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A Conceptual Model for Measuring a Circular Economy of Seaports: A Case Study on Antwerp and Koper Ports

Rebeka Kovačič Lukman [1,2], Kristijan Brglez [1,2] and Damjan Krajnc [3,*]

1 Faculty of Logistics, University of Maribor, Mariborska c. 7, SI-3000 Celje, Slovenia; rebeka.kovacic@um.si (R.K.L.); kristijan.brglez1@um.si (K.B.)
2 Faculty of Natural Sciences and Mathematics, University of Maribor, Koroška c. 160, SI-2000 Maribor, Slovenia
3 Faculty of Chemistry and Chemical Engineering, University of Maribor, Smetanova 17, SI-2000 Maribor, Slovenia
* Correspondence: damjan.krajnc@um.si

Abstract: This paper introduces a conceptual model for evaluating seaports' acceleration towards the circular economy. The model is based on the identification and definition of circular economy indicators, weighted according to the 9 R-strategy transitions towards the circular economy. We have employed the analytical hierarchy process for weight detection and further calculations of the final seaport circularity value. Our results suggest conceptual validity and provide a detailed insight into the circular activities of the seaports from the indicators, as well as 9 Rs and sustainability perspectives.

Keywords: circular economy; ports; methodology; circular economy indicators; Koper; Antwerp

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1. Introduction

Circular economy has gained significant attention at the policy level since the publication of the Circular Economy Action Plan in 2015 [1]. In 2019 the European Commission launched the Green Deal (GD) [2], where circular economy represents an essential constituent for the future sustainability of European society. Furthermore, the GD recognises ports as entities of the utmost importance for achieving sustainability goals. At the beginning of 2020, the European Sea Ports Organisation (ESPO), representing port authorities in the European Union Member states, introduced a position paper regarding a GD and circular economy [3], mirroring seaports as strategic partners implementing the GD objectives. In the document, seaports are illustrated as excellent entities for practising and implementing circular economy. They are interlinked with the industry and urban areas, constantly exchanging materials and resource flows, including waste, with their neighbourhood environment and hinterland. Thus, seaports have recently been focusing on circular economy transition. However, limited research exists regarding the ports and their acceleration towards a circular economy, as discussed by several authors, such as Carpenter et al. [4]; Mankowska et al. [5]; Haezendonck and Van den Berghe [6]; Roberts et al. [7], especially from the practical and implementation perspectives. Roberts et al. [7] claim that current circular economy activities in ports are low. Still, substantial improvements are envisaged when ports overcome the implementation obstacles, causing the current implementation inhibition in adopting a circular economy.

However, we have detected ports' initiatives towards the circular economy. They have been gathered under the umbrella of the LOOP Ports project, as part of the Circular Economic Network of Ports, funded within the Climate-KIC Programme [8]. The network carries out activities, such as sharing good practices and examples in ports regarding the circular economy, analysis of main drivers and barriers and identifying opportunities, development of training materials, establishing a database to map ports regarding circular economy activities, creation of a pan EU-network, etc. [8]. Furthermore, based on a review of annual sustainability reports, we have indicated agile circular economy activities. Seaports are very active in defining their circular economy visions, strategy, and participation in circular economy projects. Moreover, the scientific literature indicated vivid seaport activities. For example, the Port of Gävle showed that contaminated dredge material could create new land using a circular economy approach [4]. Karimpour et al. [9] examined the feasibility of the closed-loop at the Copenhagen–Malmö port, using a circular economy model and considering a cost–benefit analysis.

Likewise, Haezendonck and Van den Berghe [6] examined circular economy patterns at seaports in Belgium, mapping the circular economy initiatives considering their strategic focus, several initiatives, and alignment with R-strategies. At the same time, Roberts et al. [7] examined various perspectives on ports, assuming a current and future interest in adopting a circular economy, implementation barriers, and local inhabitants' views. The authors indicated an increase of 60% in future adoption.

However, published seaports' annual sustainability or circular reports and published papers reveal several challenges regarding the circular economy in seaports. These challenges relate to seaports' actual and objective measurements or evaluations, using indicators that illustrate their acceleration towards a circular economy. In other words, to explicitly define their current status and their approximation towards circular economy goals. Some evaluation attempts were perceived. For example, the LOOP Ports [8] project identified 45 variables, merging into seven groups, where only one, in particular, relates to the circular economy and CE strategies. Other variables comprehend statistical data and information, such as cargo and industrial sector variables, statistics about the size of the areas, etc.

Moreover, Gravagnuolo et al. [10] developed a framework for evaluating circular cities, focusing on a built environment and using port cities as a testbed. However, the authors stated that their indicators represent a starting point for evaluation and cannot be presented as an actual degree of circularity. Another evaluation attempt emerged within the Horizon 2020—Defining the concept of "Port of the Future" [11]. A focus has been given to defining suitable sustainability indicators within the key performance indicator set. The United Nations' sustainable development goals [12] were considered as a basis. Circularity is only briefly mentioned to support the UN SDGs and quantified only to reduce waste.

Furthermore, we have reviewed existing scientific literature in the Web of Science, and no results were obtained emphasising circular economy indicators for seaports. Thus, we have indicated that the topic is still unexplored but urgently needed to better understand the state of the art at the seaports regarding the circular economy and its implementation. In addition, such evaluations bring an objective comparative declaration, increasing the level of confidence in the circular economy activities of seaports and a more transparent decision-making process for seaport authorities as well as improvement possibilities towards the circular economy.

Our paper brings added value from two main perspectives. First, a methodological one, as we have developed a conceptual model for measuring and evaluating seaports from the circular economy perspective. The methodology offers an examination of numerous indicators that are aggregated into simplified one-dimensional information. The second one relates to implementing the conceptual model—the evaluations themselves, where seaports can carry out self-evaluations or comparisons with other seaports, particularly defining the state of the art in the circular economy activities and recognising weaknesses, strengths, opportunities, and improvement possibilities by using thirty-one indicators. Furthermore, such explicit evaluations, based on the objective data and methodology, foster decision-making processes, on the one hand, by the port authorities, and on the other introduce the level of circular economy transition by the ports concerning the European directives and policies, such as the GD goals or Circular Economy Action Plans [13,14]. The novelty and originality of this paper is reflected in a holistic and comprehensive set of indicators to measure the circular economy in seaports and in an approach that takes into account the weighing of specific indicators and groups them into the clusters of 9 Rs, following the definition of the circular economy concept by Kirchherr et al. [15], developed by

Potting et al. [16]. The 9R framework is one of the most sophisticated R-structured frameworks, which represents core principles for CE, used as a framework among academics, industry, and CE practitioners on "how-to" implement and execute CE in practice [15]. We have developed a conceptual model and indicators to offer an in-depth view of the circular economy activities of seaports. In this paper, we have examined two ports—the Port of Koper, Slovenia, and the Port of Antwerp, Belgium—to reveal their level of circular economy transition.

The paper has been organised into the following sections: Section 2 presents the methods and the methodology, comprehending an introduction to the case studies and a data collection. Section 3 represents the results obtained, containing the weight results from indicators and the case study evaluations and comparisons from the indicators and 9 Rs perspectives. Section 4 presents the discussion, followed by conclusions.

2. A Literature Review

This section presents a comprehensive literature review sourced from Web of Science databases. The literature review considers only research and review papers. The review comprehended the time frame from 2010 to 2022, which is in line with the development of the circular economy field. In this review, we have given special attention to the circular economy indicators, the methodologies for measuring circular economy in ports, and the practical implications.

As mentioned in Section 1, the circular economy concept has a strong and varied research coverage. We have found that many authors focus primarily on incorporating CE models and concepts in various industrial sectors. Some studies are proposing the importance of measuring the success of such endeavours [17]. Thus, a need for incorporating tools to measure CE clearly exists [18].

For example, the report for OECD countries by Căutişanu et al. [19] pointed out a need for indicators to cover renewable energy sources, solid waste and recycled waste quantities, and the average education level of companies' employees. Moreover, Salguero-Puerta et al. [20], discussed a need for implementing sustainability indicators in waste management, while Florinda et al. [21] focus on analysing fuel consumption and its environmental impacts, suggesting a mathematical concept with the indicators as a basis.

Furthermore, we have detected studies, such as Calzolari et al. [22], focusing on the identification of the CE indicators in supply chains, and Nocca et al. [23], proposing an evaluation tool by the inclusion of indicators to ease the measurement of CE in cultural heritage conservation. Lindgreen et al. [24] exposed a need for practical evidence in assessment practices and sustainability indicators to ease the transition of a business from a linear economy towards a circular economy. In contrast, Pacurariu et al. [25] represented the current overview of indicators used under the Monitoring Framework in the transition to the CE and their contribution towards sustainable development.

At the same time, additional concepts were found in manufacturing sectors supporting circularity, such as circular economy rebound. Zink & Geyer [26] presented circular economy rebound as an approach, including the limited ability of secondary products to substitute primary products and price effects, used mostly in production processes. Furthermore, D'Adamo & Lupi [27] introduced the term "circular premium" to measure the difference between the circular price and the normal price, which is important for identifying sustainable products, as the authors illustrate with the example of the textile and clothing industry.

With CE being implemented across various industry sectors, with the inclusion of logistics and, more importantly, the shipping sector, it would be self-explanatory to include circularity in seaports. Although El Jihad & Bordanova [28] provide some insight into the current indicators used by ports in the EU, these indicators' focus lies primarily in the economic sustainability pillar, with environmental and social pillars lagging behind. The lack of indicators to cover all aspects of CE is further mentioned by Mankowska [5], Haezendock and Van der Berghe [6], who provide insights into the CE initiatives in seaports but no practical models to measure them. It is visible that seaports are relying on CE to develop further and regenerate the surroundings. Yet, as Williams [29] suggests, there is a need to measure the success of such endeavours and their contribution. Thus, this research paper focuses on establishing a conceptual model to measure the circular economy and comprehensively analyse circular developments in seaports.

3. Methods

This section presents our methodological approach and methods, including the identification and definitions of circular economy indicators, a selection of case studies, and methods for measuring circular economy at seaports.

3.1. Identification and Definition of Circular Economy Indicators

We have carried out an in-depth literature and sources review to identify and define the appropriate indicators representing the circular economy in seaports. We have implemented this assignment in two ways. The initial activities were a selection of ports. We have selected two large EU northwestern ports, Antwerp and Amsterdam. According to Haezendonck and Van den Berghe [6], they are undertaking circular economy activities to become the flagship seaports in the field. Furthermore, we have added other larger ports, e.g., Port of Genova, Port of Barcelona, and Port of Koper, to comprehend a broader EU area. After identifying and selecting the ports, we have precisely reviewed and analysed all the circular economy accessible indicators on the seaports' webpages and freely accessible annual and sustainability reports (see Table 1).

Table 1. Reviewed annual reports of the selected seaports during the search for circular economy.

Port	Annual Reports
Port of Antwerp	Annual Report 2016 [30] Facts & Figures 2019 [31] Yearbook of Statistics 2020 [32] Sustainability Trend Report [33]
Port of Amsterdam	Annual Report 2017 [34] Annual Report 2018 [35] Annual Report 2020 [36]
Port of Genova	Relazione annuale 2014 [37] Relazione annual 2015 [38] Relazione annuale 2017 [39]
Port of Barcelona	Annual Report 2018 [40] Annual Report 2019 [41] Annual Report 2020 [42]
Port of Koper	Annual Report 2018 [43] Sustainability Report 2018 [44] Annual Report 2019 [45] Annual Report 2020 [46]

Simultaneously, a comprehensive literature review in the Web of Science has been carried out, using the following search combinations of terms: "circular economy" AND "ports", "circular economy" AND "indicators", and "indicators" AND "port(s)". In total, the result amounted to 312 hits. We have reviewed these papers. However, it is important to notice that we have searched only for those papers which contained methods, methodologies on measuring CE, or proposals for quantitative indicators that would be linked to CE. Thus, a total of 34 papers containing information about circular economy indicators were identified and shortlisted. Within these two initial activities, we have identified 153 potential circular economy indicators, of which some were repeated. However, we have pre-defined features which the indicators and the final circular economy evaluation for the port should have, and which are based on the modified Directives of the European Commission [47,48]:

- the indicator is made up of a definition, a value, and a measurement unit
- the indicator is relevant to measure a circular economy
- indicators are objective (assuring open accessibility) and expressed in a quantitative term
- the indicator is linked to the circular economy policies or strategic dimensions
- the indicator is based on needs and interventions
- the evaluation methodology is designed in a transparent way and with high-quality indicators and data
- simplified one-dimensional information about the circularity of the seaports give an added value, compared to the individual indicators
- the weighing methods are transparent and statistically reliable

Considering the principles mentioned above or features regarding the indicators, a shortlist of 31 circular economy indicators for seaports has been established.

3.2. Grouping and Sorting Process

With the number of indicators amounting to $n = 31$, we were introduced to the complex problem of comprehensively evaluating the seaports' circular economy transition. It is essential to note that our research focused on circular economy transition and group selected indicators. For this reason, two conceptualisations were used: the Kirchherr et al. [15] conceptualisation of the circular economy definition, and the Potting et al.'s [16] 9 Rs conceptualisation, which identifies a transition from the linear to the circular economy using recovery, recycling, repurpose, remanufacture, refurbish, repair, reuse, reduce, rethink, and refuse strategies. The 9R method enables a systematic distribution of ten identified circular economy strategies listed across a "focused dimension" from the established linear economy, on the left side, towards the circular economy, on the right side. This also indicates the relation of selected indicators to either one of the two economic models. According to the definition of an indicator, we have grouped it within the R0 to R9 strategies (see Figure 1).

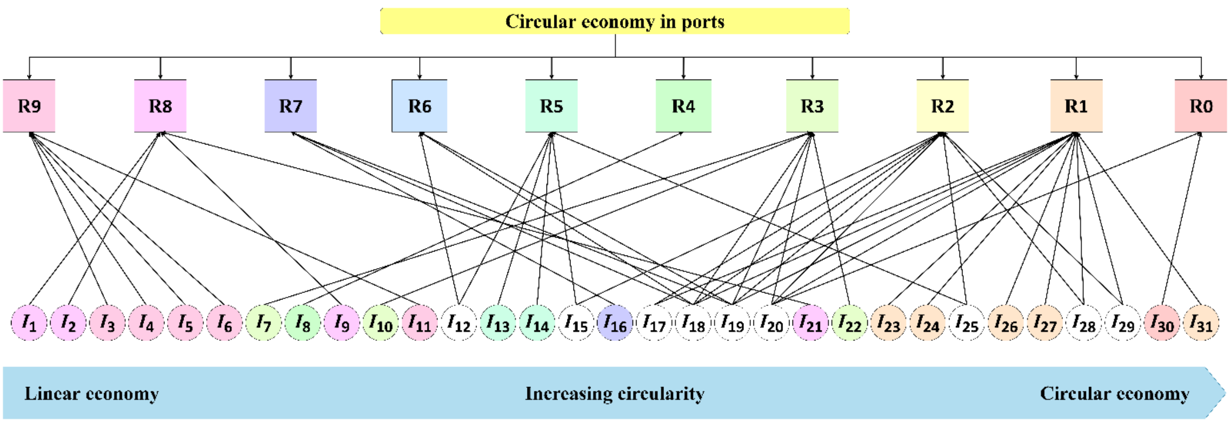

Figure 1. Grouping of individual indicators per R-strategy.

Figure 1 shows a different group of indicators (I), belonging to R-strategies, marked with different colours. Thus, we have used a methodological approach to condense numerous indicators into more simplified information within the R-strategies, merging them into one-dimensional information on seaport circularity. This is vital information for seaports, their authorities and other stakeholders for identifying the acceleration towards a circular economy. However, some indicators belong to more than one R-strategies group. These indicators are marked with white colour. The upper squares represent the R strategies of the 9R framework, while the circles represent each of the identified indicators. Notice the colours representing each indicator's relation towards an R strategy. In some cases, the indicator circle is white (e.g., I12, I15, etc.), indicating that the indicator falls under at least two or more R strategies. When the indicator is associated with several strategies, we used for its calculation the distributed weight obtained by equally distributing the weight of each strategy according to the number of strategies to which the indicator belongs.

Furthermore, upon the grouping, we have focused on the indicators' sortation. We have listed them into three sustainability dimensions, onto which the indicators were distributed, namely:

- The economic dimension, where the main focus lies in creating economic welfare and advantages for the ports while including the main principles of circularity and promoting the transition from linear activities into circular ones (e.g., waste management in ports, producing electricity with alternatives).
- The environmental dimension, with the focus on reducing the environmental impacts of port activities in the port area and its vicinity, contributes to increasing biodiversity and mitigating the damage to the environment (e.g., cleaning operations, reducing bad economic practices).
- The social dimension, which focuses on creating equality in the workforce and workplace, enabling further education and promotion among workers, and promoting the inclusion and integration of political, communal, and social entities within the port— all in the direction of promoting the circular economy (e.g., enabling different types of transport to work, funding activities and projects that encourage circularity in nearby communities).

3.3. Determining Weights by Using an Analytical Hierarchy Process

The final circular economy value for the seaports represents an integrated function of the separate groups of indicators (R-strategies). To define the importance of each R-strategy and, consequently, each indicator, we have employed the analytical hierarchy process (AHP) developed by Saaty [49], denoting the relative importance of the evaluated variables. AHP is a general theory of measurement used to obtain scales either from discrete or continuous paired comparisons [49,50]. The AHP method helps prioritise the importance of sustainability indicators. Therefore, it has been used to assess sustainability in various research areas, such as agriculture [51], sustainability assessment at the level of countries [52], regions [53], or companies [54]. In our case, the method was used as a priority evaluation theory, with the mutual comparison of priority scales based on a judgement matrix. The method was chosen for its practical implementation and ease of application.

Thus, we have prepared a pair-wise comparison of the 9R strategies, whereas in Saaty [49] a 9-point scale was used for the transformation of verbal judgements into numerical quantities, where a judgement matrix is obtained. According to Saaty [49,50,55], the priorities and weights are estimated by revealing the judgment matrix's leading eigenvector (λ_{max}). However, a consistency test must be carried out to examine the level of consistency required for the validity of results, using a consistency ratio (R_{C}) (see Ramanathan [56]):

$$R_{\text{C}} = \frac{I_{\text{C}}}{R_{\text{I}}} \quad (1)$$

where the R values of randomly generated matrices have been provided by Saaty [49,50], while the I_{C} is a consistency index, which can be calculated from Equation (2):

$$I_{\text{C}} = \frac{\lambda_{\text{max}} - N}{N-1} \quad (2)$$

where λ_{max} introduces the largest eigenvalue of the matrix, while n represents the matrix's dimension. If the I_{C} of the matrix is higher, the input judgements are not consistent, and hence not reliable. In general, a consistency index of 0.10 or less is considered acceptable. If the consistency index value is higher, the judgements may not be reliable.

To carry out the weighing process, we have prepared a pair-wise questionnaire in Google forms, which has been sent to 30 individuals from several European countries (Slovenia, Denmark, Austria, Romania, The Netherlands) (see Appendix C), with each chosen expert being an individual with an in-depth knowledge of the circular economy, either from a practice or a research perspective. We checked the references of the experts (scientific publications in the last five years in the field of CE, published expert papers, and/or work on CE projects). The questionnaire was sent to the following groups of experts: Academics (professors, researchers), the real sector (ports, companies), and non-governmental organisations working in the field of circular economy. As online questionnaires are a "cold methodological approach" (links were sent to email addresses), the response rate was 0.53). The questionnaires were developed and distributed in May 2020 within the project Circular Economy in Seaports [57]. We have gathered 16 fully filled-in questionnaires used for further analyses.

3.4. Obtaining Seaports' Data and Their Normalisation

In line with the identified indicators and the determination of the weighing process, we have carried out a secondary search to obtain seaports' data for our calculations. We have divided this process into three approaches:

(1) a secondary review of the literature provided in Table 1 focused on the identification of seaports' data meaningful for further calculations of indicators and final seaport circularity
(2) a secondary review of existing literature (e.g., scientific papers) as well as a Google search for calculating proposed indicators (I_n)
(3) phone calls to the seaports listed in Table 1 in search of personnel responsible for circular economy and sustainability activities. After acquiring the email addresses, a short questionnaire was prepared and sent to each of the five mentioned seaports and their personnel.

Unfortunately, none of the seaports responded to our questionnaire. The results of the secondary review of the literature were also meagre, with many data either unavailable or not provided. Therefore, due to the lack of data, we have focused on the two seaports with the most available data, the Port of Antwerp, Belgium, and the Port of Koper, Slovenia. The search for statistical information was followed up by a need to normalise the values, since we cannot compare two ports by the data alone, and they need to be normalised by a common determinator. Thus, we have used a "maritime freight volume" as a normalisation value, which both ports in their annual reports have provided. We are enclosing a compilation of the data used in Appendix A.

4. Results

This section presents our results, composed of the results obtained from the AHP process to determine the weights and importance of the indicators, allowing us to evaluate each indicator and both seaports used as case studies regarding their circular economy performance.

4.1. Results from the Weighing Process

Following the questionnaire results provided by the circular economy experts, we have prepared an inverse matrix, as seen in Table 2, which has been calculated using the AHP method to obtain the importance (weight) of each R strategy. Before continuing the calculations, a consistency check has been carried out to affirm the validity of the results, employing Equations (1) and (2) from the Methods section. The R_C value was 0.007, which aligns with the requirements, as R_C has to be below 0.1. This has confirmed a satisfactory consistency and allowed us to continue with the calculations.

Table 2. Inverse matrix for calculating the importance (weight) of R strategies.

	R0	**R1**	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**	**R9**
R0	1.000	1.880	1.000	1.150	1.150	1.000	0.880	0.680	0.600	0.750
R1	0.530	1.000	2.500	0.630	0.520	0.580	0.630	0.600	0.650	0.520
R2	1.000	0.400	1.000	1.000	0.480	0.580	0.470	0.580	0.580	0.750
R3	0.870	1.600	1.000	1.000	1.000	1.150	0.680	0.650	0.410	0.410
R4	0.870	1.930	2.070	1.000	1.000	1.670	1.150	0.560	0.560	0.500
R5	1.000	1.730	1.730	0.870	0.600	1.000	0.830	1.070	0.650	0.540
R6	1.130	1.600	2.130	1.470	0.870	1.200	1.000	0.710	2.500	0.540
R7	1.470	1.670	1.730	1.530	1.800	0.930	1.400	1.000	1.250	0.650
R8	1.670	1.530	1.730	2.470	1.800	1.530	0.400	0.800	1.000	0.750
R9	1.330	1.930	1.330	2.470	2.000	1.870	1.870	1.530	1.330	1.000

According to the 9R method, the indicators were classified into n = 10 strategies mentioned in the Methods (see Table 3). The distribution was conducted per adequacy of each indicator with the description of the aforementioned R strategies, with the results presented. As can be seen, the indicators are, according to their definitions, aligned with the strategies, which indicates an increased circularity from R4 to R0.

Table 3. Indicator's distribution within 9Rs strategies groups.

R-Strategy	**Indicators**	**No. of Indicators**
R0	I_{20}, I_{30}	2
R1	I_{17}, I_{18}, I_{19}, I_{20}, I_{23}, I_{24}, I_{26}, I_{27}, I_{28}, I_{29}, I_{31}	11
R2	I_{15}, I_{17}, I_{18}, I_{19}, I_{20}, I_{25}, I_{28}, I_{29}	8
R3	I_7, I_{10}, I_{18}, I_{19}, I_{20}, I_{22}	6
R4	I_8	1
R5	I_{12}, I_{13}, I_{14}, I_{15}	4
R6	I_{12}, I_{18}, I_{19}	3
R7	I_{16}, I_{18}, I_{19}	3
R8	I_1, I_2, I_9, I_{21}	4
R9	I_3, I_4, I_5, I_6, I_{11}	5

The calculated relative weights of the R strategies in correlation with the number of indicators emerging within the R-strategy allowed us to calculate each indicator's weight for an overall view divided into three tables per dimension, as mentioned in the Methods section. This sortation can be seen in Tables 4–6. We can conclude that most of the indicators identified and defined focus on environmental challenges, followed by social and economic ones.

As a final check of the correctness of the indicator weights, a sum for each of the mentioned dimensions was conducted, with the value being 0.8426 for the environmental dimension, 0.0636 for the economic dimension, and 0.0938 for the social dimension. The result equals 1, confirming the correctness of the indicator weights and continuing with the next step.

Table 4. Indicators and their weights are arranged by the environmental dimension of the circular economy.

Indicator	Indicator Full Name	Indicator Weight
I_1	Fraction (in %) of recycled waste in comparison with the total waste produced	0.0300
I_2	Fraction (in %) of recycled plastic waste in comparison with the total plastic waste produced	0.0300
I_3	Faction (in %) of waste produced in the port that goes to landfill in comparison with the total waste produced	0.0308
I_4	Amount of materials (e.g., plastic, tiers) used for alternative fuel (t/a)	0.0308
I_5	Fraction (in %) of biogas produced from the total biodegradable waste produced	0.0308
I_6	Fraction (in %) of waste used for energy production in comparison with the total waste incinerated	0.0308
I_7	Quantity of the reused materials (t/a)	0.0128
I_8	Fraction (in %) of repaired/maintained products	0.0970
I_9	Fraction (in %) of the recycled goods used	0.0300
I_{10}	Fraction (in %) of waste reused	0.0128
I_{11}	Unsold products recovered for redistribution at the market itself or through nearby community facilities (t/a)	0.0308
I_{12}	Fraction (in %) of water consumption for habitat (reduction, for example, thanks to harvesting rainwater on the roofs)	0.0609
I_{13}	Fraction (in %) of green roofs	0.0223
I_{14}	Fraction (in %) of food waste reused against the total food waste produced	0.0223
I_{15}	Fraction (in %) of retrofitting interventions on buildings	0.0303
I_{16}	Fraction (in %) of degraded buildings	0.0403
I_{17}	Fraction (in %) of synergies in the supply chain (energy, resources), compared to the whole supply chain	0.0144
I_{18}	Fraction (in %) of processes designed for flexibility by using modular, synergy systems	0.1062
I_{19}	Fraction (in %) of symbiotic and synergistic relationships in the port area and among the port area and the city	0.1062
I_{20}	Amount of sea sewage materials used for new products (e.g., bricks) (Mt/a)	0.0732
SUM TOTAL		**0.8426**

Table 5. Indicators and their weights are arranged by the economic dimension of the circular economy.

Indicator	Indicator Full Name	Indicator Weight
I_{21}	Revenue from recycled goods (bn EUR/a)	0.0300
I_{22}	Value of material reused (bn EUR/a)	0.0128
I_{23}	Circular economy innovation budget (bn EUR/a)	0.0064
I_{24}	Circular-economy-related grants from the local, national EU budget (bn EUR/a)	0.0064
I_{25}	Direct and indirect new investments generated and considering circular economy (bn EUR/a)	0.0080
SUM TOTAL		**0.0636**

Table 6. Indicators and their weights are arranged by the social dimension of the circular economy.

Indicator	Indicator Full Name	Indicator Weight
I_{26}	A fraction (in %) of the circular-economy-related position in a port, compared to all the position	0.0064
I_{27}	A fraction (in %) of new circular economy jobs created in a port, compared to all the position	0.0064
I_{28}	A fraction (in %) of events and dissemination activities about circular economy within the port compared to all the events	0.0144
I_{29}	A fraction (in %) of active employees in circular economy initiatives, compared to all employees	0.0144
I_{30}	Number of innovation awards related to a circular economy	0.0460
I_{31}	A fraction (in %) of employees attending internal/external circular economy capacity building	0.0064
SUM TOTAL		**0.0938**

4.2. Calculation of the Circularity Value of the Case-Study Seaports

A normalisation process was carried out to calculate the final circularity value of the seaport data obtained with open-access information. As mentioned in the Methods section, the maritime freight volume was used for the normalisation volume, which relates to the amount of annual manipulated tonnage (both loading and unloading) provided by both seaports (Antwerp and Koper). After the normalisation of the data, the calculation of the final values of 31 indicators has been conducted, as seen in Figure 2. As shown in Figure 2, some values were represented with zero values for both ports, e.g., indicator I_4. Such discrepancies happened due to two reasons:

- the seaports did not provide such data or the statistical data for the mentioned indicator and open access (e.g., annual reports), and they could not be obtained from the available literature and websites that are freely accessible, and
- the seaports do not have such activities on the premise of their seaport area, and as such do not provide statistical data.

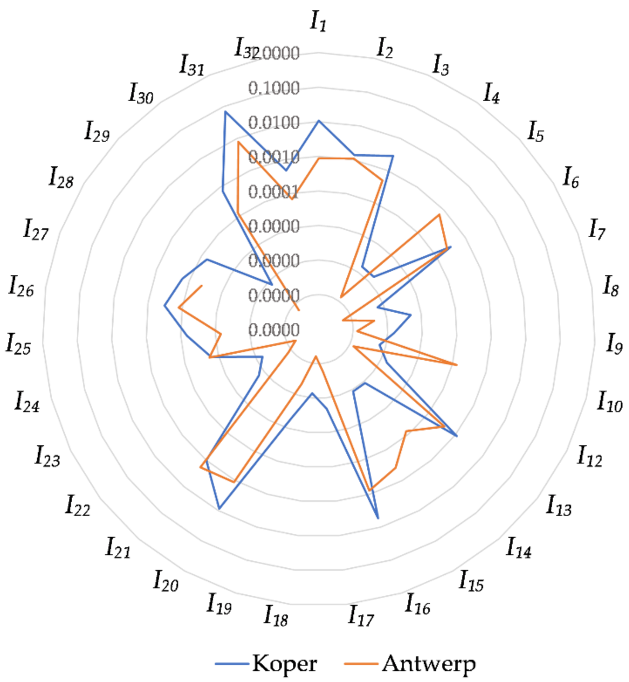

Figure 2. Distribution of values per indicator for the Ports of Koper and Antwerp.

A notable exception to these complications is indicator I_{27} in the case of Port of Antwerp, which can be seen as a missing line in Figure 2. This happened because the logarithm scale cannot include negative values, which was the case of the Port of Antwerp. Thus the value is not represented in the graph itself.

Finally, an evaluation of the circular performance of both seaports was conducted from the 9R perspective (see Figure 3), along with a final circularity index for both seaports (see Table 7). As perceived from the results, the Port of Koper has better values within circular economy indicators, which is reflected in its higher final circularity value.

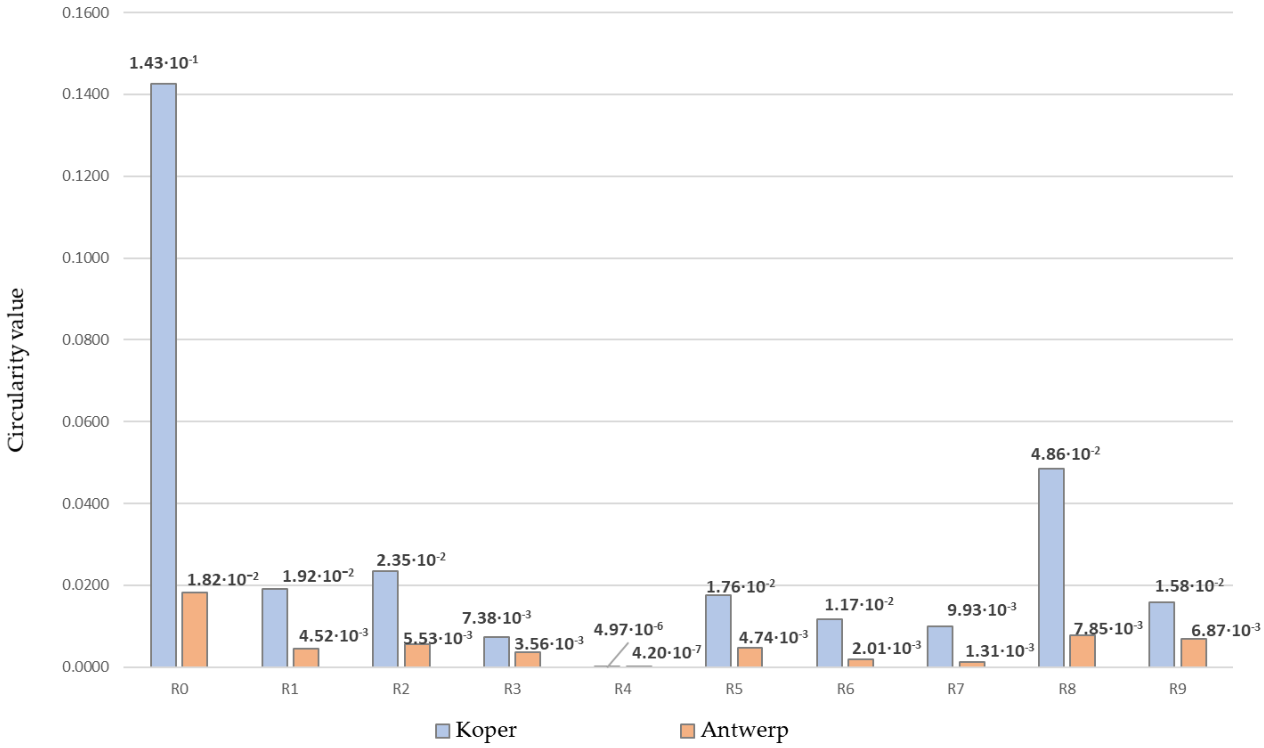

Figure 3. Distribution of values per R-strategy for the Ports of Koper and Antwerp.

Table 7. Port circularity index for the studied ports.

Seaport	Final Circularity Value
Port of Koper	0.1041
Port of Antwerp	0.0164

5. Discussion and Conclusions

The developed conceptual model has shown the implications of evaluating seaports according to the 9R strategies and analysed their transition towards a circular economy. As perceived from the results, both ports are very active and show a high measurement and performance in the field of circular economy, which is reflected in the higher performance of indicators within R0 to R4. Our case study evaluation has shown that from this conceptual model we can get many circular economy information about the seaports' features, characteristics, and orientation, and about their actual transition towards the circular economy. Such an evaluation also allows for the assessment and analysis of the current state of the art and further development. However, as the indicators were also listed within the sustainability dimensions, this perspective can also be evaluated. As can be perceived from the Results section, such a model quickly reveals potential weaknesses and opportunities. Our conceptual model is transferable and flexible, enabling the inclusion of more circular economy indicators. There is no need to repeat the AHP process, as it has been carried out for the 9 R strategies of the circular economy transition.

In addition, a limitation exists in our study, which is related to the number of indicators comprehended (n = 31) and their essential features in terms of open accessibility and the objectivity obtained from the available public sources. This may entail that seaports are implementing circular economy principles even more in-depth, as proposed by our concept. However, the data or information were not available or accessible. As shown from our results, seaports are not publishing or evaluating data. For example, indicators such as I_4 or $I_{7–9}$ were not evaluated by the seaports but impaired the circular economy transition.

Thus, this conceptual model can offer a first step towards standardising circular economy seaport indicators for assessing the seaport transition towards the circular economy. This can also encourage seaports to gather circular economy indicators data and publish them openly within their sustainability or circular economy annual reports. Such an approach could also help implement the LOOP Port activities under the Climate-KIC supervision of developing a comprehensive circular economy data platform for the ports. Climate-KIC can help verify whether the data and information are authentic. It is vital to notice that all the information for testing the developed conceptual model has been obtained via open-access documents, from annual reports, seaports webpages, and Google searches. However, to fully evaluate the circular economy, ports need to measure and publish circular economy indicators and not put emphasis only on the financial and environmental ones.

Our case study suggests that the Port of Koper is very active in implementing circular economy activities. It is in a forefront position compared to Antwerp. This might be a consequence of the circular actions at the national level, where Slovenia has been chosen as a European and global leader in implementing circular economy models, within the project "Circular Slovenia", commonly executed by the EIT Raw Materials, EIT Climate-KIC, the Joint Research Center of the European Commission, and the Government of the Republic of Slovenia. We should mention that our conceptual model has been created to examine the transition of the seaports towards the circular economy to determine their opportunities and improvement options, which will foster improvements at the seaport level and at broader levels, from a strategic point of view. Furthermore, the conceptual model offers a better understanding of seaports' acceleration towards the circular economy.

However, further research is needed, especially in terms of port data disclosure, objectivity, access, and in-depth mapping of ports' circular economy activities. CE also falls under the SDG framework, which includes the "3 pillar system" and the collection of "17 interlinked goals". Further research on the subdivision of indicators under these goals would be interesting to correlate CE ports' practices with future research, which could also focus on the role of the SEZ (Special Economic Zone) in providing financial support to seaport areas and investigating the role of the NGEU (NextGenerationEU) [58] in promoting the transition to greener, digitised, and circular seaports.

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Appendix A

For the normalisation and further calculation of the ports' circularity index, we needed initial values for the Port of Antwerp and the Port of Koper, as described in Section 3.4. The identified values were presented in a table, as seen in Table A1. Indicators for which values were unavailable due to not being disclosed by port authorities, or which the port did not include under its activities, received a value of 0.

Table A1. Distribution of initial values of the indicators for the Port of Koper and the Port of Antwerp.

Indicator	Port of Koper—Indicator Values	Port of Antwerp—Indicator Values
I_1	70% [46,59]	67% [31]
I_2	9% [46,59]	84% [33]
I_3	18% [46,59]	36% [33]
I_4	n.a.	n.a.
I_5	n.a.	49% [33]
I_6	2% [46]	18% [33]
I_7	n.a.	n.a.
I_8	n.a.	n.a.
I_9	n.a.	n.a.
I_{10}	n.a.	24% [33]
I_{11}	n.a.	n.a.
I_{12}	3.6% [46]	15% [33]
I_{13}	n.a.	8% [31]
I_{14}	n.a.	40% [31]
I_{15}	35% [45]	60% [31]
I_{16}	n.a.	n.a.
I_{17}	n.a.	n.a.
I_{18}	n.a.	n.a.
I_{19}	16% [46]	25 [31]
I_{20}	0.0267 Mt/a [46]	0.5768 Mt/a [33]
I_{21}	n.a.	n.a.
I_{22}	n.a.	n.a.
I_{23}	0.0050 bn EUR/a [46,60]	0.0680 bn EUR/a [31,33,61]
I_{24}	0.0200 bn EUR/a [46,60]	0.0250 bn EUR/a [31,33,61]
I_{25}	0.0800 bn EUR/a [46,60]	0.3670 bn EUR/a [31,33,61]
I_{26}	5% [46]	15% [31]
I_{27}	2% [46]	−3% [31]
I_{28}	n.a.	n.a.
I_{29}	10% [46]	20% [31]
I_{30}	No. 3 [60]	No. 4 [61]
I_{31}	15% [46]	25% [31]

n.a.: not available.

Appendix B

For the identification of the circular economy indicators, we needed initial literature sources, as described in Section 3.1. The identified and shortlisted papers in Table A2 provided valuable information about potential circular economy indicators. For a better overview, a research focus of each individual paper was provided.

Table A2. List of papers containing information about circular economy indicators.

Year	Author	Research Focus
2010	Lukman et al. [62]	Indicators for school education on university
2016	Instituto Mexicano del Transporte [63]	Methodology for seaport indicators
2016	Valenzuela-Venegas et al. [64]	Indicators for the assessment of CE in Eco-Industrial parks
2016	Gearaedts [65]	Indicators for assessing energy adaptiveness in buildings
2016	Franklin-Johnson et al. [66]	Managerial indicators for CE performance in the resource sector
2016	Niero et al. [67]	LCA assessment of aluminium cans
2017	Huysman et al. [68]	Selection of performance indicators in CE with a focus on plastic waste
2018	Yang et al. [69]	Environmental and economic indicators in industrial parks
2018	Jacobi et al. [70]	Socio-economic indicators for CE (in the case of Austria)
2018	Cobo et al. [71]	Circularity indicator of components
2018	Hens et al. [72]	Cleaner Production and "Corporate Social Responsibility" assessment
2018	Van Eygen et al. [73]	Collection, selection, and recycling rate of waste
2018	Paulik [74]	Assessment of CE standard BS 8001:2007
2018	Căutişanu et al. [19]	Indicators for recycled resources, education level, waste, etc.
2019	Zhao et al. [75]	Emergy Sustainability Index
2019	Williams [29]	Green Space Index in seaports
2019	Salguero-Puerta et al. [20]	Sustainability indicators for Waste management
2019	Florinda et al. [21]	Consumption of fossil fuels for energy and environmental impacts
2019	Kayal et al. [76]	Economic index for the circularity of businesses
2019	Howard et al. [77]	CE indicators in the regenerative supply chain
2019	Pieratti et al. [78]	Economic and environmental indicators in the wood industry
2019	Sterew et al. [79]	Resource prod. and recycling rate of municipal waste indicators
2019	Niero & Kalbar [80]	Material circularity and lifecycle-based indicators
2019	Girard & Nocca [81]	Review of tools to measure circularity and CE
2020	Kristensen & Mosgaard [82]	Micro-level indicators of CE
2020	Rossi et al. [83]	CE indicators in the plastic, textile, and electronic industry sectors
2020	Völker et al. [84]	Indicator development on a par with CE policies within EC
2020	Lindgreen et al. [17]	Methods and Tools for assessing CE
2021	Nocca et al. [23]	Integration of CE with cultural heritage conservation
2021	Pacurariu et al. [25]	EU key indicators in transitioning towards CE
2021	Stavropoulos et al. [85]	Innovation in relation to circularity in economy
2022	Agrawal et al. [86]	Industry 4.0 integration within CE
2022	Calzolari et al. [22]	CE indicators for supply chains
2022	Lindgreen et al. [24]	Assessing practices engaged towards/within CE

Appendix C

List of experts and their fields to whom the questionnaires were distributed (Table A3).

Table A3. List of experts with gender and characterization explanation.

Expert No.	Gender [1]	Work Place and Working Time	Research Field
1	M	Over 40 years' experience in academia	cleaner production, sustainability, circular economy
2	M	Over 25 years' experience in academia	sustainable indicators, LCA, circular economy
3	F	Over 20 years' experience in academia	sustainable production and consumption, LCA, circular economy
4	M	Over 40 years' experience in academia	cleaner production, sustainable production and consumption, circular economy
5	M	Over 40 years' experience in academia	sustainable production and consumption, circular economy, waste management
6	M	Over 25 years' experience in academia	sustainable production and consumption, circular economy
7	F	Over 25 years' experience in company	sustainable production and consumption, circular economy
8	F	Over 25 years' experience in company (port)	sustainability management, circular economy
9	M	Over 15 years' experience in company (port)	sustainability management, circular economy

Table A3. *Cont.*

Expert No.	Gender [1]	Work Place and Working Time	Research Field
10	M	Over 20 years' experience in companies and NGOs	sustainability, circular economy
11	M	Over 20 years' experience in academia	sustainability, carbon footprint, circular economy
12	M	Over 20 years' experience in academia and companies	sustainability, measuring sustainability, circular economy
13	M	Over 30 years' experience in academia	LCA, circular economy
14	M	Over 30 years' experience in academia	sustainability engineering, circular economy, environmental technologies
15	F	Over 30 years' experience in academia and NGOs	environmental impacts, circular economy
16	F	Over 10 years' experience in academia	sustainability, environmental impacts, circular economy
17	F	Over 7 years' experience in academia	sustainability, closed loops, environmental impacts
1	M	Over 6 years' experience in academia and companies	business processes, LCA, circular economy
19	M	Over 6 years' experience in companies	sustainability, circular economy
20	M	Over 6 years' experience in companies	sustainability, circular economy
21	F	Over 7 years' experience in academia and companies	sustainability management, circular economy
22	M	Over 30 years' experience in academia	sustainability, circular economy
23	F	Over 30 years' experience in industry	environmental protection, circular economy
24	M	Over 10 years' experience in industry and NGO	sustainability, circular economy
25	F	Over 20 years' experience in NGO	sustainability, climate change, circular economy
26	M	Over 20 years' experience in industry	recycling, circular economy
27	F	Over 20 years' experience in academia and research	sustainability, circular economy
28	M	Over 30 years' experience in industry	recycling, circular economy
29	F	Over 30 years' experience in industry, academia, NGOs	climate change, raw materials, circular economy
30	F	Over 15 years' experience in industry	eco-design, sustainability, circular economy

[1] M = Male, F = Female.

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