conventional concretes. These kinds of concretes use a higher amount of cement (400–500 kg/m³), lower water/cement ratio (less than 0.3), incorporate additives and additions such as superplasticizers and silica fume (in addition, the nature, type, and maximum size of the aggregates should also be carefully studied [17–19]). These concrete types can be of significant interest to improve the lifespan of the infrastructure, although they can affect to a greater extent the carbon footprint of the construction works. Moreover, the use of special concrete requires more technology and prior studies which could imply longer execution times. Hence, any assessment of the most sustainable solution should require thorough study.

The method applied to estimate the sustainability of the works performed on the south-west stretches of the M-30 is the multi-criteria decision-making model named MIVES (initials in Spanish, *modelo integrado de valor para una evaluación sostenible*) [18,20,21]. It has been well reported that the construction sector causes a significant environmental impact during material extraction and production, the building process, service life, and end of use and demolition of an infrastructure [22,23]. Therefore, to assess the sustainability of such an infrastructure, several factors and situations should be considered. In such a way, the aforementioned multi-criteria decision-making method (MCDM) is suitable when a large number of factors is considered and, especially, when such factors are on occasions difficult to measure. Additionally, these models are also able to integrate socio-economic factors into the environmental requirements [22]. In such a way, the MIVES method includes the environmental and socio-economic impacts of the infrastructure in the analysis. With this purpose, the inputs of the method have been a result of the factors and values defined and discussed during seminars delivered by experts [24]. Therefore, to assess the impact of M-30 works, MIVES was applied both before and after renovation, considering the current conditions and the 14 years of service life of the tunnels. During the last few years, new greener and improved materials have been used in the construction sector, such as recycled aggregates and self-compacting concrete. Therefore, an additional sustainability study of the section that considers materials is also performed.

Following this rationale, this research seeks to apply the MIVES method to the buried stretch of the south-west sector of the M-30 in Madrid. It is also the purpose of the paper to make a scientific

analysis of several aspects that are mainly subjective and qualitative and turn them into objective and quantitative matters in order to analyze three different and possible alternatives:

- (a) Non-buried M-30: in this situation, the former layout of the M-30 was considered, before the construction of the tunnels and the creation of the Madrid Río park.
- (b) Buried M-30 by using conventional materials: this is the current condition of the road and, thus, the solutions to improve its environmental and socio-economic impact on the area were analyzed.
- (c) Buried M-30 by using improved materials: this alternative considers the application of greener and improved construction procedures and materials to evaluate its influence on sustainability.

2. The MIVES Method and Its Application to the Renovation of the South-West Section of M-30

Considering the large number of heterogeneous factors that must be taken into account to perform this sustainability analysis, experience has shown the use of a multi-criteria decision-making method (MCDM) as the most suitable given that MCDM breaks down the problem studied into its elemental pieces so as to completely understand the evaluation process [25,26]. It is also noticeable that the selected method must be versatile enough to be applied to the great complexity of the infrastructure when analyzing socio-economic and environmental factors [5]. Additionally, it has been stated that sustainable engineering is an adequate field to use MCDM [27].

There are a wide range of methods to assess the sustainability of a building or a civil engineering work, but they have different scopes and approaches [22,25]. For instance, Life Cycle Assessment (LCA) [16,22,28–34] evaluates the sustainability of a building analyzing its environmental burden during its life cycle, namely, it considers the environmental inputs, outputs and impact during the life service of an infrastructure. Another kind of analysis is the one carried out by Life Cycle Cost (LCC) [16,22,35] which performs an economic study taking into account the purchasing and operating phases of the infrastructure in a period of time. Other complementary methods are: Life Cycle Energy Analysis (LCEA) [22,36] which studies the energy inputs over the service life of a infrastructure; Material Flow Analysis (MFA) [22,37] which analyses transformation, transport or storage of construction materials and Energy Flow Analysis (MEFA) [22,38] which adds the energy flow to the study. However, previous researchers came to the conclusion that the methods mentioned above are not fully appropriate to evaluate the sustainability of infrastructures [26,27,39]. In addition, there are some MCDM used in the construction sector such as ANP, DEA/ELECTRE, TOPSIS, or PROMÉTHÉE which are only used in some geographical frameworks [30,31].

In this context, MIVES is a genuine MCDM as it combines a holistic discriminatory tree of requirements, criteria and indicators [5,22,40]; the value function concept [41] and seminars delivered by experts to evaluate the functions and weights using the Analytic Hierarchy Process (AHP) [22,26,42]. Therefore, this method allows researchers to obtain a scientific and sustainability-based rationale to make a decision between different alternatives [26]. Nevertheless, the main drawback of the method is that, as it involves an exhaustive and rigorous process and seminars delivered by experts on each field, it might not be suitable for urgent assessments [22].

Also, the MIVES method has already been used in several sustainability analysis of both architectural and civil works [16,20,22–25,43–55], so taking into account the similarities between these projects and the case study of the M-30 burial, and considering the strengths of the method, MIVES was the chosen MCDM to perform this analysis. It is also remarkable that MIVES is the proposed method to evaluate the sustainability of concrete structures in the Spanish Structural Concrete Code EHE-08 [19,22,56,57].

As mentioned above, the MIVES method combines qualitative and quantitative factors for sustainability assessments in order to obtain a single general and non-dimensional sustainability index (SI, [58]). Therefore, before starting the process, an awareness of the problem and solutions should be obtained [22,23,58]. Once defined, a holistic decision tree with three levels (that is to say, requirements, criteria, and indicators) is required as shown in Figure 2. The indicators are evaluated by using value functions which turn the qualitative factors into quantitative variables with the same units

and scales. Consequently, experts weight each requirement, criteria, and indicator in order to assess their importance in the model and the final SI. Lastly, the alternative solutions previously proposed are analyzed in order to select the most suitable one [5,22,23,58].

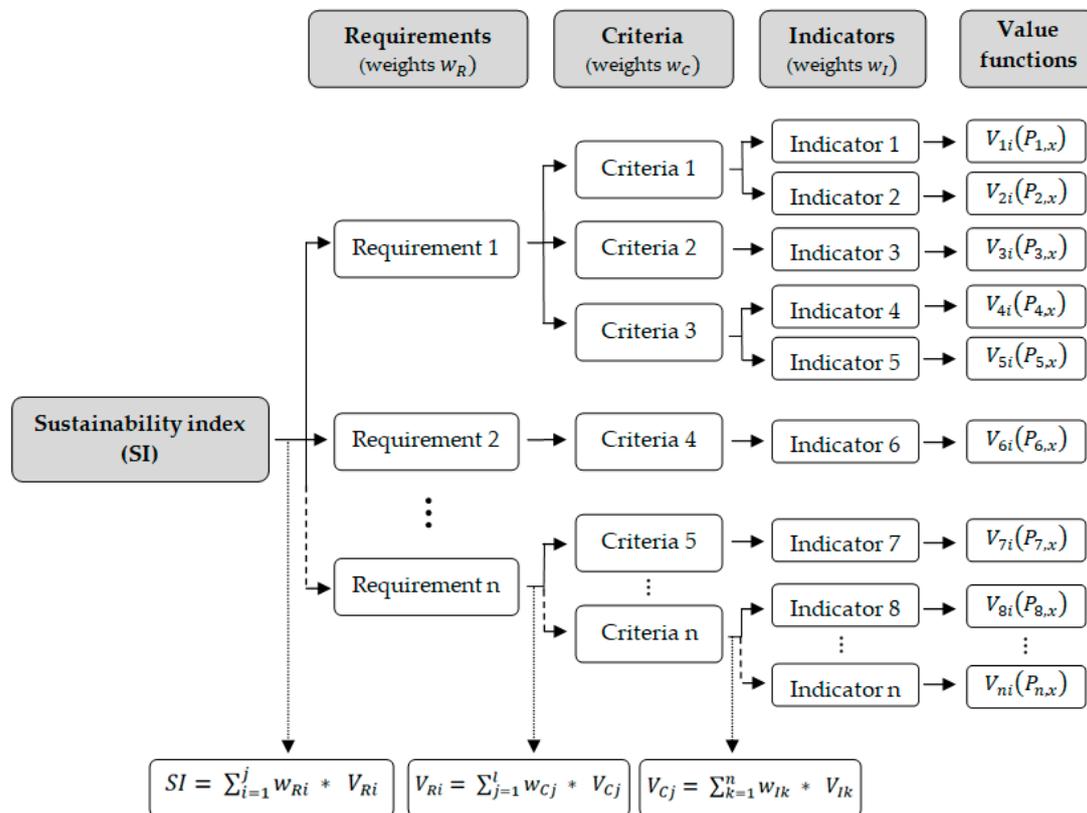


Figure 2. Structure of a generic modelo integrado de valor para una evaluación sostenible (MIVES) decision tree (modified from [40], Copyright CIMNE, 2016.).

Following the methodology, in order to assess the environmental and socio-economic benefits of renovation, especially on the south-west stretch, three alternatives were defined. They considered the influence of the construction materials used for the infrastructure, as follows:

- (a) Non-buried M-30: in this situation, the former layout of the M-30 was considered, before the construction of the tunnels and the creation of the Madrid Río park.
- (b) Buried M-30 by using conventional materials: this is the current condition of the road and, thus, the solutions to improve its environmental and socio-economic impact on the area were analyzed.
- (c) Buried M-30 by using improved materials: this alternative considers the application of greener and improved construction procedures and materials to evaluate its influence on sustainability.

Once the alternative solutions to study the impact of the burial of the south-west corridor were defined, the requirements, criteria, and indicators to prepare the model were established as shown in Table 1 and described below.

It should be noted that the weights applied to each requirement, criterion, and indicator are a subjective matter, based on the opinion of experts and they are always defined prior to make any calculation in order to ensure its neutrality. The weights assigned in this research are based on literature review of previous studies of civil engineering works [16,22,24] and adapted to this particular case, adding specific criteria and indicators and granting a special importance to the social aspects, as they are remarkably significant to this study.

Table 1. Requirements, criteria, indicators, and weights.

Requirements	(R. Weights)	Criteria	(C. Weights)	Indicators	(I. Weights)
R1. Economic	40%	C1 Total costs. Direct + Indirect	30%	I1 Total costs, including construction time	100%
		C2 Quality	10%	I2 Non-quality costs	100%
		C3 Dismantling	10%	I3 Dismantling costs	100%
		C4 Service-life	30%	I4 Cost of service. Maintenance. Energy. Change of use.	80%
				I5 Resilience. Risk of disaster × cost of reconstruction + lack of use	20%
		C5 Benefits for the surrounding area	20%	I6 Real-estate market	50%
				I7 Tourism increase	15%
				I8 Cultural boost	35%
				I9 Cement	25%
		R2. Environmental	30%	C6 Material consumption at construction time	15%
I11 Reinforcement (steel mesh, steel fibres and polyolefin fibres)	15%				
I12 Water	25%				
I13 Auxiliary materials	15%				
I14 Reused material	10%				
C7 Material consumption for maintenance	20%			I9 Cement	25%
				I10 Aggregates	10%
				I11 Reinforcement (steel mesh, steel fibres and polyolefin fibres)	15%
				I12 Water	25%
				I13 Auxiliary materials	15%
				I14 Reused materials	10%

Table 1. Cont.

Requirements	(R. Weights)	Criteria	(C. Weights)	Indicators	(I. Weights)		
R2. Environmental	30 %	C8 Emissions at construction time	10%	I15 Global-warming potential	80%		
				I16 Total waste	20%		
		C9 Emissions for maintenance	10%	C10 Emissions during exploitation	20%	I15 Global-warming potential	80%
						I16 Total waste	20%
		C11 Energy	10%	C12 Ecosystems in Manzanares River	15%	I17 Carbon dioxide uptake by cementitious materials	15%
						I18 Air quality (road, tunnel and parks)	30%
						I19 Speed limit dependent emissions	25%
		C13 Design	20%	R3. Social	30%	I20 Particle pollution. Exploitation	30%
						I21 Embodied energy	20%
						I22 Construction energy	40%
						I23 Service and maintenance energy	40%
						I24 Pollution	50%
C13 Design	20%	R3. Social	30%	I25 Recovery of fluvial system	35%		
				I26 Ecosystem (endemic flora and fauna)	15%		
				I27 Comfort. Thermal, air and, among others, noise	10%		
				I28 Noise pollution. Construction	15%		
				I19 Particles pollution. Construction	15%		
C13 Design	20%	R3. Social	30%	I20 Traffic disturbances. Construction	15%		
				I28 Noise pollution. Maintenance	15%		
C13 Design	20%	R3. Social	30%	I29 Particles pollution. Maintenance	15%		

Table 1. Cont.

Requirements	(R. Weights)	Criteria	(C. Weights)	Indicators	(I. Weights)		
R3. Social	30 %	C14 Risks	30%	I30 Traffic disturbances. Maintenance	15%		
				I31 Health and safety during construction	20%		
				I32 Health and safety during maintenance	20%		
				I33 Occupant safety. Risk of disaster × cost of life disruption	20%		
				I34 Accident rate. Exploitation	20%		
				I35 Disease due to fume inhalation. Exploitation	20%		
		C15 Accessibility and traffic connectivity	20%			I36 Traffic fluency	25%
						I37 Traffic connectivity and districts fluency (people)	25%
						I38 Universal accessibility (people)	25%
						I39 Commercial sector	25%
		C16 Comfort. Exploitation	30%			I27 Comfort. Thermal, air and, among others, noise	30%
						I28 Noise pollution. Exploitation	35%
I40 Green and promenade areas	35%						

- (1) Economic requirements: it has been widely reported that roads promote the economic development of a given territory, changing the mobility patterns of the population, improving accessibility and having direct repercussions on the standard of living of people who reside in urban areas [40,59]. Therefore, it is relevant to evaluate the balance between the direct costs of the construction and indirect economic benefits generated by renovation of surrounding areas. Thus, the direct costs considered are those resulting from both the construction of the infrastructure and the future operations of maintenance and dismantling (Table 1). In addition, the non-quality costs should be taken into account, given that they are defined as those costs generated when a product of inadequate quality is obtained [60] and, consequently, increases maintenance costs [61]. So, in this case, non-quality costs were included to estimate the economic repercussions of the possible rejections and consequence of not having, for instance, a proper quality control or highly qualified and experienced labor force. As studies have shown, conventional materials are cheaper than the improved ones, though they will need a more exhaustive maintenance in the future. Equally, the purpose of the designers was to improve the environmental and social-economic regeneration of the surrounding areas of the M-30, especially with the creation of Madrid Río [13]. Thus, the indirect economic benefits obtained from construction were, for example, the enhancement of the real-estate market and improvement of tourism in the area (Table 1).
- (2) Environmental requirements: the criteria and indicators studied were related to the material and energy consumption during construction, exploitation, and maintenance of the infrastructure. These criteria and indicators were focused on differentiating the use of conventional and improved construction materials. It should be noted that dosage would differ from that of conventional concretes. These kinds of concretes use a higher amount of cement (400–500 kg/m³), have a lower water/cement ratio (less than 0.3), incorporate additives and additions such as superplasticizers and silica fume [17,19]. The nature, type and maximum size of the aggregates are also carefully studied. Equally, it has been reported that transport is a significant and increasing source of air and noise pollution worldwide [13,62]. In particular, road transport is responsible for 93% of the environmental costs produced by traffic in Europe, which represent approximately 4% of the gross domestic product (GDP) of the area [63,64]. Therefore, the pollutant and noise emissions during the construction, exploitation, and maintenance of the road and tunnels analyzed were also considered (Table 1). Lastly, given that one of the main goals of the renovation of the M-30 entailed linking the fluvial system of the Manzanares river with the urban landscape of Madrid [13,65], the recovery of the Manzanares river ecosystems in the Madrid stretch of the river and related criteria was also considered.
- (3) Social requirements: such requirements evaluate the positive and negative effects that the renovation of the M-30 implies on workers, users, and residents of the surrounding areas on the basis of the impact on people, their community and the way of life which may occur during project design, construction, and use of the road (Table 1, [66]). Equally, the criteria were also selected by considering that roads may produce direct or physical and indirect or physiological effects on workers, users and residents [67]. Therefore, social criteria with these direct or physical effects were those related with health and safety, such as air and noise pollution or accident rates (Table 1). By contrast, social criteria with indirect or psychological effects were, for example, those related with traffic and people fluency, travel time, and accessibility (Table 1).

Once the requirements, criteria, and indicators are established (Table 1), the value functions for each indicator should be defined. Value functions convert the criteria magnitudes and units into a common, non-dimensional value [22] and delimit the units of the function. In this case, indicators would take values between 0 and 10, with 10 being the highest degree of social satisfaction and sustainability and 0 the lowest.

Lastly, the SI of each alternative of the M-30 considered: that is to say, non-buried, buried by using conventional materials and buried by applying new materials as calculated with Equations (1)–(3) [22].

The value of a generic criterion (V_{Cj}) is supplied by Equation (1). It shows the addition from $K = 1$ to n (where n is the number of indicators that there are in the criterion) of the product of the value of each indicator group (V_{Ik}), by the weight associated with the same (w_{Ik}).

The same approach is used in the assessment of the requirements, obtaining the value of a requested generic (V_{Ri}) in Equation (2), which expresses the sum from $j = 1$ to l (with l being the number of criteria that are in the requirement) of the products of the value of each criterion of the Group (J_{cv}), by the weight associated with the same (w_{Cj}).

Lastly, the rate of sustainability of a building (SI) is obtained by the sum of the dimensionless values of each of the requirements (V_{Ri}) multiplied by the weight corresponding to each of them (w_{Ri}) as shown in Equation (3). The subscript i represents the number of established requirements, which is 3 (economic, social, and environmental) for sustainability studies.

$$V_{Cj} = \sum_{k=1}^n w_{Ik} \cdot V_{Ik} \quad (1)$$

$$V_{Ri} = \sum_{j=1}^l w_{Cj} \cdot V_{Cj} \quad (2)$$

$$SI = \sum_{i=1}^j w_{Ri} \cdot V_{Ri} \quad (3)$$

3. Results and Discussion

The values of each indicator, criterion and requirement considered for the sustainability analysis of the renovation of the south-west sector of the M-30, as well as the SI for the three alternative solutions studied, are shown in Table 2. It can be observed that the SI of the buried M-30 situation doubles the SI of the previous layout of the road. However, the SI of the buried M-30 built with new materials is only 0.5 higher than by using conventional materials. These scores may be attributed to the premise that the M-30 regeneration was designed with consideration of the environmental and socio-economic and I enhancement of the area [14,61,67] (Tables 1 and 2). In this sense, it may be observed that several of the indicators selected have the same value regarding the use or not of greener and high-performance materials, as they evaluated the difference between the buried and non-buried solutions (Table 2).

- Economic requirements: from the economic point of view, it is noticeable that indicators based on the costs of the infrastructure, especially its renovation and dismantling, have a value contrary to the renovation of the M-30 (C1, C3, Tables 1 and 2). It could be assumed that the first solution, the non-burial of the M-30 stretch, means that the tunnels and park are not built and does not imply any construction cost. Equally, it could also be assumed that the dismantling of a surface road layout will be cheaper than the dismantling of the tunnels. By contrast, although the renovation of the layout implied several direct and indirect costs, it could be observed that the costs generated during the service life of the structure and the indirect economic benefits of the surrounding area were considerably enhanced (C4, C5, Tables 1 and 2). It should also be considered that the older an infrastructure is the more maintenance operations it will require. As the lifecycle of the structure progresses, its resistant capacity starts to decrease, as a consequence of the inevitable deterioration of the construction materials, such as the carbonation process and, among others, reinforcement corrosion. This deterioration is slower in the early years of the structure and faster when it is reaching the end of its lifecycle [68]. So when analyzing the service life of this particular infrastructure, it is clear that the first alternative (non-buried M-30) will be the most penalized, given that structures would be older and require more maintenance (to some extent, similar to those of bridges located on the same road such as the Avenida del Mediterráneo and Avenida de la Paz). Thus, given that the accident rate was remarkably higher [9],

it would have demanded relevant measures to reduce such a rate and repair damage caused by vehicle collisions. Furthermore, some of the road restraint systems would have required modernization to meet the requirements included in the Spanish standards [69]. It should also be noted that as noise levels in the surroundings of the highway were higher than those accepted for urban and residential areas [10,70], installation of sound-absorbing acoustic screens would have been necessary. Concerning the construction of the tunnels with conventional or improved materials, the first option will require more maintenance than the second one (for this reason, material consumption will be higher, as well as noise production and pollution and traffic disturbances), as improved materials will have high-performance properties regarding durability and will need less maintenance. Additionally, the average price of dwellings around the M-30, considering the size and real-estate characteristics of the districts, the real-estate value between 2005 and 2015 increased by approximately 500 euros per square meter due to the improvements provided by works [71]. This increase in real-estate values is directly related to the creation of Madrid Río which has boosted cultural and leisure activities, as well as commercial activities, in the vicinity [14,61,67]. Due to the new green area created and its connection with relevant tourist attractions of Madrid, such as the Royal Palace, the Cathedral, the Matadero cultural and exhibition center and the Campo del Moro Gardens, Madrid Río has become a new tourist point of interest of the city. However, the whole potential of the infrastructure in this sense is not completely exploited, due to a lack of information offered to tourists [72]. It is also remarkable that the economic benefits for the city as a consequence of the tunnels are only dependent on the overall design of the infrastructure, as they are unaffected by the use of greener and improved materials.

- Environmental requirements: from the environmental point of view, function values of the material consumption at construction time (C6, Table 1) follow a similar trend to C1 and C3 (total costs and dismantling, Tables 1 and 2). Again, it could be assumed that non-modification of the road implies that no materials are used and then the impact of this factor is zero. By contrast, the burial of the M-30 involved consumption of several building materials, especially concrete which is made up by water, cement, aggregates, chemical additions and, in the case of reinforced structures, steel [73]. The environmental impact of the extraction, production and transport of these raw materials has been evaluated as a medium impact (I9-I13, Table 2). However, this impact increases when considering greener and improved materials; for example, high-strength concrete requires low water cement/ratios and high-strength aggregates [74,75]. That means that the consumption of cement will rise and, consequently, so will its environmental impact. Equally, the use of high-strength aggregates can raise the costs and environmental impact of the exploitation and transport of these materials, with it being the least sustainable alternative from the point of view of the environmental aspects during construction. It should also be mentioned that the trend of the function value concerning the use of recycled materials is different from that explained before (I14, Table 2). Non-recycled materials were used during the construction of the old and new layout. However, the third alternative considers the use of recycled materials as greener building materials, enhancing the sustainability of this indicator (Table 2). Moreover, the use of greener and improved materials such as high-performance or self-compacting concretes, improves the durability characteristics of the infrastructure, decreasing the number and scope of maintenance operations and extending its service life [76,77]. Thus, such an alternative is the most suitable (C6, Table 2).

Additionally, one of the aims of the renovation of the M-30 was to increase the capacity of the road and improve traffic flow [9]. Such improvement and the burial of the former layout were also responsible for the enhancement of environmental indicators in the area (C9, C10, Table 2). It may be observed that the emissions of noise and pollutants increased during the construction works of the M-30 (C8, Table 2). However, once the works were finished, the environmental benefits produced by the renovation of the road were easily recognized (Table 2). For example, as shown in Figure 3, before the construction of the tunnels (2006), in the district of Arganzuela

(Figure 1) which is located in the south-west sector of the M-30, the noise level was above 75 dBA. By contrast, in 2011, it was generally about 60 dBA except at the entrances and exits from the tunnels, where it was higher [10]. Spanish law [70] limits the noise levels to 65 dBA in residential areas. Therefore, the score obtained with the function value will be 0 if this limit is exceeded. Considering 45 dBA as an acceptable noise level (satisfaction value 10), the function value will exhibit a decreasing concave curve, where satisfaction will drop rapidly when approaching the point of minimum satisfaction (Figure 3, [22]). It is remarkable that the burial of the M-30 and the construction of the tunnels led to a reduction of noise pollution of the area [10]. However, although noise levels were lower after the works than before them, the value of the recovery has been considered medium (I28, Table 2) given that the increase of the traffic, especially in the access to the tunnels, has raised the noise disturbance in the area [10].

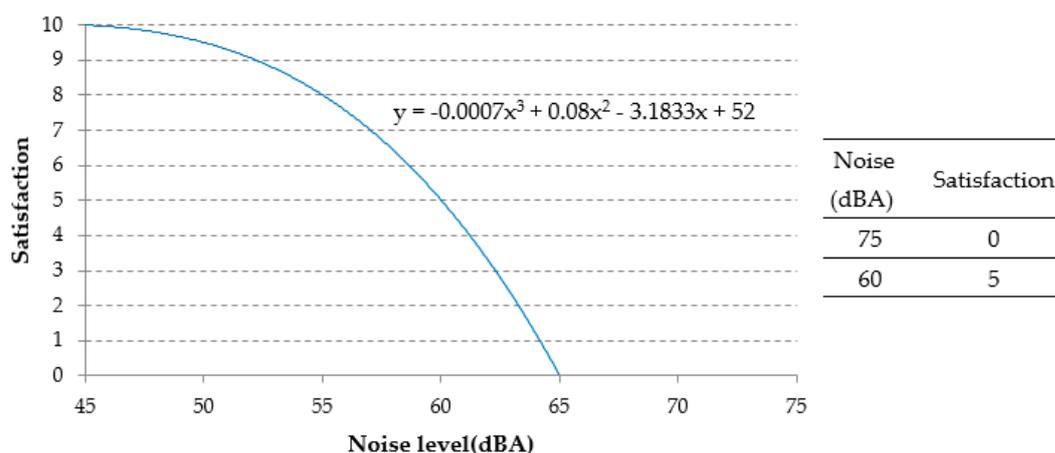


Figure 3. Value function for noise pollution during exploitation and scores obtained.

The same situation occurs with pollutant emission indicators (Table 2). Although emissions are lower than before the construction of the tunnels [10], they remain higher than the annual medium limit established by Spanish law for NOx gases (40 µg/m³, [78]). It should be mentioned that these emissions have also been reduced by the speed limit applied to the road, due to safety reasons, from 90 km/h to 70 km/h [1]. It has been shown that application of speed limits is an effective way to reduce vehicle emissions [79–81]. In particular, reducing it from 90 km/h to 70 km/h leads to a 15% and 16% reduction in CO₂ and NO_x emissions, respectively, on the M-30 (although emissions during peak hours may be increased) [1,79,80]. Therefore, given that speed limits in Spain range from 50 km/h to 120 km/h, the indicator can be assessed for the speed limit dependent emissions function (I19, Table 2) the value 0 when speed limit is 120 km/h (as it will provide higher emissions) and the value 10 when speed limit is 50 km/h. With a decreasing lineal function, as shown in Figure 4, the scores for the indicator at 90 km/h (before the construction of the tunnels) and 70 km/h (after the construction of the tunnels) are obtained. However, it must be noticed that these values of the function are only evaluating pollutant emissions depending on speed limits, as it is known that an excessive reduction of the speed limits will have negative impact on travel times and traffic fluency [1].

It should be highlighted that noise and pollutant emissions are, again, indicators independent from the materials selected in the structure. However, recent studies have shown that cement-based materials can absorb CO₂ during their lifecycle [15,81,82]. In particular, during its lifecycle concrete can absorb 20% of the CO₂ produced by calcination to manufacture the cement [15]. Therefore, the buried M-30 solution will have a greater CO₂ uptake compared with the non-buried solution, as the volume of concrete used to build the structure is bigger. Equally, when comparing the use of conventional and high-performance materials, given that the latter will normally have a higher cement content [17] it could be considered that the CO₂ uptake in this case will also be higher.

Table 2. MIVES results for the analysis.

Requirements	Criteria	Indicators	Non-Buried M-30				Buried M-30. Conventional Materials				Buried M-30. Improved Materials			
			Score × Rweights	Score × Cweights	Score × Iweights	Score (0–10)	Score × Rweights	Score × Cweights	Score × Iweights	Score (0–10)	Score × Rweights	Score × Cweights	Score × Iweights	Score (0–10)
R1. Economic	C1	I1	1.50	3.00	10.00	10	2.29	1.50	5.00	5	2.32	0.90	3.00	3
		I2		0.10	1.00	1		0.60	6.00	6		0.80	8.00	8
	C3	I3		0.30	3.00	3		0.10	1.00	1		0.10	1.00	1
		I4		0.36	0.00	0		1.98	5.60	7		2.46	7.20	9
	I5	1.20			6	1.00			5	1.00			5	
	C5	I6		0.00	0.00	0		1.55	4.00	8		1.55	4.00	8
		I7			0.00	0			0.60	4			0.60	4
		I8		1.17	0.00	0		1.62	3.15	9		1.99	3.15	9
I9		2.50	10		1.25	5	0.75		3					
R2. Environmental	C6	I10	1.35	1.00	10	0.68	0.50	5	0.73	0.40	4			
		I11		1.50	10		0.75	5		1.05	7			
		I12		2.50	10		1.25	5		1.25	5			
		I13		1.50	10		0.75	5		0.90	6			
	C7	I14	0.20	0.00	0	1.26	0.00	0	1.72	0.50	5			
		I9		0.25	1		1.75	7		2.25	9			
		I10	0.20	0.20	2	1.26	0.70	7	1.72	0.90	9			
		I11		0.15	1		1.05	7		1.35	9			
		I12	0.20	0.25	1	1.26	1.75	7	1.72	2.25	9			
		I13		0.15	1		1.05	7		1.35	9			
		I14	0.20	0.00	0	1.26	0.00	0	1.72	0.50	5			
		I14		0.00	0		0.00	0		0.50	5			

Table 2. Cont.

Requirements	Criteria	Indicators	Non-Buried M-30				Buried M-30. Conventional Materials				Buried M-30. Improved Materials			
			Score × Rweights	Score × Cweights	Score × Iweights	Score (0–10)	Score × Rweights	Score × Cweights	Score × Iweights	Score (0–10)	Score × Rweights	Score × Cweights	Score × Iweights	Score (0–10)
R2. Environmental	C8	I15	1.17	1.00	8.00	10	1.62	0.22	1.60	2	1.99	0.52	4.00	5
		I16			2.00	10			0.60	3			1.20	6
	C9	I15		0.20	1.60	2		0.60	4.80	6		0.80	6.40	8
		I16			0.40	2			1.20	6			1.60	8
	C10	I17		0.45	0.30	2		1.14	0.90	6		1.23	1.35	9
		I18			0.90	3			1.50	5			1.50	5
		I19			1.07	4			1.79	7			1.79	7
		I20			0.00	0			1.50	5			1.50	5
	C11	I21		0.68	2.00	10		0.54	1.00	5		0.68	2.00	10
		I22			4.00	10			1.60	4			1.20	3
		I23			0.80	2			2.80	7			3.60	9
		I24			0.00	0			4.00	8			4.00	8
	C12	I25		0.00	0.00	0		0.98	1.75	5		0.98	1.75	5
		I26			0.00	0			0.75	5			0.75	5
R3 Social	C13	I27	0.77	1.12	0.80	8	2.34	1.36	0.50	5	2.42	1.37	0.40	4
		I28			1.20	8			0.75	5			0.60	4
		I19			1.50	10			1.20	8			1.05	7
		I20			1.20	8			0.75	5			0.60	4
		I28			0.30	2			1.50	10			1.50	10
		I29			0.30	2			1.05	7			1.35	9
		I30			0.30	2			1.05	7			1.35	9

Table 2. Cont.

		Non-Buried M-30			Buried M-30. Conventional Materials			Buried M-30. Improved Materials			
R3 Social	C14	I31	1.14	2.00	10	2.22	1.60	8	2.46	1.60	8
		I32		0.00	0		1.40	7		1.80	9
		I33		1.00	5		1.60	8		2.00	10
		I34		0.80	4		1.40	7		1.40	7
		I35		0.00	0		1.40	7		1.40	7
	C15	I36	0.20	0.75	3	1.85	1.75	7	1.85	1.75	7
		I37		0.25	1		2.50	10		2.50	10
		I38		0.00	0		2.50	10		2.50	10
		I39		0.00	0		2.50	10		2.50	10
	C16	I27	0.09	0.30	1	2.39	2.70	9	2.39	2.70	9
I28		0.00		0	3.50		10	3.50		10	
		I40		0.00	0		1.75	5		1.75	5
Sustainability index (SI)			3.43			6.26			6.74		

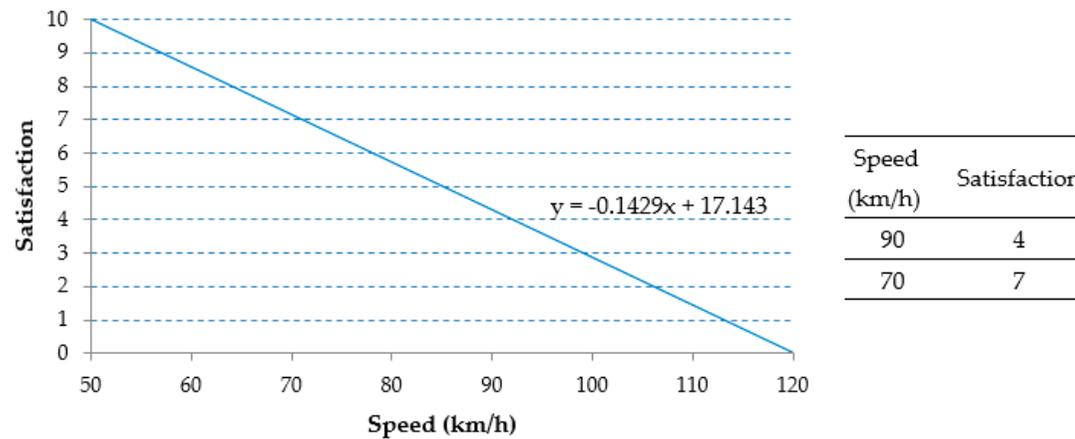


Figure 4. Value function for speed-dependent emissions and scores obtained.

Similar to the aforementioned indicators, energy consumption grew during the regeneration works, with this parameter being less suitable during this period of time. However, the new facilities built were designed to reduce energy consumption (for example, in the tunnels, where energy consumption savings are 21% or 3.73 MWh/year) compared with the previous and due to the implementation of light-emitting diode (LED) technology and adjustment of the intensity of tunnel lighting according to the daylight [83], thus enhancing this indicator during the service life of the structure.

Lastly, the main action performed to improve the environmental sustainability of the south-west section was the creation of Madrid Río and recovery of the fluvial system and its ecosystem (C12, Table 2). The burial of the road and reuse of the land around the area as a green area with more than 33,000 newly planted trees and 470,000 shrubs, and 210,000 square meters of low water demand meadow, enables a reduction of 35,000 tons of CO₂ from the air pollution, as well as the significant reduction of noise pollution [14,61]. However, the enhancement of these indicators has been considered medium because the original design of Madrid Río did not contribute to restoring the natural characteristics of the Manzanares river and additional actions were performed in subsequent years [84]. It is also notable that the criterion involving the fluvial ecosystems is only dependent on the design of the structure and use of new materials does not change its value (C12, Table 2).

- Social requirements: from the social point of view, the main disturbances (noise, dust and, among others, traffic congestion) produced by the M-30 renovation on the users and residents of the area should be taken into account (C13, Table 2). The works caused traffic interruptions and produced additional noise and pollutants (dust) in the area. However, the comfort of users and residents was widely increased with the construction of the tunnels and Madrid Río. It is remarkable, for example, that the cases of people being hospitalized with health issues related to the inhalation of NO_x have decreased since the renovation of the road, even when NO_x still exceeds the maximum limits established by Spanish law [10]. The burial of the road and creation of the Madrid Río park also redefined the land use of the area, enhancing leisure and cultural activities available to residents and visitors. They also influenced the mobility patterns in the area, increasing the permeability among the neighborhoods that had been historically separated due to the barrier of the Manzanares river and the M-30 [84]. The purpose of the renovation design was to improve the accessibility of the section, not only for drivers but also for pedestrians, creating a park with slopes ranging from 4% to 6%, a wide network of pedestrian paths, 30 km of segregated bike lanes, and bridges that cross the river [14,61]. The park also enhances the leisure, sport and cultural activities with development of children's playgrounds, basketball, handball and tennis courts, and cultural centers [13]. Thus, this significant improvement in the conditions of the collective use of the space has been positively perceived by the population, increasing social comfort in the area. Again, it should be highlighted that these indicators are directly dependent on the design of the work and the application of new materials has null or low impact on these indicators.

In view of the result obtained from the MIVES analysis, although it may be concluded that the alternative existing nowadays shows a high level of sustainability, it could have been improved by using high-performance materials. It should also be considered that the use of these kinds of materials would have involved longer construction times, higher construction costs, and arguably recruitment of a more specialized labor force.

The use of conventional materials would lead to the need of a more exhaustive maintenance (one which should be carried out as soon as needed) to avoid possible structural damage derived from durable issues. It is then vital to count on a thorough and detailed inspection program, involving regular and specific inspections, and perform maintenance actuations where needed [68,85].

Such maintenance may also improve, to some extent, the state of the infrastructure if it seeks not only to repair the damage but also prevent it from appearing again [68], applying durable procedures

such as anti-carbonation painting and hydrofugant coatings in presence of water, improving the drainage systems or the waterproofing of structural joints.

4. Conclusions

MIVES is thus a powerful tool and a highly suitable method available to evaluate the sustainability of the structures in various scenarios in which a high number of heterogeneous factors are involved. This is due to its capability to combine socio-economic and environmental and criteria, as well as qualitative and quantitative indicators.

The results of the application of such a method to assess the sustainability of the works performed on the M-30, consideration of the alternatives (a non-buried M-30, buried M-30 by using conventional materials and buried M-30 with improved materials) could be summarized as follows: the burial of the south-west section of the M-30 has significantly improved the sustainability of the road and surrounding areas. Thus, the above mentioned environmental and socio-economic benefits provided by the renovation of the layout outweigh the disturbance and interruption generated during the works.

The level of sustainability obtained could have been slightly improved if high-performance materials had been used, although the use of new materials would have involved longer construction times, higher construction costs and arguably recruitment of a more specialized labor force. It should also be considered that the use of improved materials would have only concerned indicators that evaluated economic and environmental criteria. This would be because several environmental and, especially, socio-economic indicators are primarily dependent on the design of the infrastructure and not only on the materials used during construction.

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