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Circular Economy 4.0 Evaluation Model for Urban Road Infrastructure Projects, CIROAD

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Abstract: This paper provides a multicriteria evaluation model, based on the AHP methodology for the evaluation of the Circular Economy 4.0's, which develops the metric called "Circularity indicator for urban road projects (CIROAD)". The main contribution of this work is to provide a measurement scale specifically designed for urban road infrastructure projects. It is a useful tool to assess the degree of implementation of the principles of the Circular Economy (CE) and the Fourth Industrial Revolution (I4.0) in an integrated manner in these types of projects, generating valuable information for all stakeholders and contributing to the objective of accelerating the transition towards a Circular Economy 4.0 model in the construction industry. The model is defined with twenty-five sub-criteria and seven general criteria, which are: (1) Circular Materials; (2) Circular Design Approaches; (3) Circular Construction Approaches; (4) Circular Operation Approaches; (5) Approaches to Deconstruction and Resource Recovery; (6) Social Value Creation; and (7) Economic Performance. The developed CIROAD model was applied to three projects in the urban transport area of the Chilean Ministry of Housing and Urbanism (MINVU/SERVIU) in the Santiago Metropolitan Region (RM). In these three projects, low performance was observed in terms of CIROAD scores (between 21% and 28% of a maximum of 100%); that is, there is a significant opportunity for improvement by incorporating more circular practices in the development of projects by the studied organization. To accelerate the transition to a circular economy model in the development of its projects, it is proposed that the organization prioritize improving the following circular practices (in order of importance): (1) the design of pavements with environmental criteria; (2) preserving value; (3) conducting cost–benefit analysis (CBA) of waste management; (4) environmental declaration of materials (EPD); (5) the used of recycled materials; and (6) BIM-based design. Finally, the suggestion for the organization in charge of these projects is to use the developed CIROAD model as a tool to support decision making regarding the prioritization of its project portfolio. That is, the organization should use CIROAD to generate a ranking score for each project and allocate resources for investment in the initiatives that show the best circularity performances, as estimated by CIROAD.

Keywords: circular construction; indicator of circularity; construction 4.0; sustainable construction industry 4.0

Citation: Piñones, P.; Derpich, I.; Venegas, R. Circular Economy 4.0 Evaluation Model for Urban Road Infrastructure Projects, CIROAD. *Sustainability* **2023**, *15*, 3205. https://doi.org/10.3390/su15043205

Academic Editors: Jerzy Rosłon, Mariola Książek-Nowak, Aleksander Nicał and Paweł Nowak

Received: 15 December 2022
Revised: 29 January 2023
Accepted: 30 January 2023
Published: 9 February 2023

1. Introduction

Recent decades have witnessed unprecedented growth in resource demand, driven by rapid industrialization in emerging economies and continued high levels of material consumption in developed countries. As a result, the weight of materials consumed worldwide has more than doubled since 1980 and has increased tenfold since 1900 [1]. By 2060, the world's population is expected to increase from approximately 7 billion to approximately 10 billion [2]. At the same time, the per capita income of the world population is expected to approximately triple [1]. This will substantially increase the demand for natural resources, especially if global production and consumption patterns converge with those of OECD countries. In this sense, empirical evidence confirms the strong relationship between resource consumption and GDP (Figure 1). In fact, historically, for every 1% increase in GDP, on average, the resource use has increased 0.4%.

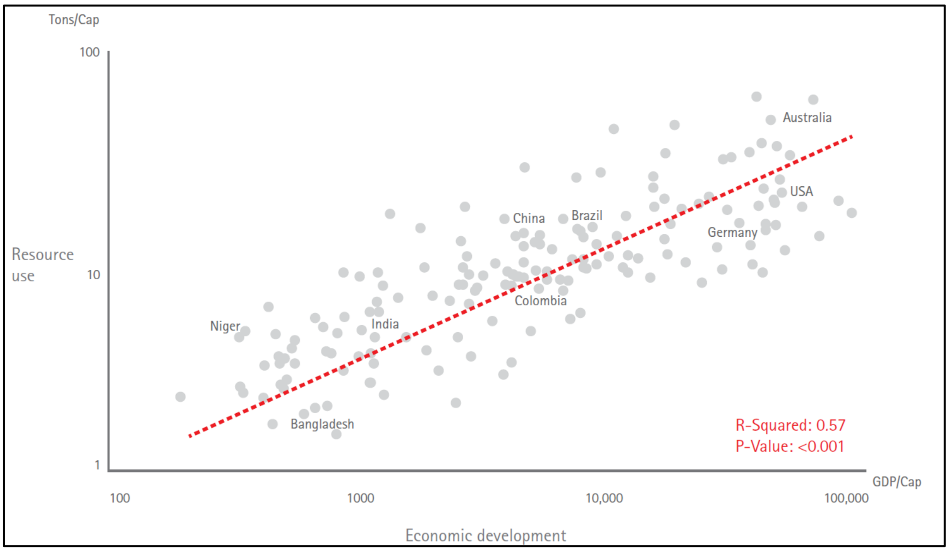

Figure 1. Correlation between consumption (tons per capita) of resources and GDP per capita. Source: Reprinted from Accenture (2014) [3].

Thus, humanity is already consuming approximately 1.6 times the resources that the planet is capable of regenerating in one year. At the current rate, we will consume three planets by 2050 [3]. The OECD model indicates that global raw material use may more than double from 79 Gt in 2011 to 167 Gt in 2060 if the current trends persist [1]. By 2017, the total resources consumed annually by the total global economy reached 100.6 Gt, of which 38.8 Gt were consumed by the built environment (building and infrastructure), corresponding to 38.6% of the total resources consumed in the world in one year [4]. Globally, construction is a key economic sector, with more than USD 10 trillion spent annually on goods and services delivered by the sector [5]. Its most significant effect, however, is manifested in social benefits for users, such as providing housing solutions for families, or infrastructure works that provide connectivity to cities and countries, enabling long-term economic growth. Nevertheless, it has also been estimated that approximately 40% of global materials are used for construction [6]. In the European Union (EU), construction and demolition waste (CDW) currently represent approximately 25–30 of the total waste generated and consists of numerous materials, including concrete, bricks, plaster, tiles, ceramics, wood, glass, metals, plastics, solvents, asbestos, and excavated soil, many of which can be recycled [7]. The world produces more than 400 million tons of single-use plastics annually, 16% of which are produced for the built environment [7]. With heavy reliance on virgin materials, the construction industry is challenged by resource scarcity, e.g., global steel demand is expected to increase annually by at least 1.1% through 2030, driven by demand from emerging economies [8]. In the case of concrete, one of the most widely used materials in construction, while raw materials are generally abundant and found locally around the world, some materials such as natural sand and limestone can be in short supply locally. For concrete, we need to extract 30 billion tons of sand each year—equivalent to almost 4 tons per person [6]. Most of this sand is extracted from rivers and coastal areas, which increases their vulnerability, where a significant part of the human settlements is located [9]. In the area of energy consumption, if no measures are taken to improve energy efficiency in the building sector, energy demand is expected to increase 50% by 2050 [10]. To limit global temperature increase to 2°C as set out in the Paris Agreement, the building sector would need to achieve an estimated 77% reduction in total carbon dioxide (CO_2) emissions generation by 2050 compared to the levels of today [6]. The construction sector is the largest energy consumer, which accounts for more than one-third of final global energy consumption and is a major source of CO2 emissions [10]. Moreover, about 20% of global Greenhouse Gas (GHG) emissions are related to construction [9].

In the case of Chile, over the past ten years, the construction industry has accounted for an average of 6.5% of the entire output of the Chilean economy, with a maximum contribution of 7.0% and a minimum of 6.3% [11]. The construction industry represents 8.4% of jobs [12], and 34% of solid residue generation [13]. Likewise, potable water, which is mainly used in buildings, accounts for 6% of the consumption of water resources. On the other hand, 33% of GHG emissions are generated by the residential, public, and commercial sectors, which are entirely related to buildings. Finally, the construction industry is also accountable for 26% of the country's final energy expenditure considering the operation stage alone [10]. By 2023, the generation of Construction and Demolition Waste (CDW) is projected to reach 7,455,602 tons per year considering housing alone, which is over 7 million cubic meters, a volume of 15.5 soccer stadiums for 50,000 people [14]. This volume does not include CDW generated by the construction of public buildings, infrastructure, demolition, or debris from natural disasters. This situation is critical considering that, at present, nine regions of Chile do not have authorized disposal sites for solid assimilable waste. Therefore, there is no national coverage for its proper disposal, and an institutional framework at the national level in charge of waste management is nonexistent [14]. From the above figures, it can be concluded that the changes in this regard have great potential for impact. With developments such as population growth, continued urbanization, climate change, and resource scarcity, the sector needs to drastically change the way it operates, as we will need to achieve growth while operating within planetary boundaries. This means that population and economic growth are key drivers of resource demand. Clearly, economic development as we know it and resource scarcity are on the course for collision.

1.1. Circular Economy for Decoupling

One way to achieve economic growth and higher levels of social welfare within planetary boundaries could be through a green economy model, referring to a low-carbon, resource-efficient economy that improves human welfare while reducing the planetary impact of human activities [15]. All this constitutes a decoupling of natural resources and environmental impacts from economic growth and human well-being (as explained in various publications [16]), as well as from materials, among other factors, that are used to produce economic development and deteriorate the environment [15]. As such, it constitutes a strategic approach moving towards a global green economy, one that "results in greater human well-being and social equity, while reducing environmental risks and ecological scarcity" [15]. The most promising channel to achieve decoupling is the application of circular economy (CE) models and "circular modes of production". A circular economy can be defined as: "An industrial system that is restorative or regenerative by intention and design. It replaces the concept of end-of-life with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals that prevent reuse and return to the biosphere, and aims to eliminate waste through superior design of materials, products, systems and business models" [17]. Most authors agree with the fact that a CE is part of the solution to achieve sustainable development [18,19], constituting an alternative model of production and consumption, a growth strategy that 'decouples' the use of resources from economic growth [15,18,20,21]. In the same vein, it has even been stated that "Climate change and the imminent scarcity of raw materials calls for a shift from linear waste to circular zero-waste cycles" [22]. Likewise, the Ellen MacArthur Foundation considers that "the call for a new economic model (EC) is getting louder" [17]. "The Paris Agreement's goal of limiting global warming to 1.5 °C above pre-industrial levels can only be achieved through a circular economy" [23]. Based on the above, it is possible to state that there is a broad consensus in the literature that a circular economy is the most promising production model to achieve a decoupling between natural resource consumption and the environmental impacts of economic growth and human welfare.

1.2. Low Productivity in the Construction Sector and Technologies of the Fourth Industrial Revolution as Sources of Improvement

Labor productivity growth in the construction sector averaged 1% per year over the past two decades, compared to 2.8% for the total world economy and 3.6% for manufacturing [24]. In a sample of countries analyzed, less than 25% of construction firms matched the productivity growth achieved in all economies over the last decade [24]. If construction labor productivity were to catch up with advances in other sectors over the past 20 years or with the total economy, it is estimated that this could increase the value-added of the construction industry by USD 1.6 trillion per year. By reaching this target, half of all global infrastructure needs would be met and the global GDP would be boosted by 2% per year. A third of the opportunity is in the United States, where, since 1945, productivity in manufacturing has grown by as much as 1500%, but productivity in construction has not increased at all [24]. In general in the world, even in the most developed economies, the labor productivity of the construction sector is below the productivity of the total economy and well below the productivity of the manufacturing sector. The labor productivity performance of construction sectors around the world is not uniform. There are large regional differences, as well as visible pockets of excellence. In the United States, for example, the sector's labor productivity is lower today than it was in 1968 [24], and Europe's productivity generally maintains acceptable levels; China and South Africa are increasing their productivity rapidly, albeit from a low baseline, while countries such as Brazil and Saudi Arabia are lagging. Some countries, notably Australia, Belgium, and Israel, are managing to combine high productivity levels with comparatively rapid growth. According to MCKinsey [24], Chile is classified among the "accelerator" economies, defined as those with a positive labor productivity growth rate, but below the international average. Chile is one of the countries with the lowest construction labor productivity in the world, and the gap with respect to other OECD countries is increasing, as will be detailed later in this chapter.

According to a recent study by Chile's National Productivity Commission [5], regardless of the indicator used, the productivity of the construction sector in Chile is lower than the OECD average and the rest of the Chilean economy. First, the construction productivity gap between Chile and the OECD average increased 20% during the 2009–2018 period, from 43% to 52% [5]. The conclusion is that the productivity of international benchmarks is more than twice Chile's productivity level. Second, the productivity of construction in Chile is lower than that of most other sectors, equivalent to 80% of the average of the rest of the economy. Measuring productivity as added value, national works average USD 99 per person-day, while in the international sample, it is USD 317 per person-day: 220% higher [5]. The World Economic Forum has pointed out that for Chile to improve its global competitiveness, it must focus on deepening its teaching curriculum and investing in innovation and sustainability, aspects that are underdeveloped in the construction sector [5]. In the case of productivity at the project level, the evidence shows that, on average, high-rise building projects in Chile have an average productivity of 0.24 m2 per person-day, while international benchmarks show that the average productivity was 0.37 m^2 per person-day, i.e., productivity in Chile represented 65% of the productivity of the benchmarks; therefore, there is a 35% gap with regard to the average of the benchmarks [5].

To close this gap, it would be necessary to increase the average productivity of high-rise construction in Chile by 53% [5]. For road projects, the information collected for 2019 shows that the value added per person-day for the case of Chile was USD 99 versus USD 317 per person-day for the international benchmark sample [5]. In other words, Chilean productivity represents only 31% of the productivity of the benchmarks, so the gap was 69% [5]. This implies that to close this gap, Chile's average productivity would have to increase by 220%. Regarding deadlines, the information shows that at the national level, the delays occur in 27% of projects with regard to planning, while for the international case, delays occur in approximately 8% of projects [5]. It is estimated that if the construction industry were to move towards a manufacturing-inspired mass production system, it would increase productivity up to tenfold. It is important to note that three out of the seven areas identified by [24] are directly related to the application of Fourth Industrial Revolution (I4.0) technologies. In terms of design and engineering processes, the greatest impact on productivity would come from moving to a production system, which encourages off-site manufacturing, minimizing on-site construction through extensive use of precast technology, panel assembly in factories, and then on-site finishing units [24]. In the area of improving procurement and supply chain management, it is desirable to have a supply chain that reacts to potential disruptions and market dynamics, with supply replenishment predictions informed by inventories connected to the Internet of Things (such as wearable devices, radio frequency identification tags, and sensor technology) [24]. In the realm of infusing digital technology, new materials, and advanced automation, the use of 3D Building Information Modeling (BIM), digital collaboration tools, and drones for scanning, monitoring, and mapping is recommended. The use of 5D BIM tools can establish more transparency in terms of design, costs, and progress visualization; the use of advanced analytics enabled by the Internet of Things to improve the on-site monitoring of materials, labor, and equipment productivity is also desirable, as is digital collaboration and mobility tools (such as construction management apps loaded on mobile devices) to better track progress and collaborate in real time [24]. On-site productivity can be increased by as much as 50% by implementing cloud-based monitoring that quickly gathers accurate data in near real time. Automated advanced robotics tools and equipment for masonry can also help speed up on-site execution [24]. In the case of Chile, the National Productivity Commission [5] also recommends the implementation of BIM methodologies and industrialized construction to help solve problems of coordination, quality, cost overruns, and time overruns, taking advantage of the incorporation of these methodologies and the technological leap they imply to improve productivity. As can be seen, the application of Industry 4.0 technologies is of vital importance to improve productivity and increase sustainability in the construction industry.

1.3. Industry 4.0 Technologies as Enablers for Circular Business Models

Moving towards a circular building environment implies a change in roles and business models for active stakeholders in this sector. However, barriers related to culture, regulations, market, technology, and education have stagnated the transition [6]. One of the most relevant barriers to achieve the transition to the circular economy is technology, which is why the relationship between circular economy and technologies of the Fourth Industrial Revolution (I4.0) is gaining increasing importance. Some authors state that "from a practical point of view, these results suggest that the choice to implement the CE model depends on the application of I4.0 systems" [25], or even that "we definitely cannot have a circular economy without the 4th industrial revolution, and we cannot have a sustainable social utility of the 4th Industrial Revolution without moving to the circular economy" [25]. "The analysis shows how CE and I4.0 are closely linked: CE is developed using business models, technologies and skills related to Industry 4.0. Technologies can positively support CE in the ability to have more knowledge (measurement, traceability) and traceability of processes and products" [25]. In the context of the relationship between the CE and I4.0 (what we call the Circular Economy 4.0 or CE-4.0), "I4.0 is identified as a technology with the potential to unlock CE opportunities" [26]. These same authors, among their conclusions, also recognize the importance of integration between I4.0 and a CE in achieving sustainable development goals, stating that "the study findings confirm that Industry 4.0-CE integration has the potential to improve the triple bottom line of sustainability by optimizing materials, discarded products, and carbon footprint" [26]. Moreover, the authors argue that "ultimately, Industry 4.0 serves the purpose of the 3Rs, i.e., reduce, reuse, and recycle to obtain CE and preserve the product, use value of its materials and components over an extended period". In this sense, and as part of concrete applications, the authors state that Industry 4.0-CE integration could offer promising solutions to monitor waste and natural resources, modernize supply chains, and control carbon and energy consumption. In the same vein, I4.0 provides favorable bases to reinforce circular strategies such as remanufacturing and recycling, and it also improves maintainability and extends the life cycle and value of products [26].

1.4. Moving towards a Circular Construction Model 4.0 and the Need for Circularity Indicators

The circular economy (CE) has attracted both public and private interest as a way to overcome the contradiction between economic growth and environmental sustainability by moving away from the current linear business model (take, make, use, and dispose) to a circular business model (reduce, reuse, recycle, and recover) [27]. The construction industry, however, has faced challenges in adopting CE practices that are being successfully implemented in many other industrial sectors [28]. Several different general CE frameworks have been suggested so far [29]; however, as CE is relatively new in its conceptualization and implementation within the built environment, only a few evaluation frameworks have been specified in relation to the complex problems of the construction industry. Research on ways to measure and evaluate the circular economy at its different levels (e.g., national, industry, company, or product levels) is very recent. In this sense, the topic has been the focus of many questions raised by researchers, such as how circularity should be measured at the product level [30], how to measure progress in the transition to a circular economy [31], and how circularity should be measured at the level of companies and economies [32]. According to EASAC [33], companies may lack information, confidence, and capacity to move to circular economy solutions due to a lack of (i) indicators and targets, (ii) awareness of alternative circular options and economic benefits, and (iii) skills gaps in the workforce and lack of higher education programs at all levels of education (e.g., in design, engineering, and business schools). On the other hand, Haas et al. [34] argue that it is essential to determine the current state of circularity so that one can have a benchmark against which to track improvements. In the same vein, according to Kingfisher [35], a system cannot obtain a more closed loop unless you know how closed it was to begin with. In fact, it should be relevant to measure the degree of circularity of current systems, processes, and products, to be able to assess the remaining distance to achieve a truly circular economic self-sufficiency [36]. It is widely recognized in the literature that it is essential to incorporate monitoring and evaluation tools to measure and quantify progress in order to promote CE [33,34,37–43]. In addition to academic literature, this acknowledgement transcends supranational political levels, such as the European Commission, which has also recognized the need for circularity indicators through its action plan for CE [44], stating that to "assess progress towards a more circular economy and the effectiveness of action at EU and national level, it is important to have a reliable set of indicators". Consequently, it is possible to observe more and more attempts to develop indicators for the concept of the CE in the literature [41]. At the national level, the need for indicators and evaluation tools has been recognized by the Construction Circular Economy CDW Roadmap 2035 [14], which has established among its objectives for the year 2025 the need for the country to have information and indicators of a CE under construction. In summary, to decouple the consumption of natural resources, environmental impacts, economic growth, and human wellbeing, it is necessary to move towards a circular economy model [14,41,44]. However, to unlock the opportunities and potential of the circular economy, its integration with the technologies of the Fourth Industrial Revolution is indispensable. Therefore, a new economic model based on EC-I4.0 integration is absolutely essential to meet sustainable development goals. In the construction sector, such a model would enable improving the triple environmental, social, and economic results while also achieving improvements in labor productivity that would allow elevating the construction sector to at least the level of the average of the total economy. According to the above, the construction industry must make a quantum leap to a circular construction model 4.0. Therefore, this paper contributes to accelerating and promoting the transition to a CE 4.0 model in the built environment and also to the fulfillment of the objectives of the RCD Roadmap for the Circular Economy in Construction 2035 [14] through the development of a multicriteria assessment tool (AHP) of the potential performance of a CE 4.0 model applied to urban road infrastructure projects.

In this sense, this paper contributes directly to the implementation of public CE policies in the construction sector that the Chilean state has set as a goal until the year 2035.

2. Circular Economy Indicators, Industry 4.0 Technologies Applied to Construction: Literature Review

To understand which indicators are specifically used in the measurement of CE, it is necessary to review the existing conceptual classification frameworks to understand its scopes, purposes, and potential uses, as well as to improve the understanding of CE indicators and to have tools for their selection. To achieve this objective, the updated literature on the subject was reviewed, including the works developed by De Pascale et al. [45], Kristensen et al. [46], Moraga et al. [47], Saidani et al. [37], Banaité et al. [48], and Elia et al. [49]. Rodriguez et al. [50] developed a measurement method based on an iterative process in which experts are asked, indicators defined by them are followed, and the Delphi method is used in several stages. Rincón-Moreno et al. [51] propose indicators for government agencies based on the literature and refined by experts.

On the other hand, to understand which industry 4.0 technologies are used or will be used in the construction industry, the updated literature on the subject was reviewed, including the work developed by Braña [52], Osunsanmi et al. [53], Villegas [54], Agarwal et al. [55], and Chavarri [56].

The bibliographic review process carried out will be described in greater detail below, including: (1) conceptual frameworks for the classification of CE indicators, (2) CE indicators, (3) circularity assessment tools, and (4) Industry 4.0 technologies applied to the construction sector.

2.1. Conceptual Frameworks and Classification for Circular Economy Indicators

Saidani et al. [37] point out that finding suitable indicators can be a difficult task considering the large number of existing CE indicators but argue that it could be facilitated by the design of appropriate planning schemes and an associated selection tool. In another article, Ibáñez-Forés et al. [57] created a methodology measure and monitored the transition toward a circular economy in the studied organizations. In a recent paper, Kulakovskaya et al. [58] propose indicators of circularity of supply chain value, which include mid-level economic indicators. In another seminal article, Saidani et al. [37] clarify the confusion about current CE indicators and, therefore, visualize their usefulness in an organized, understandable, and usable way. They propose a taxonomy of CE indicators, adapted for users (engineers, designers, or managers) or policy makers. In short, Saidani et al. [37] propose 10 categories for classifying, differentiating, and guiding the use of CE indicators. Elia et al. [49], after analyzing different documents in the literature, propose a four-level framework to support the measurement of the adoption of the CE paradigm; the four levels described are the processes to monitor, the actions involved, the requirements to measure, and, finally, the levels of implementation of the CE paradigm. Starting from the first category, the CE paradigm generally involves five main phases: material input, design, production, consumption, and, finally, end-of-life (EoL) resource management, which provides inputs for the first phase in a closed-loop logic. In the proposed framework, these phases represent the processes whose performance must be measured to asess the overall circularity of the system under analysis. Regarding the requirements to be measured, Elia et al. [49] deduce five main categories from a European report [59]:

- Reduction in inputs and use of natural resources: the main objective is to reduce the erosion of the natural ecosystem currently caused by linear models. In short, the objective is to deliver more value from fewer materials. The direct consequence is also the preservation of natural resources, with efficient use of raw materials, water, and energy.
- Reduction in emission levels: this refers to both direct and indirect emissions.
- Reduction in losses of valuable materials: the implementation of closed-loop models to recover and recycle products and materials through reverse flows allows avoiding

production waste, minimizing incineration and landfill, and decreasing energy and material loss.

- Increasing participation of renewable and recyclable resources: the goal is to reduce emissions throughout the material cycle by using fewer raw materials and more sustainable sourcing; another issue is to achieve less overall pollution through cleaner material cycles.
- Increase the durability value of products: this objective can be achieved through the extension of the useful life of products, the adoption of new business models based on the use of services (e.g., leasing and bundling of products), the reuse of products as well as components, and a high diffusion of recycling of materials.

Finally, Elia et al. [49] identify three main fields of intervention of the CE paradigm [21]: the micro level, referring to individual companies or customers; the meso level, i.e., ecoindustrial parks; and the macro level, from cities to nations.

From the review of the different classification frameworks and selection tools, it can be observed that the work developed by Moraga et al. [47] and Saidani et al. [37] are the broadest in terms of the different classification categories considered. Figure 2 shows the classification framework proposed by Moraga et al. [47].

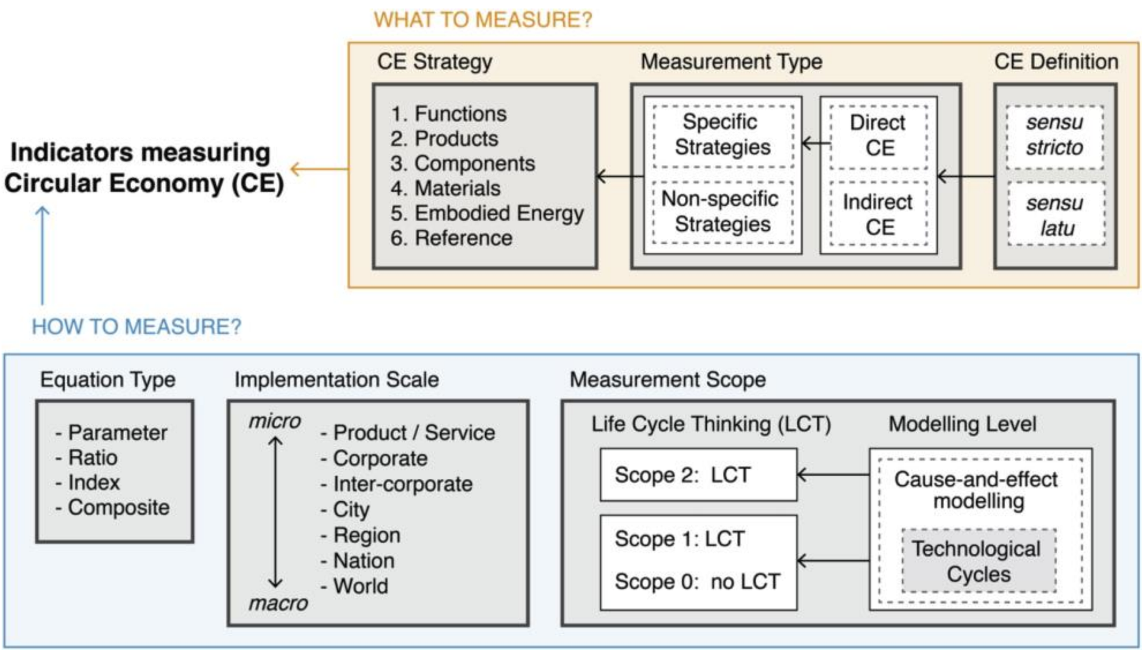

Figure 2. Classification framework for EC indicators. Source: Reprinted from Moraga et al. (2019) [47].

In the framework proposed by Moraga et al. [47], CE strategies are grouped for the preservation of functions, products, components, materials, and embodied energy. The proposed framework is useful as a reference to clearly identify what to measure and how to measure with CE measurement indicators.

A summary of the main conceptual frameworks and classification of the circular economy indicators proposed in the reviewed literature was generated, which allowed the identification of 14 classification categories for a CE indicator. The results are shown in Table 1. These categories were used for the design of CIROAD, allowing a specification of the model, making its classification in each of the categories.

Table 1. Summary of categories considered in different circularity indicator classification frameworks.

N°	Category	Moraga et al. [47]	Saidani et al. [37]	Elia et al. [49]	Banaité et al. [48]
1	Scale implementation	Yes	Yes	Yes	Yes
2	Circular economy strategy	Yes	Yes	Yes	Yes
3	Direct circularity or not	Yes	Yes	No	No
4	Timing	No	Yes	No	No
5	Use or user of the indicator	No	Yes	No	No
6	Transversality	No	Yes	No	No
7	Dimensionality	Yes	Yes	No	No
8	Measurability	Yes	Yes	No	No
9	Format	No	Yes	No	No
10	Origin	No	Yes	No	No
11	Modeling level	Yes	No	No	No
12	Life Cycle Approach	Yes	No	Yes	Yes
13	Scope of the definition of circular economy	Yes	No	No	No
14	Sustainable development	Yes	No	No	Yes

2.2. Circularity Indicators

To prepare a first list of indicators, various bibliographic sources were reviewed, all directly related to indicators to measure and/or evaluate circularity. Below, Table 2 details the references consulted.

Table 2. Bibliographical references consulted regarding CE indicators.

Ref.	Author	Title	Year
[45]	De Pascale et al.	A systematic review for measuring circular economy: The 61 indicators	2021
[60]	Sánchez-Ortiz, J., Rodríguez-Cornejo V., Del Río-Sánchez R., García-Valderrama T.	Indicators to Measure Efficiency in Circular Economies	2020
[61]	Fundación COTEC para la innovación	Situación y Evolución de la Economía Circular en España, Informe 2019	2019
[62]	Green Building Council España	Indicadores para medir la circularidad en el sector de la construcción.	2019
[29]	Pauliuk S.	Critical appraisal of the circular economy standard BS 8001:2017 and a dashboard of quantitative system indicators for its implementation in organizations.	2018
[63]	Circle Economy, DGBC, Metabolic, SGS Search, Revevco Foundation	Framework for Circular Buildings Indicators for possible inclusion in BREEAM.	2018
[64]	Núñez-Cacho P., Górecki J., Molina V., Corpas-Iglesias F.	New Measures of Circular Economy Thinking In Construction Companies.	2018
[65]	Fundación CONAMA (España)	Economía Circular en el Sector de la Construcción. Grupo de trabajo GT-6 Congreso Nacional del Medio Ambiente 2018	2018
[66]	Fundación COTEC para la innovación	Situación y Evolución de la Economía Circular en España.	2018

Table 2. *Cont.*

Ref.	Author	Title	Year
[33]	European Academies Science Advisory Council (EASAC)	Indicators for a circular economy.	2016
[67]	Verberne, J.	Building Circularity Indicators—An Approach for Measuring Circularity of a Building.	2016
[41]	Akerman, E.	Development of Circular Economy Core Indicators for Natural Resources—Analysis of existing sustainability indicators as a baseline for developing circular economy indicators.	2016

An exhaustive review of each of the references was carried out, focusing on the identification of the indicators proposed by each one. Subsequently, the indicators proposed by each referent were extracted. In total, 158 potential indicators were identified. For the elaboration of the circularity multicriteria evaluation model, it is interesting to discriminate associated indicators at the micro level (appropriate to implement at the project level) and that are applicable to the construction sector. In accordance with the above, all the indicators and areas of impact were classified by scale (macro, meso, micro) and also with respect to their potential application to the construction industry. By applying these filters (at the micro level and applicable to construction projects), it was finally possible to identify 56 indicators, which can be considered as potential indicators to be incorporated into the circularity multicriteria evaluation model. This analysis allowed us to have a broad database of CE indicators, which were used as a reference for the development of the circular economy measurement tool.

2.3. Circularity Assessment Tools

The list below comprises the existing and freely available circularity assessment tools currently available at the micro level, i.e., tools which can be applicable to organizations, products, or projects, the latter being the focus of this work:

- Circulytics [68];
- Circularity Potential Indicator (CPI) [37];
- Circular Economy Index (CEI) ([64];
- Circular Economy Indicator Prototype (CEIP) [40];
- Building Circularity Indicator (BCI) [67];
- Material Circularity Indicator (MCI) [69];
- Circular Economy Toolkit [70].

From the literature review, no specific circularity assessment tools were found for application in road infrastructure projects; however, at least three sustainability assessment tools for infrastructure were found to exist, so they were also included in the review. These three reviewed tools are mentioned below:

- INVEST: Infraestructure Voluntary Evaluation Sustainability Tool, Versión 1.3 [71];
- ENVISION: Rating System for Sustainable Infraestructure [72];
- Greenroads Rating System [73].

Under the idea of defining ideal requirements or characteristics to design a framework with the aim of measuring and/or evaluating and monitoring the circularity of the built environment, the revised tools are subjected to a comparative analysis based on the pyramid of desired characteristics to design a circularity measurement framework proposed by Saidani [74]. This pyramid considers five cornerstones for a CE measurement framework: (1) Systemic by design; (2) Integrated and Operational; (3) Adaptive and Flexible; (4) Intuitive user interface; and (5) Connection with the pillars of sustainable development. The objective of this comparative analysis is to identify the good practices of the existing tools (+) and to identify the margins of improvement (−). Tables 3 and 4 show the results of the review of the six main CE measurement tools, based on the identification of their strengths, weaknesses, and limitations.

Table 3. Positioning of the CE assessment tools with respect to the five proposed requirements (products).

Tool Requirements	Circularity Potential Indicator (CPI)	Material Circularity Indicator (MCI)	Circular Economy Toolkit (CET)	Circularity Indicator Prototype (CEIP)
Systemic by design	+: Life cycle thinking (although greater emphasis on manufacturing is lacking). +: Consideration of a large number of DfX related to the circular economy. −: Without distinction of circularity loops.	+: Life cycle thinking (but focused exclusively on the origin of the material, recycling and reuse). −: The main DfX related to the circularity performance of the product are not taken into account. −: Without distinction of circularity loops.	+: Life-cycle thinking (complete, i.e., pre-life, useful-life, and end-of-life phases are covered). +: Consideration of various DfX related to the circular economy. −Without distinction of circularity loops.	+: Life Cycle Thinking (but mainly focused on manufacturing and end of life). +/−: Consideration of some DfX but exclusively related to manufacturing and end-of-life steps. −Without distinction of circularity loops.
Integrated and Operative	+: Provides practical guidance to improve product circularity	−: Lack of support in the construction of data. Do not provide practical guidance to improve product circularity.	-: Lack of support in the construction of data. It does not provide concrete guidance for improving product circularity.	−: Lack of support in the construction of data. Superficial commitment to decision making.
Adaptive and Flexible	+: Applicable to a wide range of products. +: Excel data sheets that can be edited	+: Applicable to all types of real physical products. +: Excel data sheets that can be edited.	+: Applicable to a wide range of products. −: User interface not editable.	+: Excel data sheets that can be edited. −: Specially designed for the home improvement sector.
Intuitive user interface	+: Free, available on demand, easy to use, and understand. It is time efficient, that is, once one has all the data, it takes around 15 min.	+: Free download, easy to use and understand. It is very time efficient, that is, once one has all the data, it takes less than 5 min.	+: Free, available online, easy to use and understand. It is time efficient, that is, once one has all the data, it takes around 15 min.	+: Free, available on demand, easy to use and understand. It is time efficient, that is, once one has all the data, it takes around 15 min.
Connection with the pillars of sustainable development	−: Performance impacts of product circularity on the three pillars of sustainability are not explicitly addressed.	-: Performance impacts of product circularity on the three pillars of sustainability are not explicitly ad-dressed.	+: Business opportunities are covered (including financial viability and market growth potential). −: Other aspects are not addressed directly.	−: Performance impacts of product circularity on the three pillars of sustainability are not explicitly addressed.

Source: Adapted from Saidani (2018) [74].

The four tools reviewed in Table 3 share the strengths of being easy to use, even for a non-circular economy specialist, and in a short time, they provide a first overview of product circularity performance. However, all four tools have both weaknesses and limitations in measuring product performance in light of the circular economy in that this set of tools (with the exception of MCI) is similar to a checklist for a qualitative environmental assessment study with a trinary questionnaire. With the trinary scale, the user is in the habit of putting the cursor in the middle. In addition, this causes the evaluation to have too subjective characteristics.

Table 4. Positioning of the CE assessment tools with respect to the five proposed requirements (construction and building sector).

Tool Requirements	Circular Economy Index (CEI)	Building Circularity Indicator (BCI)
Systemic by design	+: Life cycle thinking. +: Consideration of DfX related to the circular economy. −: Without distinction of circularity loops.	+: Life cycle thinking (but focused exclusively on the origin of the material, recycling and reuse). +: Consideration of DfX related to the circular economy. −: Without distinction of circularity loops.
Integrated and Operative	+: Provides practical guidance to improve product circularity.	−: Lack of support in the construction of data. Do not provide practical guidance to improve product circularity.
Adaptive and Flexible	−: Applicable only to construction companies (Building) −: User interface not available.	−: Applicable to office building projects +: Excel data sheets that can be edited.
Intuitive user interface	−: Not available	+: Available on demand, it requires studying and understanding the structure of the tool before using.
Connection with the pillars of sustainable development	The performance impacts of product circularity on the three pillars of sustainability are not explicitly addressed.	−: The performance impacts of product circularity on the three pillars of sustainability are not explicitly addressed.

Source: Own elaboration based on the circularity measurement framework proposed by Saidani [74].

In the case of tools focused specifically on the construction sector (see Table 4), the BCI is postulated as a tool capable of generating a global analysis of circularity at the level of materials, products, and systems of an office building. However, the tool based on the MCI is not easily usable for a non-expert in circular economy. In the case of the CEI, the possibility of obtaining results at a deterministic and probabilistic level stands out, which gives the tool the ability to provide the user with more robust information for decision making. On the other hand, the model establishes fixed compliance goals for each attribute, which may need to be adapted according to the realities of each country or region. It also does not explicitly consider the sustainability approach.

One of the strengths shared by almost all the analyzed tools (with the exception of the MCI) is that they consider Design for X (DfX) concepts, such as design for disassembly and design for remanufacturing, among others.

In addition to the weaknesses identified in Tables 3 and 4, two elements were identified that, in our opinion, are relevant when developing a CE 4.0 measurement tool, which are (1) the absence of an in-depth discussion on metrics and measurement systems scoring and (2) the absence of the application of enabling technologies of Industry 4.0.

In general, from the analyses carried out, the following four limitations can be verified for the analyzed tools:

1. Inadequate coverage of the problem of data availability: This applies to all the tools analysed, including those for assessing the sustainability of infrastructure. In all cases, it is assumed that data and information are available to answer the questions associated with the different criteria, which is probably not always possible.
2. Lack of consideration of the pillars of sustainable development: The performance impacts of product circularity on the three pillars of sustainability (environmental, economic, and social) are not addressed together.
3. The absence of the application of enabling technologies of Industry 4.0: It is the same for all the reviewed tools, with the exception of the Circular Economy Index (CEI), which sometimes considers the incorporation of BIM-based design among its criteria. However, it does not consider other types of enabling technologies.
4. The absence of an in-depth discussion on metrics and scoring systems: It is the same for all the tools analyzed, with the exception of the MCI and the BCI (which is based

on the MCI), including those for evaluating infrastructure sustainability. In all cases, with the exceptions already mentioned, there is no deep reflection on the metrics and scoring systems to measure circularity. There is a theoretical gap regarding the definitions of scores and the mathematical bases that support their construction.

2.4. Industry 4.0 Technologies Applied to the Construction Sector

A review of the literature on Industry 4.0 technologies applied to the construction sector was carried out, with the aim of obtaining references of possible indicators for their subsequent incorporation into the EC 4.0 evaluation model. For this, we review the works developed by Braña [52], Osunsanmi et al. [53], Villegas [54], Agarwal et al. [55], and Chavarri [56]. According to these authors, there are six ways in which the construction industry could be transformed in the coming years, which are detailed below:

1. High-definition surveying and geolocation;
2. Building Information Modeling (BIM);
3. Virtual Reality (VR) and Augmented Reality (AR);
4. Digital collaboration and mobility;
5. Internet of Things (IoT) and advanced analytics;
6. 3D printing.

These technologies served as a reference for the preparation of the circularity evaluation model 4.0 proposed in this work.

3. Methods: Design of the Circular Potential Yield Model, CIROAD

Once the review of the literature on CE indicators and industry 4.0 technologies applied to the construction sector is complete, we begin the design of the evaluation tool. As a starting point, the conceptual frameworks and classification for CE indicators, the indicators obtained from the literature review are taken as a reference, in addition to the strengths, weaknesses, and limitations of the existing evaluation tools consulted. Therefore, the evaluation tool to be proposed must share the same strengths of the existing tools reviewed and overcome their limitations, that is, address and overcome the identified weaknesses. As a starting point for this chapter, the requirements and proposed solutions to the four limitations identified for the existing tools reviewed above are presented:

- Data availability problem: to overcome this limitation, the information needed to answer the questions for the evaluation of the different criteria of the model should come from the engineering design background (budgets, plans, and technical specifications) of the project to be evaluated.
- Failure to consider the pillars of sustainable development: This limitation is overcome by explicitly incorporating the social and economic aspects in the model, leaving the environmental aspects implicit based on the different circularity criteria considered.
- The absence of the application of Industry 4.0-enabling technologies: to overcome this limitation, this research carried out a process of reviewing references and interviews with experts regarding the most relevant Industry 4.0 enabling technologies.
- The absence of in-depth discussions of metrics and scoring systems: this theoretical gap is resolved using the AHP multicriteria evaluation method [75].

Before defining a hierarchical structure for the circular economy measurement model, it is necessary to classify the model according to the 14 categories defined in Table 1 in order to define the scope, characteristics, and requirements of the circularity indicator develop. The different classification categories defined for CIROAD are shown in Table 5.

Table 5. Classification categories defined for CIROAD.

N°	Category	Classification for CIROAD Model
1	Scale implementation	The circularity indicator will be implemented at the micro level, given that it seeks to be applicable at the project level.
2	Circular economy strategy	The circularity indicator will consider the feedback loops corresponding to the 9R framework, as defined by Kirchherr et al. [19], considering strategies aimed at a smarter use and production of products (Mainly the "Reduce" strategy), extension of the useful life of parts and products (mainly the "Reuse" and "Restore" strategies), and useful application of materials (mainly "Recycle").
3	Direct circularity or not	In general, as no data are available, the indicator will use auxiliary approaches to assess indirect effects of circularity in the economy.
4	Timing	The indicator will be used for prospective (potential) or ex ante evaluation. Project circularity should be measured at the design stage.
5	Use or user of the indicator	The use of the indicator has been defined for information purposes, helping to understand the situation (e.g., monitoring progress, benchmarking, identifying areas for improvement).
6	Transversality	The indicator will be of a specific nature, given that it is designed to evaluate the potential performance of urban road infrastructure projects.
7	Dimensionality	The indicator can be considered of medium dimensionality, because although it will translate circularity into a single number, it will also be complemented with circularity indicators for the different criteria of the hierarchical structure.
8	Measurability	The units used to calculate circularity will be qualitative and quantitative.
9	Format	The evaluation interface associated with the indicator is not part of the objectives of this work, although its implementation in a web environment that allows online self-evaluation is recommended in the future.
10	Origin	The indicator has an academic origin.
11	Modeling level	Indicators measure the effects (burdens/benefits) of technology cycles on environmental, economic, and/or social concerns in a cause-and-effect chain model.
12	Life Cycle Approach	The indicator considers the life cycle thinking (LCT) approach during the design, construction, operation, and deconstruction cycles according to Moraga et al. [48].
13	Scope of the definition of circular economy	The indicator will use a broad definition of circular economy: lato sensu according to Moraga et al. [48].
14	Sustainable development	The lato sensu definition of circular economy pushes the focus towards sustainability and the effects of CE strategies on the economy, the environment and society (what we call the triple bottom line).

As previously indicated, for this work it was decided to use the AHP multicriteria evaluation method [75] because it presents a robust mathematical support, allows qualitative and quantitative criteria to be measured through a common scale, allows the participation of different people (experts) to be included, which is highly relevant for analyzing complex problems with practical applications. Finally, the method makes it possible to verify the logical consistency index of the judgments made, which gives greater mathematical support to the evaluations made with the model. The method was chosen mainly for its practical implementation and ease of application.

One of the relevant aspects of the application of the AHP method is the correct selection of the committee of experts that will weigh the criteria and subcriteria of the model. In this case, the following criteria were defined for the selection of the experts: (1) they were relevant decision-makers in CE matters at the national level and (2) they held technical positions but in high-level positions within their organizations.

The list of experts and their characterization is shown in Table 6

Table 6. List of experts with characterization and type of participation.

Expert N°	Gender [1]	Academic Training	Position	Area of Professional or Research Interest	Type of Participation
1	F	Architect, MSc Environmental Design and Engineering	Executive Secretary of Sustainable Construction	Sustainable Construction	Weighting of model criteria and support in the selection of model criteria
2	F	Architect, Master in Architecture	Sustainability Coordinator	Sustainable Construction	Weighting of model criteria and support in the selection of model criteria
3	F	Architect, Master in XXI Century Housing Laboratory	Coordinator of the Regional Commission for Sustainable Construction	Sustainable Construction	Weighting of model criteria and support in the selection of model criteria
4	M	Ph.D. in Civil and Environmental Engineering	Academic, assistant professor	Road Engineering, Pavement design, Self-healing materials	Technical interview and support in the selection of model criteria
5	M	Master in Construction Management. Civil engineer	Highway engineering expert	Road Engineering, Pavement design	Technical interview and support in the selection of model criteria
6	M	Civil engineer	Head of Sustainable Building Certification	Sustainable Construction	Technical interview and support in the selection of model criteria
7	M	Architect	Circular Construction Manager	Circular construction	Technical interview and support in the selection of model criteria

[1] M = Male, F = Female.

This section presents the methodology developed for the preparation of the model, in terms of its hierarchical structure, definition of criteria and subcriteria, and weighting and validation of the model.

3.1. Design of the Hierarchical Structure of the Model and Selection of Subcriteria or Indicators

Having clear boundary conditions with which the model to be developed must comply (see Table 5), we proceeded to generate the hierarchical structure of the model. This was carried out through an iterative process. For this, the predominant conditions for the definition of the general criteria were considered to be the need for the model to have a life cycle approach and also to consider the elements of sustainable development (social, economic, and environmental impact). Regarding the latter, criteria associated with social and economic aspects are explicitly introduced, leaving environmental aspects as implicit in the model, given that the different circular economy strategies in general already incorporate environmental benefits. It is important to clarify that this first version contains a general scope of the objective, defined as the potential circularity for projects in the built environment.

In accordance with the above, the criteria that directly contribute to the overall objective (the potential circularity for projects in the built environment) were defined as follows: (1) Circular Materials; (2) Circular design approaches; (3) Circular Construction Approaches; (4) Circular Operation Approaches; (5) Approaches to Deconstruction and Resource Recovery; (6) Creation of Social Value; and (7) Economic Performance.

With this criteria structure, the subcriteria (indicators) of the literature review were added, according to the classification that corresponded to them according to the criteria structure designed. This structure was reviewed with a committee of three experts in sustainable construction and circular economy. This result is shown in Figure 3.

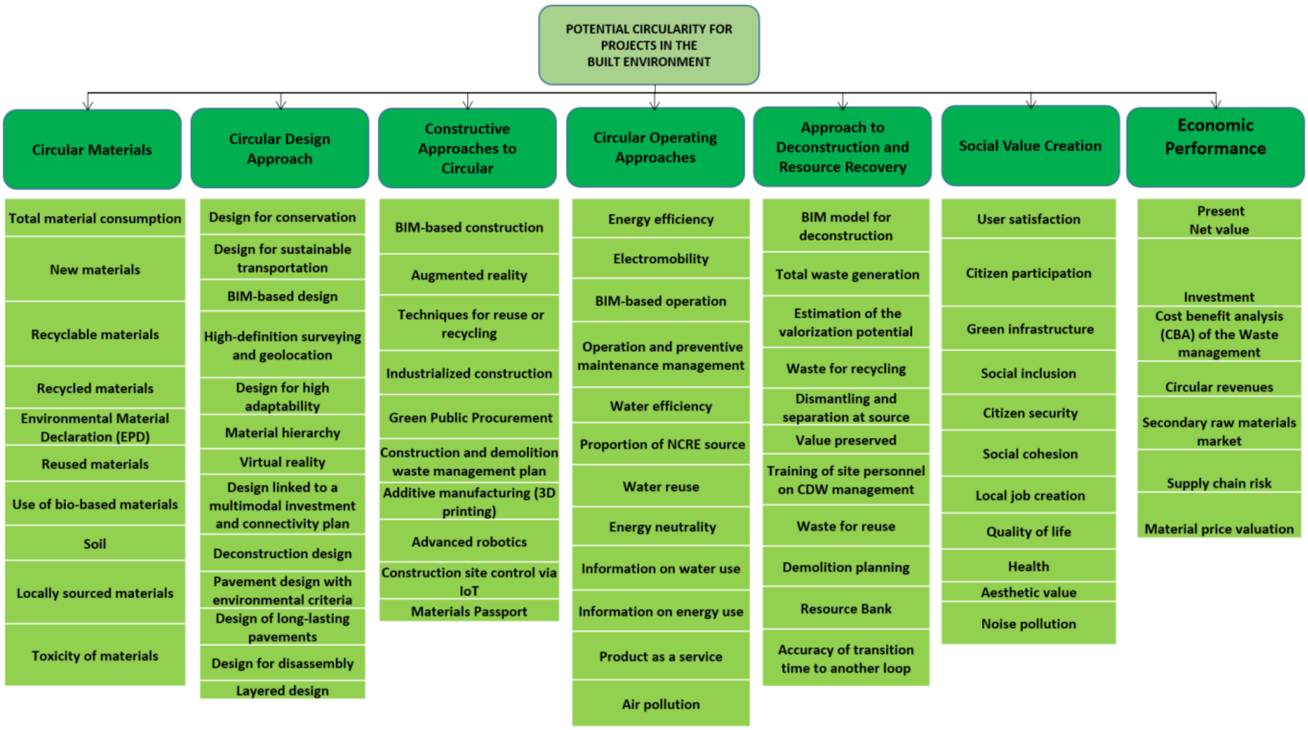

Figure 3. Hierarchical Structure of the General Potential Circularity Assessment Model for Built Environment Projects.

As this model is so general, it does not allow for studying the specificity of existing projects in the built environment because there are criteria that apply to one type of project but not to others. In addition, such a broad model is not compatible with all the axioms of the AHP method, mainly due to the possible dependence within the same level, among many of its constituting criteria. Therefore, specific models from the general model need to be built for the different types of projects in the built environment. Therefore, a more simplified version of the model was made, with the objective of having a specific application for urban road infrastructure projects and at the same time ensuring compliance with the axioms of the AHP method, especially with respect to the dependency between criteria of the same level. This is justified because the built environment involves a wide typology of projects of such a different nature that not all criteria may be applicable. With these prioritization factors, the second version of the model was prepared, which in this case corresponds to the specific application for the evaluation of the potential circularity of urban road infrastructure projects.

Therefore, we proceeded to generate a classification of projects, disaggregating the projects into two major categories: Building and Infrastructure, as shown in Figure 4. Within the infrastructure category, this work is specifically oriented to the development of a circularity evaluation model for urban road infrastructure projects. To prepare the evaluation model for urban road infrastructure projects, we worked with a committee of experts to select the criteria to be incorporated. For this purpose, 4 prioritization factors were defined, which are: 1. the degree of relevance of the criterion, evaluated as the effect of the improvement in the performance of the criterion as a result of the circularity level of the entire project; 2. the egree of maturity or experience in methodology and/or marketing and/or technology to apply the criteria to the national realty in the short or medium term; 3. ease of measuring or estimating ex ante the criterion or indicator, either by direct or indirect methods with the information available in the design background (plans, budgets, and technical specifications); and 4. review that the criterion has no dependency relationship with other criteria of the same level to be incorporated in the model. The above factors comply with the axiom of the AHP.

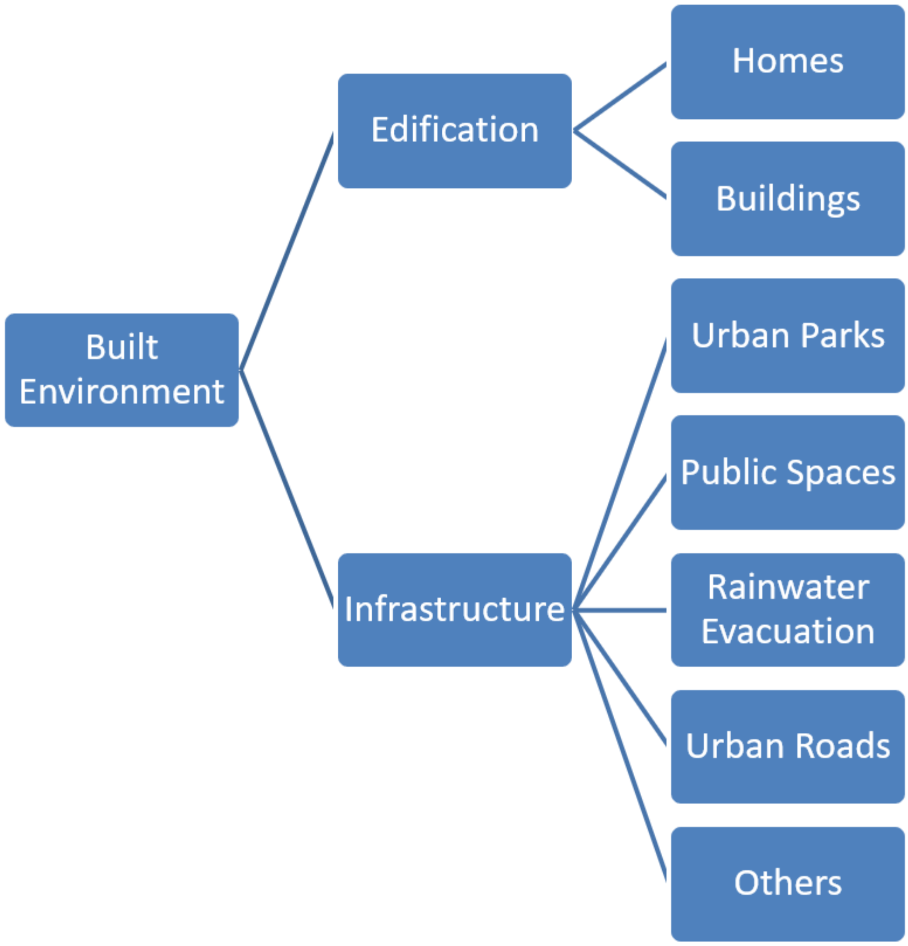

Figure 4. Categories of Construction Projects.

This version of the model was submitted to consultation and feedback from the 4 professional experts. In this instance, some criteria were added and eliminated from the model, based on the recommendations of the experts consulted, allowing the evaluation tool to be enhanced by incorporating more specific elements of road engineering projects (due to the specialist profile in the area of two of those interviewed). Once the first round of interviews was completed, a second version of the model was prepared, which is called the Circularity Indicator for Urban Road Projects (CIROAD). The final developed model is shown in Figure 5.

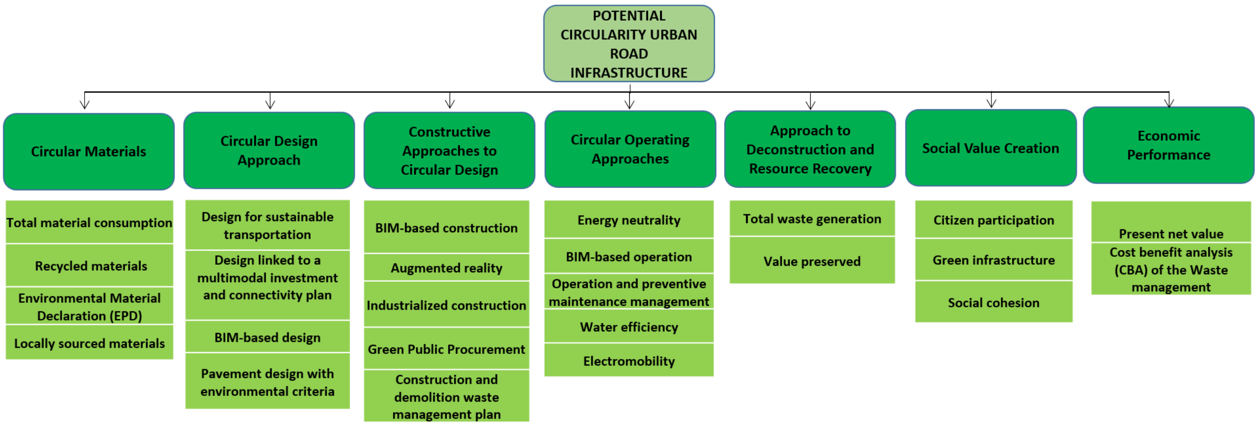

Figure 5. Hierarchical Structure Model: Circularity Indicator for Urban Road Projects (CIROAD).

3.2. AHP Model Weighting Process

The weighting process of the model was carried out independently by each of the three experts who participated in this process (see Table 6). This weighting was carried out through an interview with each expert in order to complete the peer-review process established in the AHP methodology.

The weighting of the combined model was generated by means of the judgment aggregation procedure proposed by Saaty [75]. This is one of the advantages of the AHP, since it makes group decision making possible through the aggregation of opinions. When the group consists of experts, as is the case in this paper, each one of the experts elaborates their own hierarchy, and the AHP combines the results using the geometric average [76].

Tables 7–13 show the questions, indicators, and weights of each sub-criterion, according to the result of the weighting process carried out by the committee of experts. Each of the criteria are defined below.

1. Circular Materials: evaluates whether there is replacement of traditional and virgin materials input with renewable, bio-based, non-toxic, and/or recovered materials which can be reused or recycled in the future;
2. Circular design approaches: consists of evaluating the level of circularity in the design of the project in: prioritization of sustainable transport modes, investment aimed at a multimodal strategic plan at the city level, application of 4.0 technologies, and reduction in the carbon footprint of the structural package of project pavements;
3. Circular constructive approaches: consists of evaluating the level of circularity in the application of construction elements, mainly based on Industry 4.0 technologies, green public procurement, and on-site waste management, to achieve greater efficiency, greater productivity, less waste, improved safety and minimization of externalities and environmental impacts in the construction stage of the project;
4. Circular Operation Approaches: consists of measuring the level of circularity in relation to the application of strategies aimed at efficiency in the use of resources, elimination of waste of resources and energy, internal circular resources, preventive maintenance, and minimization of externalities and environmental impacts during the operation stage of the project with the aim of optimizing the useful life of the infrastructure and increasing the possibility of reusing resources in the future;
5. Approaches to the Deconstruction and Recovery of Resources: the objective is to evaluate the level of circularity in relation to the application of strategies aimed at efficient dismantling, the separation of waste streams to facilitate recycling and reuse of these materials in other projects, with the aim of maintaining them at the highest possible value and performance and maximizing the reintroduction of these materials in the cycles of use after disposal at the end of the useful life of the project;

6. Creation of social value: the objective is to evaluate the level of circularity in relation to the social value generated by the project, understood as the contribution of value beyond the financial sphere, considering aspects such as: citizen security, social cohesion, citizen participation, etc., with the aim of obtaining the maximum performance of the materials, energy, and resources in general used in the project to generate a significant contribution to the creation of social value;
7. Economic Performance: the objective is to measure the level of circularity in relation to the creation of economic value generated by the project, considering aspects such as social NPV, material productivity, waste productivity, raw material markets, preserved value, etc., with the aim of obtaining the maximum economic profitability of the application in the project of circular business models.

Table 7. Questions, indicators, and weights of each sub-criterion of the Circular Materials criterion.

Sub-Criterion	Sub-Criterion Question	Full Name of the Indicator	Weight
Total material consumption	What is the percentage of savings in materials generated by the project compared to a traditional paving solution?	Total savings (in %) of the volume of project materials compared to an equivalent base project developed using traditional pavement structural design methodologies	0.024
Recycled materials	What percentage of the project materials are of recycled origin?	Fraction (in %) of the budget for recycled materials with respect to the total budget for project materials	0.043
Environmental Material Declaration (EPD)	What percentage of the project materials have an environmental product declaration?	Fraction (in %) of the budget of materials with DAP with respect to the total budget of materials of the project	0.049
Locally sourced materials	What percentage of the project materials are locally sourced?	Fraction (in %) of the budget of locally sourced materials with respect to the total budget of materials of the project	0.031

Table 8. Questions, indicators, and weights of each sub-criterion of the Circular Design Approaches criterion.

Sub-Criterion	Sub-Criterion Question	Full Name of the Indicator	Weight
Design for sustainable transportation	What percentage of the project area is dedicated to sustainable modes of transport?	Fraction (in %) of surface exclusively for pedestrians, cyclists, and public transport with respect to the total surface area of the project.	0.046
Design linked to a multimodal investment and connectivity plan	Is the project part of a strategic investment plan for the city and does it promote intermodality with other sustainable modes of transport?	Qualitative indicator with summable requirements: Requirement 1 (40%); Requirement (30%); Requirement 3 (30%).	0.061
BIM-based design	Is the development of the project design carried out under the BIM methodology?	Qualitative indicator at three levels: high (100%), medium (50%), and low (0%).	0.04
Pavement design with environmental criteria	Is the structural design of pavements carried out considering environmental criteria?	Qualitative indicator at three levels: high (100%), medium (50%), and low (0%).	0.085

Table 9. Questions, indicators, and weights of each sub-criterion of the Circular Constructive Approaches criterion.

Sub-Criterion	Sub-Criterion Question	Full Name of the Indicator	Weight
BIM-based construction	Is there a BIM construction model for the execution stage of the project?	Qualitative indicator at three levels: high (100%), medium (50%), and low (0%).	0.026
Augmented reality	Is augmented reality technology used for the execution stage of the project?	Qualitative indicator at two levels: high (100%) and low (0%).	0.011
Industrialized construction	What percentage of the elements of the project correspond to prefabricated?	Fraction (in %) of the budget for prefabricated materials with respect to the total budget of the project.	0.027
Green Public Procurement	Does the bidding process for the execution of the project incorporate circularity criteria in the evaluation of offers?	Qualitative indicator with summable requirements: Requirement 1 (20%); Requirement 2(20%); Requirement 3 (20%); Requirement 4 (20%); and Requirement 5 (20%).	0.034
Construction and demolition waste management plan	Is NCh 3562 on Construction and Demolition Waste Management used for the execution of the project?	Qualitative indicator at two levels: high (100%) and low (0%).	0.031

Table 10. Questions, indicators, and weights of each sub-criterion of the Circular Operation Approaches criterion.

Sub-Criterion	Sub-Criterion Question	Full Name of the Indicator	Weight
Energy neutrality	What percentage of the energy consumed in the operation stage is produced by the same project through NCRE sources?	Fraction (in %) of energy produced by the project, through NCRE sources, with respect to the total energy required for its operation.	0.035
BIM-based operation	To support the management processes of the operation stage, does the project have the BIM model of operation?	Qualitative indicator at two levels: high (100%) and low (0%).	0.016
Operation and preventive maintenance management	Does the project have a contract that ensures the maintenance and comprehensive management of infrastructure assets during its operation?	Qualitative indicator at four levels: Advanced (100%), High (66%), Medium (33%), and Low (0%).	0.034
Water efficiency	What percentage of average efficiency does the project have in the use of water for irrigation?	Weighted average efficiency (in %) of the irrigation technologies with respect to the areas irrigated by the project.	0.031
Electromobility	What percentage of the electric bus fleet in the first year of operation is contributed by the project?	Fraction (in %) of electric buses contributed by the project with respect to the total number of buses in its first year of operation.	0.02

Table 11. Questions, indicators, and weights of each sub-criterion of the Approaches to the deconstruction and recovery of resources criterion.

Sub-Criterion	Sub-Criterion Question	Full Name of the Indicator	Weight
Total waste generation	Is there an estimate of the waste generated by each project alternative at the end of its useful life?	Qualitative indicator at four levels: Advanced (100%), High (66%), Medium (33%), and Low (0%).	0.037
Value preserved	What percentage of the waste generated by the project at the end of its useful life has recovery actions?	Fraction (in %) of the volume of waste that can be revalued, with respect to the total volume of waste at the end of the useful life of the project.	0.076

Table 12. Questions, indicators, and weights of each sub-criterion of the Creation of social value criterion.

Sub-Criterion	Sub-Criterion Question	Full Name of the Indicator	Weight
Citizen participation	What degree of formality and focus does the citizen participation process of the project have?	Qualitative indicator at four levels: Advanced (100%), High (66%), Medium (33%), and Low (0%).	0.06
Green infrastructure	What is the net impact of the project in terms of carbon dioxide absorption attributable to green infrastructure?	Qualitative indicator at three levels: high (100%), medium (50%), and low (0%).	0.039
Social cohesion	What is the net impact of the project in terms of the area of public spaces for recreation and social interaction in the community?	Fraction (in %) of the increase (or decrease) in the surfaces of public spaces for recreation and social interaction (squares or parks) offered by the project compared to the base situation.	0.036

Table 13. Questions, indicators, and weights of each sub-criterion of the Economic Performance criterion.

Sub-Criterion	Sub-Criterion Question	Full Name of the Indicator	Weight
Present net value	Is the project socially profitable and satisfactorily pass the sensitivity analyses?	Qualitative indicator at three levels: high (100%), medium (50%), and low (0%).	0.044
Cost–benefit analysis (CBA) of Waste management	Does the project have a cost–benefit evaluation of waste management?	Qualitative indicator at three levels: high (100%), medium (50%), and low (0%).	0.064

The information to answer the questions of each sub-criterion, through the calculation of the model indicators (Tables 7–13), comes directly from the technical background of the design of the project under evaluation, such as plans, budgets, reports, and technical specifications. The model has quantitative and qualitative indicators. Quantitative indicators are calculated by extracting the official data and information from the project under evaluation, which makes it possible to ensure the objectivity of the evaluation (which can also be verified by a third party). In the case of qualitative indicators, these are evaluated according to achievement levels. It is important to mention that each qualitative indicator has requirements and objective means of verification for each level (which must be verifiable through the technical background of the project under evaluation). In this sense, the model has been designed so that its application avoids or minimizes the use of subjective elements.

The model developed (CIROAD) evaluates the degree of potential circularity 4.0 for urban road infrastructure projects, through a survey of 25 questions (one for each subcriterion), which are answered in a range of 0% (less circular) to 100% (fully circular). The survey (see Tables 7–13) can also be transformed into a guide for organizations in the transition towards more circular projects, since it can be used by development teams to identify the aspects of their projects to consider to achieve the maximum potential of circular 4.0 performance.

3.3. Model Logical Consistency Index Check

One of the most important aspects that the AHP method considers is the logical consistency of expert judgments. Following Saaty [75], priorities and weights are estimated using the principal eigenvector of the judgment matrix (λ_{max}). However, a consistency test must be performed to determine the level of consistency required for the validity of the results, using a consistency ratio (*CR*):

$$CR = \frac{CI}{RI} \tag{1}$$

where the *RI* values correspond to a random index, which corresponds to the consistency index of a random reciprocal matrix, with forced reciprocals [75], while the *CI* is a consistency index, which can be interpreted as a measure of the deviation of consistency of the pairwise comparisons matrix. This value can be calculated from Equation (2):

$$CI = \frac{\lambda_{max} - N}{N - 1} \tag{2}$$

where λ_{max} corresponds to the largest eigenvalue of the matrix, while n represents the dimension or size of the matrix. When the *CI* of the matrix is high in proportion to the *RI*, the input judgments are not consistent and therefore unreliable. In general, a maximum consistency ratio of 0.10 is considered acceptable. If the value of the index exceeds this value, the judgments may not be reliable.

Finally, the summary of the results of the consistency ratio for the combined model is presented in the Table 14.

Table 14. Summary of the results of the consistency index for the combined model.

Level or Hierarchy	Consistency Ratio (CR)	Compliance Verification ($\leq$0.1)
Global: Potential Circularity Urban Road Infrastructure	0.01	Yes
Circular materials	0.01	Yes
Circular Design Approaches	0.003	Yes
Circular Construction Approaches	0.01	Yes
Circular Operation Approaches	0.01	Yes
Approaches to Deconstruction and Resource Recovery	0	Yes
Creation of Social Value	0.006	Yes
Economic performance	0	Yes

3.4. Circularity Level Rating Scale

In the case of the CIROAD, it is proposed to establish circularity qualification ranges based on the score obtained by the project, in this way it is possible to establish circularity goals (qualification to be achieved within a certain period) and at the same time provide an opportunity to evaluate the progress in a process of transition from the linear economy (Letter E) to a completely circular one (Letter A+).

Table 15 below shows the relationship between the scores obtained by the evaluation model and the proposed rating scale, which is based on the Circulytics tool of the Ellen MacArthur Foundation [68].

Table 15. Relationship between the CIROAD numerical score and the circularity score.

Lower Limit (%)	Upper Limit (%)	Potential Circularity Rating 4.0
88.89	100	A+
77.78	88.89	A
66.67	77.78	A−
55.56	66.67	B+
44.44	55.56	B
33.33	44.44	B−
22.22	33.33	C
11.11	22.22	D
0	11.11	E

Source Adapted from Ellen MacArthur Fundation (2020) [68].

4. Results Case Studies

The CIROAD model developed was applied to three projects in the urban transport area of the Chilean Ministry of Housing and Urbanism (MINVU/SERVIU) in the Santiago Metropolitan Region (RM) [77]. These projects are:

1. Improvement of the "Lo Blanco" axis, which includes the municipalities of El Bosque, San Bernardo, and La Pintana;
2. Construction of the "San Francisco Trunk Canal" axis, covering the municipalities of La Pintana, Puente Alto, and La Florida;
3. Improvement of the Padre Hurtado axis (Gran Avenida—Avda. El Mariscal), which includes the municipalities of La Cisterna, El Bosque, and San Bernardo.

For the application of the CIROAD, a three-stage procedure was followed: (1) the compilation of the technical background of the projects; (2) calculation of CIROAD indicators and sub-criteria; and (3) conclusions and recommendations. In Stage 1, all the technical information necessary for the evaluation of the selected projects was collected (plans, documents, budgets, and technical specifications). In Stage 2, the calculation formulas (quantitative sub-criteria) and measurement scales (qualitative sub-criteria) contemplated by the CIROAD were applied. Finally, in Stage 3, the results are presented and analyzed, in addition to providing recommendations. In this context, the survey is applied to the projects, where the evaluated organization only provides the technical information of the same, but the answers are obtained directly from an analysis of the technical background of each project by the evaluators [77], thus ensuring an objective and verifiable evaluation according to the indicators defined by the CIROAD. The detail of the scores achieved by each project is shown in Table 16.

Table 16. Details of the scores obtained by each evaluated project.

Criterion and Sub-Criterion	Local Weighting	Overall Weighting	Improvement of the "Lo Blanco" Axis	Construction of the "San Francisco Trunk Canal" Axis	Improvement of the Padre Hurtado Axis
Circular Materials	0.146		16.380%	16.170%	17.640%
Total material consumption	0.162	0.024	0%	0%	0%
Recycled materials	0.295	0.043	0%	0%	0%
Environmental Material Declaration (EPD)	0.333	0.049	0%	0%	0%
Locally sourced materials	0.21	0.031	78%	77%	84%
Circular design approaches	0.231		20.777%	30.020	20.570
Design for sustainable transportation	0.198	0.046	52%	59%	51%
Design linked to a multimodal investment and connectivity plan	0.262	0.061	40%	70%	40%

Table 16. *Cont.*

Criterion and Sub-Criterion	Local Weighting	Overall Weighting	Improvement of the "Lo Blanco" Axis	Construction of the "San Francisco Trunk Canal" Axis	Improvement of the Padre Hurtado Axis
BIM-based design	0.173	0.04	0%	0%	0%
Pavement design with environmental criteria	0.366	0.085	0%	0%	0%
Circular constructive approaches	0.13		29.536%	27.204%	28.688%
BIM-based construction	0.204	0.026	0%	0%	0%
Augmented reality	0.089	0.011	0%	0%	0%
Industrialized construction	0.212	0.027	28%	17%	24%
Green Public Procurement	0.259	0.034	0%	0%	0%
Construction and demolition waste management plan	0.236	0.031	100%	100%	100%
Circular Operation Approaches	0.137		21.084%	26.100%	21.084%
Energy neutrality	0.257	0.035	0%	0%	0%
BIM-based operation	0.117	0.016	0%	0%	0%
Operation and preventive maintenance management	0.252	0.034	33%	33%	33%
Water efficiency	0.228	0.031	56%	78%	56%
Electromobility	0.147	0.02	0%	0%	0%
Approaches to the Deconstruction and Recovery of Resources	0.113		0%	0%	0%
Total waste generation	0.325	0.037	0%	0%	0%
Value preserved	0.675	0.076	0%	0%	0%
Creation of social value	0.135		22.350%	48.500%	22.350%
Citizen participation	0.447	0.06	50%	50%	50%
Green infrastructure	0.287	0.039	0%	0%	0%
Social cohesion	0.266	0.036	0%	100%	0%
Economic Performance	0.108		40.900%	40.900%	40.900%
Present net value	0.409	0.044	100%	100%	100%
Cost benefit analysis (CBA) of the Waste management	0.591	0.064	0%	0%	0%
Circularity Score			21.4%	27.5%	21.4%

The most relevant results obtained for each project are as follows.

4.1. Lo Blanco Axis Improvement Project

This project achieves a CIROAD score of 21.36%. This project classifies for its potential circularity 4.0 in category "D", i.e., one of the lowest circularity scales. The Figure 6 shows the circularity achieved by each criterion of the model and shows that the criterion with the highest percentage of circularity is "Economic Performance", with a score of 41%; this criterion consists of measuring the level of circularity related to the creation of economic value generated by the project. The criterion with the lowest percentage of circularity is "Approaches to Deconstruction and Resource Recovery", which has a score of 0%. This criterion consists of evaluating the level of circularity in relation to the application of strategies aimed at efficient dismantling and the separation of waste streams to facilitate recycling and reuse of these materials in other projects. In an analysis at the sub-criterion level, it is possible to observe that 16 of the 25 sub-criteria of this project have zero circularity, that is, 0%. The sub-criteria with a score of 100% are "CDW Management Plan", which answers the question "Is NCh 3562 on Construction and Demolition Waste Management applied for the execution of the project?", and "Net Present Value", which answers the question "Is the project socially profitable and satisfactorily overcomes the sensitivity analysis?".

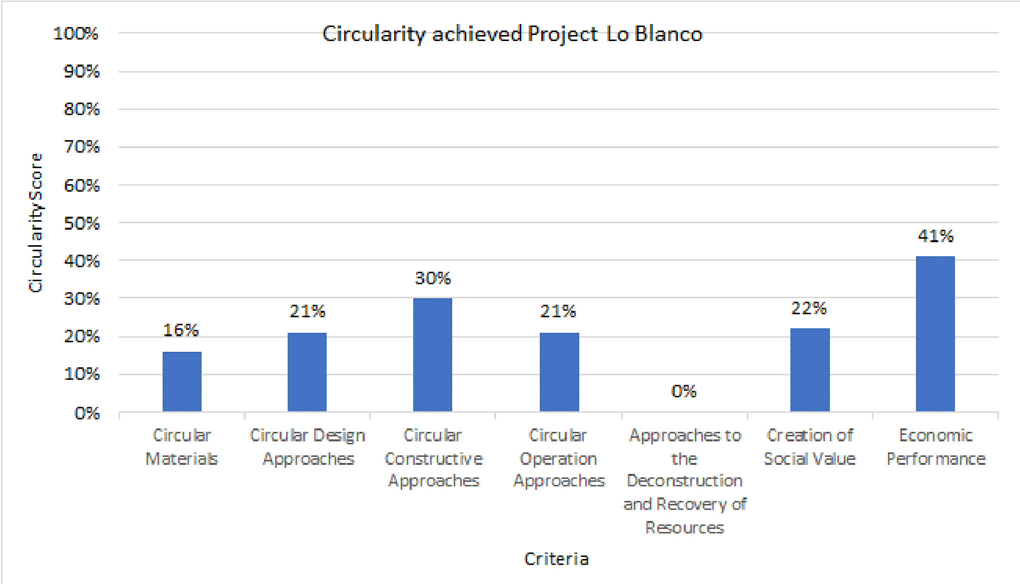

Figure 6. Circularity achieved by each criterion of the model for the Lo Blanco Axis Improvement Project. Source: Adapted from Campos, A.I.; Prieto, S.S.; Piñones (2022) [77].

Figure 6 shows the circularity score achieved by the Lo Blanco Axis Improvement Project for each CIROAD criterion.

4.2. Construction Project of San Francisco Trunk Line Axis

This project achieves a CIROAD score of 27.49%. Due to its potential circularity, this project is classified as 4.0 in category "C", i.e., it also ranks in one of the lowest circularity scales, although in a higher category compared to the other two projects evaluated. Figure 7 shows the circularity achieved by each criterion of the model, showing that the criterion with the highest percentage of circularity is "Creation of social value", with a score of 49%, which consists of evaluating the level of circularity related to the social value generated by the project, understood as the contribution of value beyond the financial aspect. The criterion with the lowest percentage of circularity is "Approaches to Deconstruction and Resource Recovery", with a score of 0%, which consists of evaluating the level of circularity in relation to the application of strategies aimed at efficient dismantling, separation of waste streams to facilitate recycling and reuse of these materials in other projects. In an analysis at the sub-criterion level, it is possible to observe that 15 of the 25 sub-criteria of this project have zero circularity, that is, a score of 0%. The sub-criteria with a score of 100% are: "CDW Management Plan", which answers the question: Is the Chilean Standard 3562 on Construction and Demolition Waste Management applied in the execution of this project?; "Social Cohesion", which answers the question: What is the net impact of the project in terms of surface area of public spaces for recreation and social interaction of the community?; and "Net Present Value", which answers the question: Is the project socially profitable and does it satisfactorily pass the sensitivity analyses? In addition, the sub-criterion "Locally Sourced Materials" obtained a score of 77%, which means that a large part of the materials used are locally sourced.

Figure 7 shows the circularity score achieved by the San Francisco Trunk Project for each CIROAD criterion.

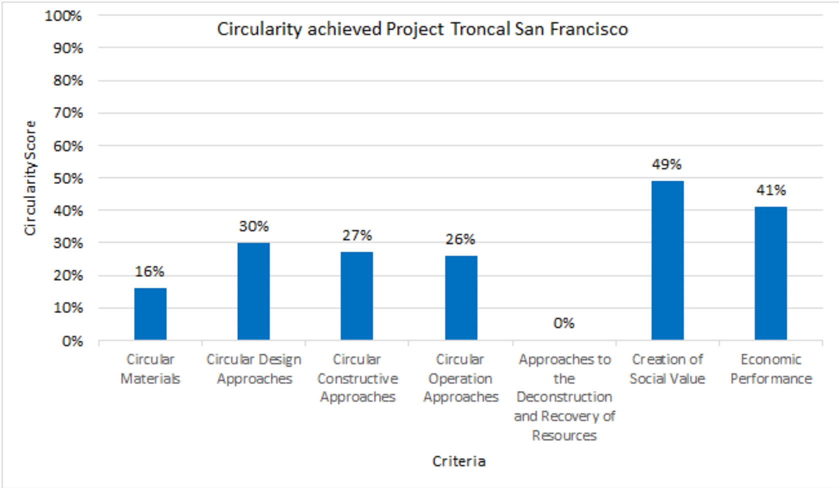

Figure 7. Circularity achieved by each criterion of the model for the San Francisco Trunk Project. Source: Adapted from Campos, A.I.; Prieto, S.S.; Piñones (2022) [77].

4.3. Project to Improve the Padre Hurtado Axis

This project achieves an CIROAD score of 21% and is classified as "D" for its potential circularity, i.e., this project classifies in one of the lowest circularity scales. The following table shows the circularity achieved by each criterion of the model. Figure 8 shows that the criterion with the highest percentage of circularity is "Economic Performance", with a score of 41%, through measuring the level of circularity related to the creation of economic value generated by the project. The criterion with the lowest percentage of circularity is "Approaches to Deconstruction and Resource Recovery", with a score of 0%, which consists of evaluating the level of circularity in relation to the application of strategies aimed at efficient dismantling, separation of waste streams to facilitate recycling and reuse of these materials in other projects. In an analysis at the sub-criterion level, it is possible to observe that 16 of the 25 sub-criteria of this project have zero circularity, that is, a score of 0%. The sub-criteria with a score of 100% are: "CDW Management Plan", which answers the question: Is NCh 3562 on Construction and Demolition Waste Management applied for the execution of the project?, and "Net Present Value", which answers the question: Is the project socially profitable and does it satisfactorily overcome the sensitivity analysis?

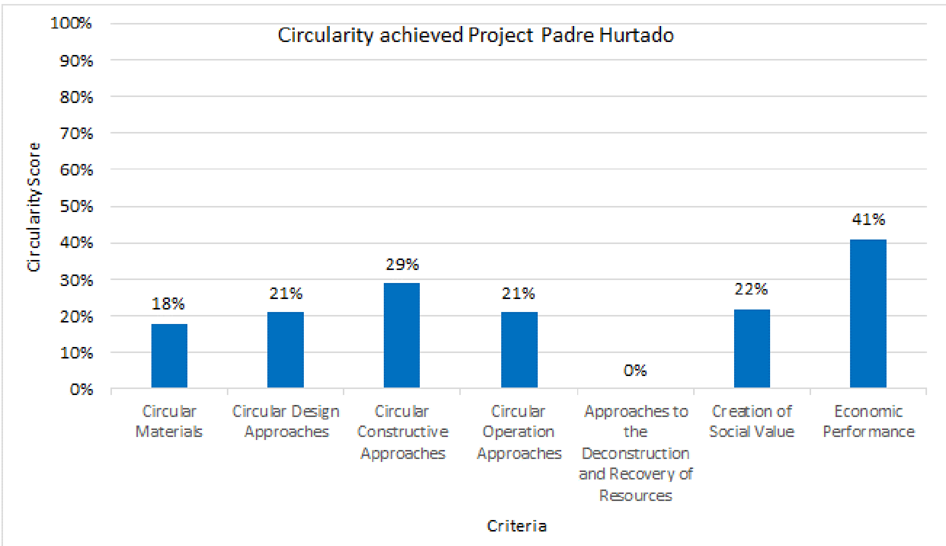

Figure 8. Circularity achieved by each criterion of the model for the Padre Hurtado axis Project. Source: Adapted from Campos, A.I.; Prieto, S.S.; Piñones (2022) [77].

Figure 8 shows the circularity score achieved by the Padre Hurtado axis Project for each CIROAD criterion.

5. Conclusions

This paper proposes a categorization of circularity based on the CIROAD score obtained by a project. This scale is based on the Circulytics tool of the Ellen MacArthur Foundation.

It is highly recommended that the CIROAD model be applied in early stages of the project life cycle, with priority given to the design stage, since it is at this stage that up to 80% of the environmental, social, and economic cost factors of a project are defined [78]. Although it is likely that, in earlier stages, such as prefeasibility, the level of development of the project will not suffice to have all the information available to feed the CIROAD model, its application is still recommended as an approximation and background for the preparation of engineering design bidding conditions and in order to incorporate the necessary elements to obtain all the information for the application of the model in the design stage. In any case, the model can be applied to projects at any stage of their life cycle, even in the execution or operation stage, as a way of obtaining ex post feedback and generating referential information [79].

Regarding the case study, the comparative results obtained from the application of the model to the three projects are shown schematically in Figure 9. In two of the three projects, the criterion with the highest score corresponds to "Economic Performance" (41%) and in the case of the San Francisco Trunk Line Corridor Construction project, this criterion is in second place (41%), behind "Creation of Social Value" (49%). In other words, there is a good performance in this criterion for the three projects, and there is coincidence in this regard. A more detailed review of the "Economic Performance" criterion shows that in all cases, the score is explained by compliance with the "Net Present Value" (NPV) sub-criterion (100% score). This means that the projects have a positive social NPV and behave robustly in sensitivity analysis. In other words, it is verified that the projects obtain good performance in sub-criteria that involve a mandatory minimum performance required by regulations (in this case positive social NPV required by the National Investment System of Chile). Therefore, one way to accelerate the transition to more circular projects would be to demand minimum standards according to our indicators to the projects, although this should be analyzed according to the technical capabilities of each service, so as not to impose standards that are practically impossible to achieve. On the other hand, the three projects obtain a score of 0% in the sub-criterion "Approaches to deconstruction and resource recovery", which shows that the practice in project development does not consider what will happen to the projects at the end of the useful life of their different elements, making it impossible to "close the cycle", which is key to enable circular business models. Therefore, it is important to incorporate as soon as possible in the development of projects the estimation of the construction and demolition waste (CDW) that each alternative solution will generate at the end of its useful life and at the same time to estimate what percentage of this CDW will have recovery actions. In the three projects, at least 60% of the sub-criteria (15 out of 25) obtain a score of 0% in circularity, i.e., there is a relevant opportunity for improvement to incorporate more circular practices in the development of projects in each of the sub-criteria with zero current performance. Considering the 10 sub-criteria with the highest weighting of the CIROAD model, in 6 of them, the projects show zero performance in terms of circularity. Therefore, in order to accelerate the transition to a circular economy model in the development of its projects, it is suggested that the institution prioritize improving its use of the following circular practices (in order of importance): (1) pavement design with environmental criteria; (2) preserving value; (3) CBA of waste management; (4) environmental material declaration (EPD); (5) use of recycled materials; and (6) BIM-based design. Finally, the suggestion for the organization of the Ministry of Housing and Urbanism in charge of these projects is to use the developed CIROAD model as a tool to support decision making regarding the prioritization of its project portfolio, that is, to use CIROAD to generate a ranking score for each project and allocate resources for investment in the initiatives that show the best circularity performances estimated by CIROAD.

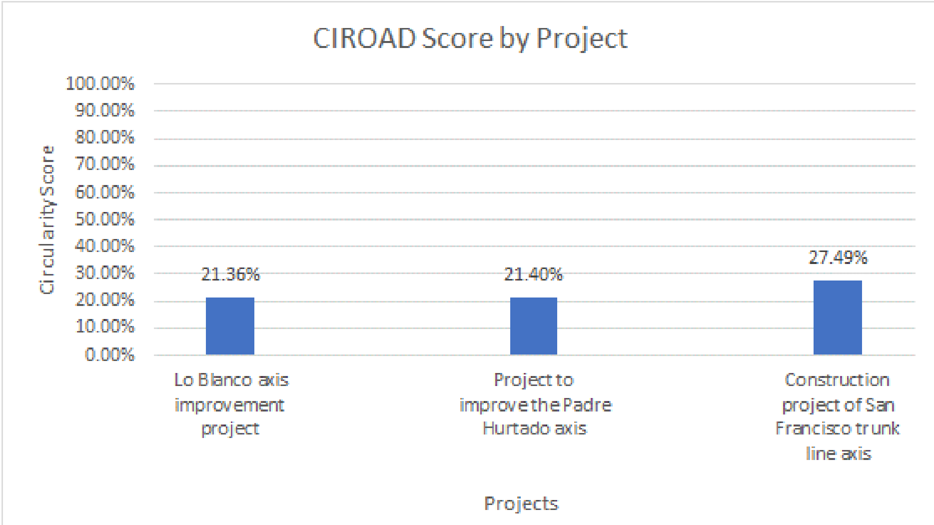

Figure 9. Results by project CIROAD scores. Source: Adapted from Campos, A.I.; Prieto, S.S.; Piñones (2022) [77].

For future research in this area, it is recommended to explore the use of evaluation methods such as the Analytical Network Process (ANP), given that one of the limitations encountered during the development of this work when using the AHP was that of not being able to incorporate criteria with dependence within the same level (internal dependence) into the model. This may open a space for future research at Center of Operations management and operations research (CIGOMM) to delve deeper into the dependency relationships between circularity criteria, with the objective of advancing towards a network evaluation model and comparing with the results obtained by applying the AHP. Another line of research in which it is recommended to advance is to quantify the environmental impacts of circular business models, especially those applied to the construction industry. This is because, although the lifecycle environmental impacts of circular goods and services are mostly significantly lower than those of linear ones, uncertainty about rebound effects, product innovation and other factors tend to cloud the picture and prevent more general conclusions from being drawn in this area.

Author Contributions: Methodology and formulations: P.P. and R.V. The testing of formulations: P.P., R.V. and I.D. Writing and editing: P.P. and I.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by DICYT-USACH, Grant N°062117DC, and The Industrial Engineering Dept. USACH.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors gratefully acknowledge the support of the University of Santiago, Chile, and the Center of Operations management and operations research CIGOMM. The authors are also grateful for the support provided by the Chilean Ministry of Housing and Urbanism.

Conflicts of Interest: The authors declare no conflict of interest.

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