

Article

A Modular Modelling Framework of Tourism Sustainability: The Case of Eco-Efficiency

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Abstract

Environmental evaluations in tourism research are often irregular and incomplete, and tourism ecolabels lack international standardisation and scientific validation. Due to the complexity of the tourism system, various evaluation scopes are needed based on specific contexts. For this purpose, a modular approach is proposed to improve the standardisation and robustness of sustainability evaluation and measurement in tourism. This paper introduces a systemic, multiperspective modular modelling framework to support multidimensional sustainability assessment in tourism. In this paper, the framework is demonstrated for the environmental dimension only through the principles of eco-efficiency. The modularity concept deconstructs system complexity from various perspectives, enabling a flexible and standardised method for measuring tourism eco-efficiency impacts using the IPAT equation. This approach enhances the evaluation process and paves the way for standardised ecolabels in the tourism industry.

Keywords: sustainable tourism; eco-efficiency; modularity; multiperspective; multidimension; ecolabel

1. Introduction

Despite the economic benefits of tourism, its activities significantly strain resources. Between 2009 and 2019, global tourism-related emissions increased at an average annual rate of 3.5%, which is twice the growth rate of the global economy, reaching 5.2 gigatons of CO₂-equivalent in 2019. This accounts for approximately 8.8% of total global greenhouse gas emissions [1]. In 2024, the tourism sector officially recovered to 2019 pre-COVID-19 levels, with 1.4 billion international tourist arrivals globally, according to UNWTO [2]. While the past footprint is alarming, the future may present even greater risks and concerning effects if no drastic measures are taken. According to the United Nations Environment Program [3], maintaining a business-as-usual scenario until 2050 could result in a 154% increase in energy consumption, a 131% rise in greenhouse gas emissions, a 152% increase in water consumption, and a 251% surge in solid waste disposal. The increasing tourist flow and negative impacts of tourism demand more robust quantitative approaches to measure and monitor tourism effects closely [4–6]. Various evaluation tools and methods address sustainability issues across economic, environmental, and social dimensions, each with specific limitations and applications. As evaluation methods become more precise, resource



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efficiency must continuously improve to keep tourism within planetary boundaries [7]. To communicate their progress in reducing negative impacts and to stand out, enterprises and destinations can seek ecolabels, as one of many measures. However, tourism ecolabels lack international standardisation and do not always rely on scientifically proven environmental evaluations [8], such as practice-based standards [9]. Research is needed to bridge the gap between evaluation tools and ecolabels, accommodating the industry's complexity and heterogeneity, and providing tourism actors with scientific and comparable eco-efficiency measures.

Since the release of the Brundtland report in 1987, studies on tourism sustainability have proliferated, highlighting the industry's complexity. The tourism supply chain, encompassing all activities and operations that deliver tourism products and services, is fragmented across various industries, such as transportation, accommodation, restauration, and activities, as well as ancillary services like banking and insurance [5]. The quality and characteristics of tourism offerings, such as transportation subcategories and the diverse array of products and services, reflect the heterogeneous nature of tourist preferences and interests, as well as types of tourism (e.g., business, adventure, cultural) and activities (e.g., attractions, tours, sports events, conferences) [10,11]). Jere Jakulin [12] describes the complexity of the tourism system as a soft organisational system, characterised by interactions among its subsystems that influence its development. These subsystems extend beyond hard systems with rules and rigid structures, encompassing various stakeholders, supply and demand dynamics, and informational, material, financial, social, and psychological components. Each component has specific behaviours and activities aimed at achieving its goals. Therefore, the implementation of ecolabels may vary based on these contextual factors, in addition to the perspectives of those concerned. Perspectives refer to the viewpoints, such as stakeholders' or products and services' standpoints, from which we analyse a system. Building on the context presented above, this study addresses the following research question: How can modularity be used to structure and support the standardisation of sustainability measurement, and, more specifically, eco-efficiency, within the complexity of the tourism production and consumption system. Consequently, this paper contributes to this literature by exploring the potential of a modular approach to standardise and structure tourism sustainability modelling, thereby enhancing the flexibility of tourism evaluation and measurement based on different lenses of the ecosystem.

This paper proposes an initial step toward structuring tourism production and consumption in ways that reconcile the sector's complexity with the imperative of sustainability. While digital platforms and centralised systems have facilitated unprecedented ease in travel planning, information regarding the environmental, social, and cultural consequences of individual choices remains limited. To address this gap, we introduce a systemic, multiperspective, and multidimensional modelling framework. The framework provides tourism stakeholders, including service providers, tour operators, government entities, tourists, and scholars, with concepts and representations for studying tourism eco-efficiency performance in a holistic and structured manner. By standardising and organising information through modularity, the framework supports the measurement of tourism resource consumption and production impacts across all types of tourism. In doing so, it enables the integration of impact-based metrics into decision-making throughout tourism supply chains, allowing stakeholders, including travellers, to align their choices with sustainability objectives. This proposal builds on the framework for sustainable production and consumption for travellers by De Camillis, Peeters, Petti, and Raggi [13], expanding tourism perspectives and evaluation tools to better address sustainability challenges.

While the focus of this paper is on the environmental dimension under the concept of eco-efficiency, it acknowledges its importance and interdependence with other sus-

tainability dimensions (e.g., social and cultural) and calls for their expansion in future contributions. Recognising that carrying capacities exhibit non-linear characteristics, where each additional unit of production-consumption can have a disproportionate impact, this study positions itself within ranges where the marginal impact is constant. Therefore, the concept of carrying capacity is integrated into the proposed modelling framework with specific thresholds. Accordingly, this paper presents and conceptually develops the framework, illustrated through two stakeholder perspectives (a supplier and a tour operator). Its operationalisation is demonstrated in Appendix A, while its extension to social and cultural sustainability dimensions and other perspectives as well as its integration with ecolabels remains avenue for future research.

This paper begins with a literature review on the emergence and current application of eco-efficiency in tourism, along with the concepts supporting the proposed modelling framework (Section 2). Section 3 details the methodology, presenting the main concepts underpinning the tourism system modelling framework presented in Section 4. The discussion (Section 5) describes the framework's application to the cases of a supplier and a tour operator, demonstrating its suitability for ecolabels. The paper concludes with the study's limitations and future research opportunities (Section 6).

2. Conceptual Foundations of the Framework

This study uses concepts from the literature, presented in Figure 1 with their relationships, and describes them in the following sections. Sources were intentionally selected for their conceptual contribution to the specific components of the proposed model through a purposive approach, rather than for exhaustive domain coverage.

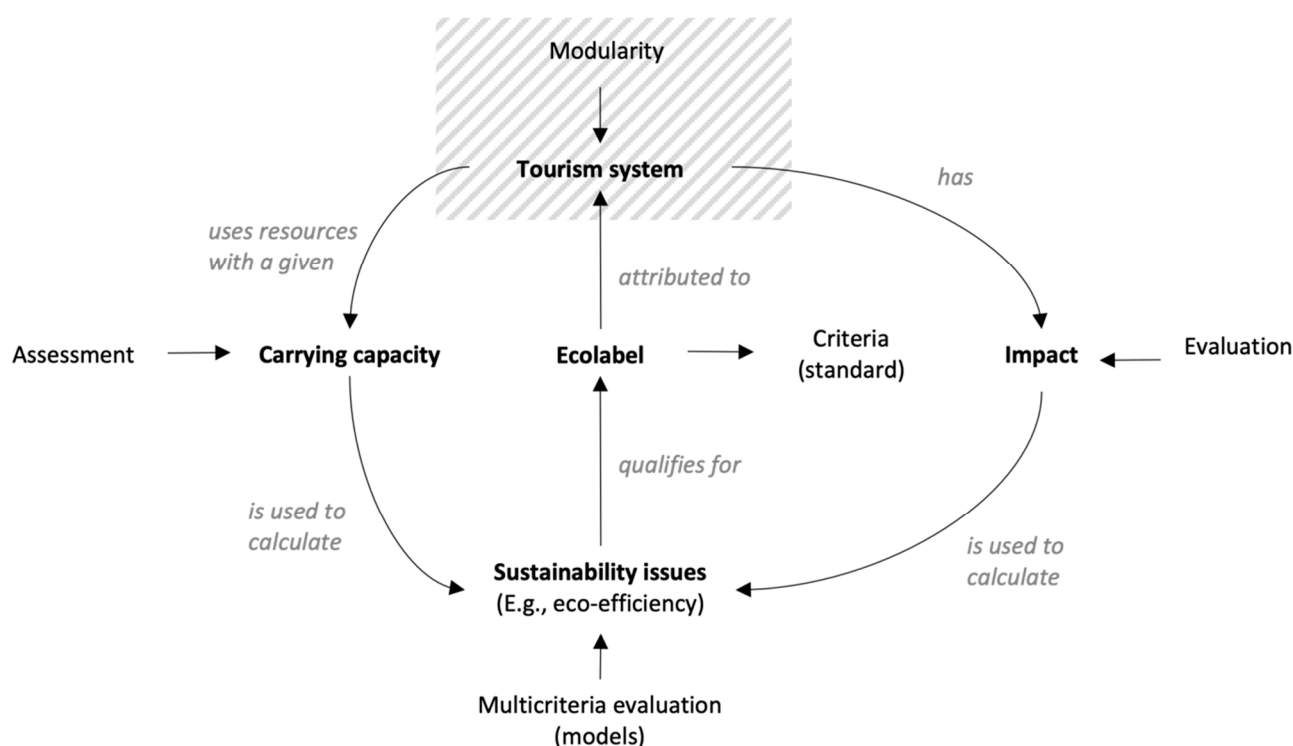


Figure 1. Mapping illustrating how concepts from the literature interconnect with a focus on the shaded area.

2.1. Tourism Eco-Efficiency

Introduced in the 1990s and recognized by the World Business Council for Sustainable Development [14], eco-efficiency aims to create equal or greater value while satisfying human needs with less environmental impact, adhering to the Earth's limits. While it

positions carrying capacity as a threshold for economic development, this notion of limits is politically unpopular [15] and context-dependent [16]. Gössling et al. [7] introduced the concept of eco-efficiency in the tourism literature, suggesting that tourism emissions per unit of value be benchmarked against an average sustainable world eco-efficiency. Tourism emissions are expected to decrease continuously as global economic growth increases, thereby remaining within the Earth's carrying capacity [7]. Sun et al. [17] identify three measuring methods in the literature for tourism eco-efficiency: single ratios, index system methods, and models. These methods range from simple to multi-factor analyses. Single ratio methods, suitable for individual projects or technical objects [17], have been applied in various scopes and contexts [7,18–21]. Index system methods [7] and model methods, such as DEA (data envelopment analysis), are suitable for scale analysis [17,22,23].

To our knowledge, comprehensive studies on eco-efficiency for tourism packages from the perspectives of tourists or tour operators are lacking. Existing studies focus on economic scales (e.g., destinations, provinces, countries), tourism components (e.g., accommodation and transportation), or specific environmental indicators (e.g., CO₂eq emissions and solid waste management). Index systems could support the evaluation of complex multi-scale systems, but are criticized for subjective weighting [24]. DEA at destination scales can overcome this shortcoming [24], but for other types of projects, indicators are either selected or weighted into combined indicators (e.g., unique score), which require subjective weighting. To overcome this limitation, participatory approaches such as Delphi or sensitivity analysis can support more robust, consensus-based module and indicator selection criteria across perspectives.

2.2. Evaluation Tools and Tourism Evaluation Models

Despite advancements in evaluation tools and proposed indicators [6], tourism impact evaluations remain disparate in methods, scope, impact spectra, and tool combinations, complicating comparisons and decision-making across stakeholders with varying objectives. Tools drawn from environmental sciences, engineering, or social science focus on specific indicators (e.g., climate change), tourism products and services or sectors (e.g., accommodation or transportation), types of tourism (e.g., ecotourism, events), scales of analysis (e.g., services, holiday packages, geographic scales), and perceptions (e.g., tourists, tour operators, governments) for different purposes (e.g., regulatory compliance, competitiveness). Despite the search for an ideal set of indicators [25,26], challenges such as data accessibility and subjective interpretation persist [27]. Multiple viewpoints are essential, as stakeholders both impact and are impacted by tourism sustainability.

Current models fail to capture the full complexity of tourism, and studies often present incomparable results unless disaggregated [18,28]. However, combining tools to enhance robustness and bypasses limitations [10,18,29] increases the complexity of measuring tourism eco-efficiency. Various tools analyse different aspects of tourism, and they include: Greenhouse Gas (GHG) Protocol [30], a hybrid multi-criteria approach [31], and Input–Output (I–O) approach [32]. Other tools include Material Flow Analysis (MFA) [21], Ecological Footprint (EF) Analysis [33], Data Envelope Analysis (DEA) [22], Life Cycle Assessment (LCA) [5], and Sustainability Indicators (SI) [34], or tool combinations such as LCA and I–O methods [28] or LCA and EF [10]. Their application remains limited by methodological and practical challenges [5].

Evaluation models in the tourism sustainability literature often portray the industry and holiday packages as linear and simple systems, whereas they are in fact complex and dynamic [5,10,35,36]. These models lack a standard consensus. More flexible, standardised evaluation models and ecolabels [8] could improve data reuse across contexts. Considering multiple perspectives, dimensions, and tools further adds to evaluation complexity, along-

side considerations of carrying capacities, whose role is acknowledged as the foundation of sustainable tourism and further developed in Section 4.5.

2.3. Tourism Ecolabel

Ecolabels provide information about a product before the purchase decision [37,38] and aim to enhance the environmental performance of the applicants, driven by market forces, peer pressure, or subsidies [8]. However, tourism ecolabels are uncoordinated internationally, numerous, and created for different players and subsectors, identifying various tourism products, scales, and quality levels (e.g., national, local, destination, spaces such as beaches and parks, and activities). The Global Sustainable Tourism Council (GSTC) publishes sustainable tourism criteria for a range of tourism stakeholders and activities as guidelines for certifications specifying what would be done, but not how to measure performance or set thresholds. Buckley [37] notes that effective tourism ecolabels should be customisable to the context of different countries, ecosystems, and activities. Conversely, Font [8] recommends standardisation, focusing on processes or performance benchmarks at the national certification authority level. This would restrict their international development due to varying legislation and requirements between sectors and countries.

Ecolabels lack methods to enforce sustainable management, measure performance, and consider improvements that do not guarantee sustainability [8], impeding international standardisation [8,38,39]. The International Organization for Standardization offers a family of standardised guidelines for applying ecolabels [40]. Type III ecolabels inform buyers of the performance of a product or service's life cycle for comparison purposes ISO [41]. Currently, standardising tourism labels for international recognition remains challenging, and no tourism ecolabels follow a standardised impact evaluation approach, allowing for the communication of sustainability evaluations or eco-efficiency performance.

2.4. Modularity to Facilitate the Transition to Eco-Efficiency

The concept of modularity offers a structured analytical approach suited to the complexity of the tourism system. In the literature, modularity addresses management [42], innovation [43], service design [44], and organisational economic issues [45]. These studies decompose complex systems into so-called “modules”, revealing their compositions, interactions, or interdependencies [45]. Avlonitis et al. [44] note that modularity research aligns with multi-level analysis, and is cohesive when services are examined from a systems theory angle, as modularity is a general characteristic of systems. Object-oriented modelling methods reduce complexity by representing the structure of real-world systems in a simplified manner [46]. This method identifies and classifies system components and behaviours as general modules to reproduce and analyse real-world instances.

Modular logics already inform several initiatives relevant to tourism sustainability, including GSTC criteria, which are organised by stakeholder type, ISO 14025 [41] Product Category Rules, and life-cycle inventory unit processes that can be combined to assess a wide range of products and services. The closest precedent in tourism by De Camillis et al. [13] proposes the use of LCA evaluations feeding a central database for the construction of tourism packages. However, this approach does not address how this approach could be generalised to other production and consumption configurations, nor the underlying information structure that would support such an initiative. To our knowledge, few prior studies have applied modularity to information management and life-cycle modelling more broadly [47–51]. These studies remain specific to LCA, and none address tourism systems or multi-perspective measurement.

These existing initiatives apply modularity to specific deliverables (certification criteria, product declarations, or LCI datasets) rather than to the structuring of the measurement

process itself more generally. The framework proposed in this paper builds on these prior contributions to provide a flexible modelling structure that can be fed by, rather than replace, existing evaluation tools and standards. It supports environmental measurement of tourism service systems that is suitable across multiple stakeholder perspectives.

2.5. Gap Summary

While the scientific community continues to improve environmental assessment tools, their application in tourism primarily focuses on destinations, products, and services, particularly accommodation and transportation. Evaluations of tourism packages, activities, and other services within the tourism system have been limited [7,35,36,52,53], especially regarding eco-efficiency within carrying capacities. Furthermore, a more comprehensive representation of the tourism system is necessary to effectively navigate its complexity and diversity. The concept of modularity holds potential for enhancing the organisation and standardisation of the complex tourism ecosystem for evaluation purposes (Figure 1). This study focuses on the modularity and modelling of the tourism system to evaluate eco-efficiency as a sustainability issue. To the best of our knowledge, no study explicitly links modularity with improving the robustness of modelling and sustainability evaluations and measurements in services or tourism, or with enhancing its eco-efficiency.

3. Methodology

The conceptual framework is based on a literature review of concepts relevant to defining, modelling, and evaluating eco-efficiency within the tourism system. These concepts include modularity, eco-efficiency, carrying capacity, and ecolabels. The modularity concept and object-oriented modelling techniques offer a flexible and “assemble on demand” approach to model and evaluate the tourism system. Perspectives and dimensions guide the eco-efficiency measure and support decision-making for stakeholders, while also setting the stage for eco-efficiency modelling scenarios (instances) using the IPAT equation and integrating economic and measurement tools such as life cycle assessment. The framework introduces opportunities for eco-efficiency modelling with impact criteria. Figure 2 illustrates a logical sequence applying these concepts. Perspectives provide viewpoints for analysing and improving the tourism system’s eco-efficiency, while modules model the system, including resources and dimensions such as the spatial, temporal, and contextual factors, to support the selection of evaluation tools. The tourism system impacts are then assessed using single or combined evaluation tools [29], and labels can be awarded based on these evaluations, though they require structure and standardisation. Therefore, modularity is suggested to standardise the building blocks of tourism eco-efficiency.

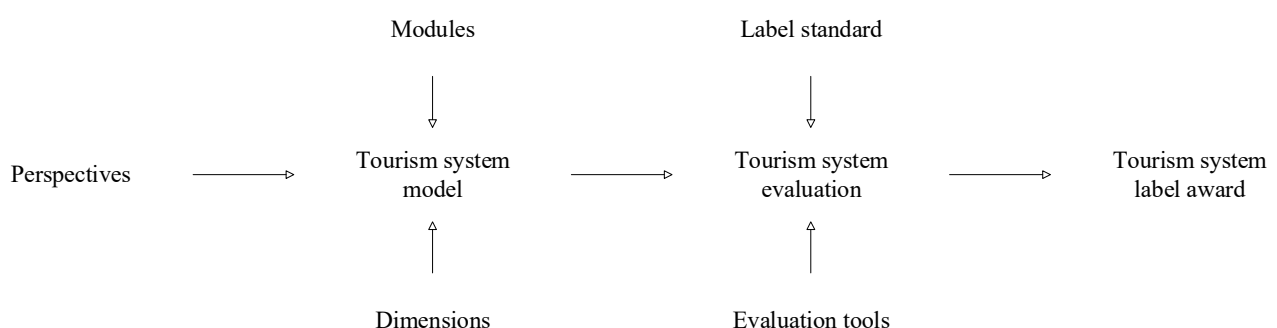


Figure 2. Logical sequence applied to the use of concepts.

4. Conceptual Models to Measure Tourism Eco-Efficiency

4.1. Tourism Multidimensional and Multiperspective Eco-Efficiency Framework

First, modularity, an engineering concept, is proposed as a means to model tourism systems using standard modules defined by specific attributes, relationships, and evaluation methods. This modelling technique provides a standardised approach to assess the eco-efficiency of a tourism offer from multiple perspectives, enabling the design and incremental improvement of eco-efficiency.

Second, eco-efficiency aims to reduce environmental impact while fostering economic growth, also known as decoupling [54]. Despite criticism that index system methods limit the isolation of indirect influences [17], they remain useful for evaluating impacts across scales [7]. This aligns with a multidimensional framework combined with a modular approach to structure tourism eco-efficiency applications. Eco-efficiency ratios can be measured using different units, such as impacts per tourist, dollar, or functional unit of the product or service consumed. Based on demand, impact extrapolation between perspectives becomes feasible. Although dollar-based ratios do not account for free public resources or activities, visitor ratios consider impacts per visitor experience or functional unit regardless of price. A modular equation, inspired by the IPAT equation, is proposed to measure the tourism system's impacts, compare its eco-efficiency, and monitor performance.

Third, the carrying capacity plays a central role in tourism eco-efficiency, aiming to sustain economic activities within resource limits before causing irreversible negative changes. In the proposed framework, carrying capacity is recognised as important, but its application is currently limited to linear impacts and thresholds. Finally, ecolabels could be used to communicate eco-efficiency status or standardization improvements for various perspectives, but their analysis and mechanisms to do so are excluded from this paper. Adopting Type III labels at different scales and perspectives, such as the products and services level, for tour operators or tourists, is encouraged to customise eco-efficiency packages, or at the industry level for a region or a country. This proposal suggests integrating modularity into the framework by De Camillis et al. [13], offering tourism sustainability standardisation. For instance, it recommends creating eco-efficient packages dynamically by assembling individual products and services modules based on key factors and labelled impacts.

4.2. Customisable Perspectives and Dimensions

The model incorporates various perspectives (viewpoints) within the tourism system and supply chain, encompassing, but not limited to, governments, destination managers, service providers, tour operators, and consumers (Figure 3). The approach per perspective emphasises the responsibility within each stakeholder's scope of action. Then, dimensions influence the choice of evaluation tools or combinations (e.g., specific or more general evaluations) to provide a multicriteria assessment reflected in a labelling system. For instance, a service provider might compare their eco-efficiency performance with that of their peers to enhance their offerings. The model is used to study inputs and outputs (resources) throughout the life cycle to offer competitive and eco-efficient products and services. From the consumer perspective (tourist), the model guides eco-efficiency consumption compromises. Despite preferences and constraints, numerous configurations for a more eco-efficient trip are possible. It can involve selecting service providers based on overall sustainable performance (supplier A versus B), choices among accommodations (hotel A, room 1 versus room 2), activities, dining options, and transportation categories. Tour operators, central to the supply chain, promote sustainable tourism development by influencing consumers, suppliers, and destinations through their sales volumes and coordination roles [55]. They can integrate eco-efficient options of products and services

into their packages. Consumer values, preferences, and social norms have the potential to be reflected in the framework. They may be considered through consumption patterns with the general equation by selecting preferred types of products and services (e.g., the most eco-efficient 5-star hotel for comfort or the least impactful hotel for longer stays). Governing bodies or organizations responsible for promoting, developing, and managing tourism sites or destinations must coordinate and deliver quality offerings while executing development plans (e.g., increasing tourist flow and expenditures). Therefore, they can offer eco-efficient services and public goods consumed by the tourism industry (e.g., national energy or transport infrastructure, tourism information centres, etc.). They can take place at various spatial scales (e.g., municipal, regional, and national levels) or for specific impacts or resources that threaten carrying capacities.

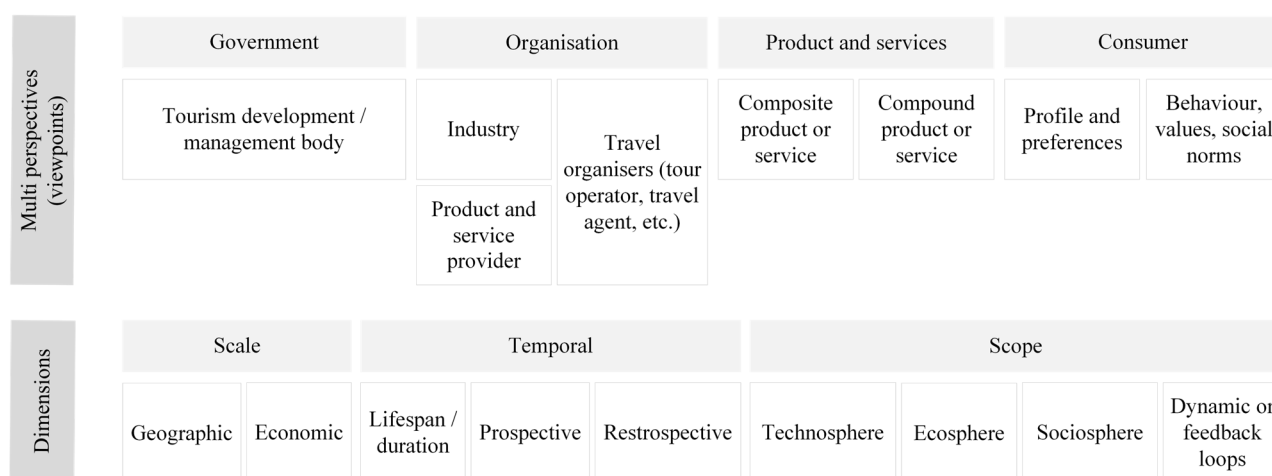


Figure 3. Multiple perspectives and dimensions.

As for dimensions, they influence the selection or combination of evaluation tools and interpretations of eco-efficiency or carrying capacity. Certain tools are more appropriate to evaluate specific economic (e.g., micro or macro data) or geographical scales (e.g., global or local impacts), prospective or retrospective scenarios, or periods covered (e.g., cumulative impacts or duration). Other tools address specific sustainability scope like technospheric (e.g., technological change in resource efficiency), ecospheric (e.g., environmental changes), or even sociospheric aspects (e.g., human social interactions). Lastly, dynamic effects can be assessed using non-linear models or simulations with feedback loops.

4.3. The Modular Tourism System Model and Composition

The model (Figure 4) borrows its structure and principles from the object-oriented modelling method in software development, and applies modularity.

This method applies the modularity concept within a system by decomposing it into subsystems with shared attributes and understanding their interrelationships to organise the system's modules. Modularity facilitates modelling by reusing a module and its data for new scenarios. This approach models the tourism system and its impact under flexible and simple structures called to evolve by adding modules (represented by boxes).

Moving across the model from left to right, it formalizes the perspective (stakeholders) that control resources through interventions (regulation or strategies) to reduce impacts. Resource consumption impacts stakeholders and the relationship (link) impacts concerns, dimensions, and evaluation tools. Impacts vary across environmental, economic, social, and cultural aspects and dimensions. The resource module encompasses both natural and manufactured resources consumed or utilized directly or indirectly by various tourism products and services created and offered on the market. Natural resources encompass food,

water, minerals, energy, waste sinks (e.g., the atmosphere for emissions), and landscapes, among others. Manufactured resources encompass a range of goods, including consumable items like cleaning products and oils, as well as capital goods such as infrastructure and equipment. In addition to the resource subcategories, carrying capacities are included.

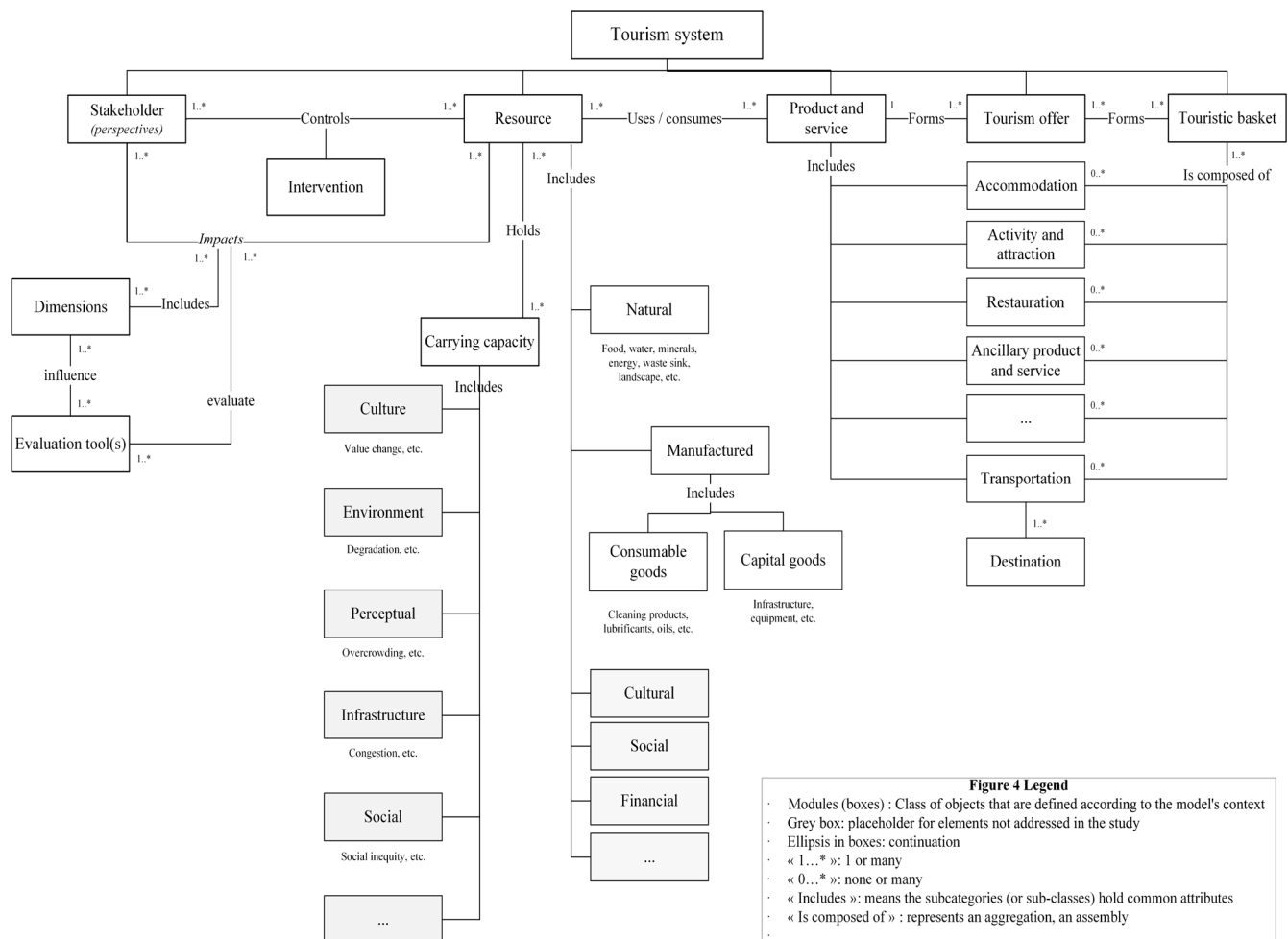


Figure 4. Modular tourism system model illustrating tourism modules, their relationships (links).

Next, the products and services offered by distinct industries use or consume one-to-many resources to create one-to-many tourism offers on the market. Touristic basket scenarios are created (one-to-many) from tourism offers to evaluate and compare their eco-efficiency (see Section 5). Tourism baskets represent specific tourism consumption, such as tourism offers (products and services) or tourism packages. Tourism sub-industries provide tourism products and services, such as accommodations, activities and attractions, dining options, ancillary products and services, and transportation. The transportation category identifies modes (air, water, roads, rail) and vehicles with varying resource consumption, technology energy efficiency, and occupation rates. It is a central element of tourism mobility, connecting one destination to many others. Each destination has a unique sociodemographic, socioeconomic, and environmental context that complexifies the compilation of impacts for multi-destination travels, justifying the need to measure one module at a time. Accommodations typically refer to a star system to indicate quality levels; higher stars usually imply more services (e.g., restaurants, pools, shuttles) with increased quality levels and potential resource consumption. Restauration refers to commercial food service (the primary business), such as restaurants and catering services, as well as non-commercial food service, including in-flight catering. Tourism activities and attractions,

engaged in before, during, and after travel, along with ancillary products and services such as shopping, guided tours, financial services, and marketing [56], should also be considered when applicable.

The tourism system models scenarios for perspectives, creating instances of the system. For example, a tour operator can combine product and service modules (or options) to create a one-week tourism package. Evaluating and comparing the impacts of this package with another composed of alternative products and services, consuming different resources or even different destinations, would provide information to identify the most eco-efficient tourism package.

4.4. Eco-Efficiency Modelling and a General Approach for Tourism Perspectives on Eco-Efficiency

The modular tourism system model in Figure 4 supports the application of eco-efficiency explanatory variables (technological and economic) found in the literature. First, a general equation is proposed to measure tourism eco-efficiency (4), inspired by the IPAT Equations (1) to (3) and compatible with life cycle assessment tools. The environmental impacts, as presented in these equations, are derived from a life cycle approach. This section models the perspectives and dimensions previously defined as part of the tourism system, including the types of impacts to be measured.

The IPAT equation embodies the fundamental concept of decoupling, which is associated with eco-efficiency and carrying capacity, where economic growth and environmental impacts are constrained by limited life-supporting systems [54]. Lonca et al. [54] developed a flexible approach using the IPAT equation to assess decoupling through circular strategies, suitable for multiple assessment scales (e.g., industrial sectors). In this context, the IPAT equation is used to model tourism eco-efficiency by applying modular building blocks to the tourism system's perspectives. Font Vivanco et al. [57] demonstrate the compatibility of the life cycle inventory and the IPAT Equation (1). The technological factor decomposition enables smaller-scale evaluations and extrapolation to larger scales, thereby overcoming shortcomings such as impacts on the life cycles of products and product systems [57].

$$i = p \times A \times T \quad (1)$$

$$Impact = Population \times Affluence \times Technology \quad (2)$$

$$i(Impact) = p(capita) \times A\left(\frac{GDP}{capita}\right) \times T\left(\frac{impact}{GDP}\right) \quad (3)$$

$$Impact = Tourist \times \left(\frac{Tourism\ consumption}{Tourist}\right) \times \left(\frac{Environmental\ impact}{Tourism\ consumption}\right) \quad (4)$$

From the IPAT Equations (1) to (3), the explanatory variables are adapted to create a reference for the tourism industry under Equation (4). The latter expresses the *impacts* of a perspective by considering explanatory variables such as the population of tourists who consumed tourism activities (*affluence*) and environmental *impacts* resulting from tourism consumption (*technology*). Like a country's *GDP* increase translating to greater environmental impacts, an increase in tourism expenditures will drive greater environmental impacts unless other variables counterbalance this effect and improve eco-efficiency within clear limits. The variables for tourism consumption encompass touristic baskets, products, services, and resource consumption. This multidimensional approach, addressing various impacts and product and service types, ensures robust modelling of the tourism consumption and production system. The model adapts to different perspectives to address stakeholder actions at diverse scales [54,57]. From these advancements, the approach is applied across different scales in the tourism industry, using modularity to measure travel packages or their tourism products and services.

From a general standpoint, modularity allows for disaggregating a system into standard parts (modules) with their associated impacts, forming touristic baskets for various perspectives. Standardising modules then facilitates their disaggregation, aggregation, and reuse to compare touristic basket scenarios. To facilitate this, key drivers of eco-efficiency are defined under the IPAT equation, along with associated multiplicative factors, as shown in Table 1. The volume of tourists p , identified by vector V , plays a scaling role. The matrices A and B indicate the affluence (consumption levels) of products and services that compose tourism packages, including night stays, meals, and hours of activities. These are represented by the quantity q of touristic baskets consumed per tourist p , and products and services a included per touristic basket q . These matrices include consumption values that define the distance, duration, and frequency [58]. These products or services require resources; therefore, technology factors (resource efficiency) within matrices P and R represent resources consumed d per product or service a , and the impacts b per resource consumed d . Then, impact per resource is primarily addressed from an environmental standpoint, but could also consider social, economic, and cultural evaluations. The types of impacts are further described in the following section. Finally, the characterisation factors under matrix F group impact b under damage categories j according to life cycle assessment methods or others that would require such aggregation. From Equations (1) to (4) and the key drivers identified in a general form is proposed using a matrix method, as outlined in Equation (5). This general equation provides a flexible and robust process, offering detailed levels for various applications. It can adapt to multiple contexts such as perspectives, quantities of tourists, quantities of baskets compared and consumed per tourist, types and quantities of products and services or resources included, and the types of impact analysed.

$$Impact = VABPRF \quad (5)$$

Table 1. Tourism eco-efficiency drivers included in the matrix and their respective associated tourism factors (inspired by Sun et al. [58]).

Factors	Volume	Consumption Level (Affluence)		Resource Efficiency (Technology)		Characterisation Factor (CF)
Matrix (or vector)	V	A	B	P	R	F
Parameters	$[1 \times 1]$	$[1 \times q]$	$[q \times a]$	$[a \times d]$	$[d \times b]$	$[b \times j]$
Tourism factors	Tourists	<u>Touristic baskets</u> Tourist	<u>PSs</u> Touristic basket	<u>Resources</u> PS	<u>Impacts</u> Resource	<u>Damage category CF</u> Impact

When studied from the supplier perspective, a supplier touristic basket q is a collection of products and services among the market tourism offers a made from a collection of resources d (manufactured or natural). The impact per product or service is impacts b per resource d . For example, the resources d consumed by hotel q , such as energy and water, can potentially improve eco-efficiency for a night's stay when choosing alternative energy sources or equipment to reduce water consumption based on impacts b or damage categories j evaluated. The supplier's product or service should be evaluated based on standard functional units agreed upon by the scientific and practitioner communities to ensure comparability (e.g., per square footage, room, tourist, or dollar for accommodations). From the perspective of a tour operator or tourist, the touristic basket is modelled as a tourism package comprising various products and services (e.g., 1 night at hotel "x" "y", 2 or 3 room.night, 350 km or 1050 km travel distance by car or train).

Therefore, a tourism package consumes resources through the products and services it provides. The total impact per package equal the sum of the impacts from the products and services provided by suppliers that comprise the tourism package. A vector is used

when comparing multiple package impacts without the scaling factor p . Figure 5 illustrates two tree nomenclature scenarios applying Equation (5). Each scenario is influenced by a specific perspective, representing a tourism stakeholder. In a matrix, unused resources for a product or service are assigned the value 0, while selected products and services are included in a package. The different impact types measured are addressed in the following section. Overall, touristic baskets are compared based on similar experiences. The same package, with additional activities, comfort, and services, may affect eco-efficiency. Similarly, a supplier's products and services may consume more resources, resulting in greater environmental impacts for the same type of experience.

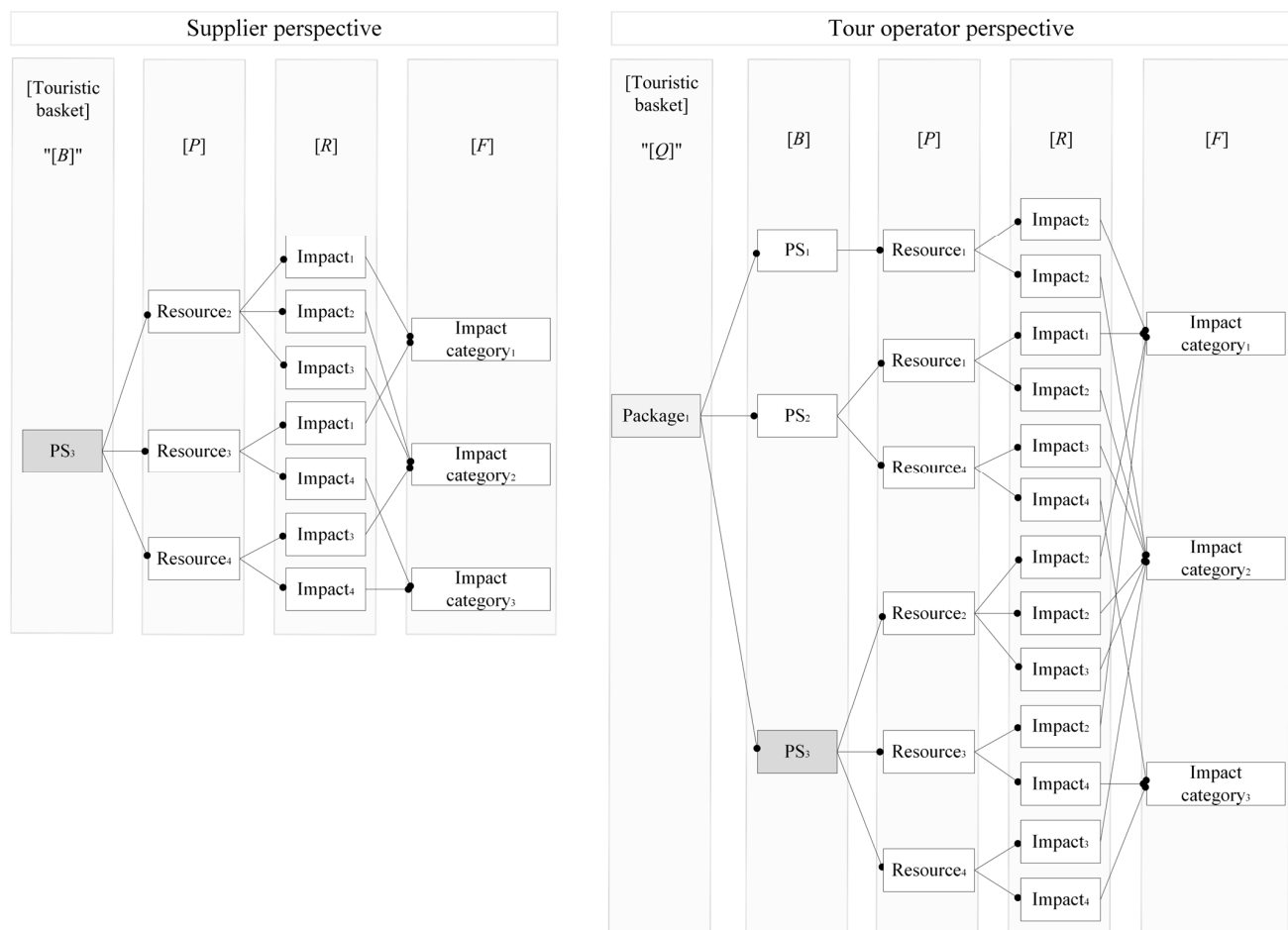


Figure 5. Tree nomenclatures for a supplier and a tour operator perspective.

To illustrate the operability of Equation (5), Appendix A presents a simplified application from the supplier perspective. It compares two 3-night energy scenarios for a small hotel, a fossil fuel baseline and a renewable energy alternative, by populating matrices V , A , B , P , R , and F with realistic values and computing comparative eco-efficiency ratios. This example demonstrates that the framework produces meaningful comparisons and isolates the contribution of individual matrix factors to eco-efficiency performance. For a more elaborated demonstration, another study is available for consultation [59].

4.5. Eco-Efficiency Impacts and Assessment Tools

The ratios used to express eco-efficiency impacts are numerous, and combining different tools can help address their respective gaps. The ratios may be described as impacts per resource or product consumed or produced. They can be expressed per function delivered for the experience (per hour of leisure, per night, per km travelled, meals or calories, etc.),

per package, per person, per group of travellers, per supplier, or per dollar. The life cycle approach considers both direct and indirect impacts throughout the life cycle of the tourism system being studied, as well as a variety of impacts to measure eco-efficiency [36]. The life cycle assessment method IMPACT World+ [60] includes 21 types of damage indicators from the economic system's interactions with the environment groups under 2 categories of damages presented under Figure 6. Examples include the contribution to climate change damage to human health and the ecosystem quality, water availability to damage on human health, terrestrial and freshwater ecosystems, and land occupation damage on biodiversity [60]. This method allows regionalisation of geographic particularities and temporal resolution of impacts over time, which is particularly relevant for the tourism system consuming resources from one destination to another.

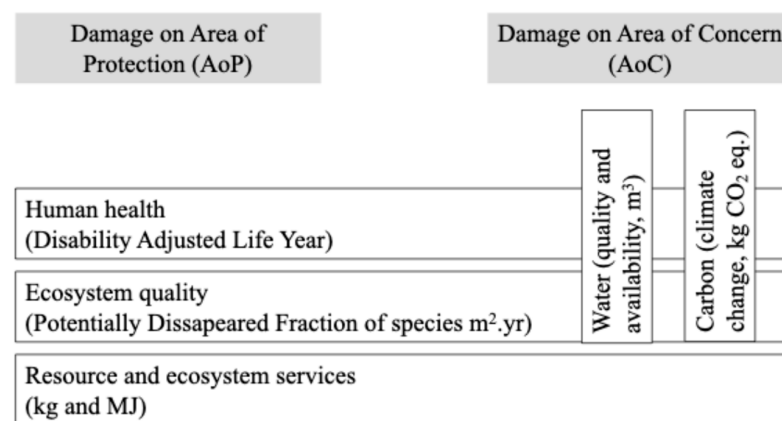


Figure 6. Environmental damage categories (adapted from Bulle et al., [60]).

To align with the destination-based nature of tourism, Table 2 proposes considering the combination of resources or products and services consumed from a manufacturing standpoint [36] and the specific stages of a service at a destination site [61]. For an ecolabel scheme, these stages and scopes offer an interesting approach for progressively applying impact evaluations to tourism offers (from manufacturing or service sectors, as well as from sub-products and services to off-site impacts). Given the size and variety of tourism organisations, these elements can be applied gradually.

Table 2. Adapted from Filimonau [36] and Graedel [61], the table presents four scopes and five life stages to evaluate the environmental impacts of the tourism sector.

Graedel [61]	Filimonau et al. [36]	Scope 1	Scope 2	Scope 3	Scope 4
Service LCA stages	Manufacturing LCA stages	PS direct impacts	PS indirect impacts	Sub-PS (Scope 1 & 2)	Time (All PS lifespan)
Site and service development and service provisioning (e.g., equipment)	Manufacturing/Assembly		X	X	X
	Transport/delivery		X	X	X
Performing the service	Use/exploitation	X		X	X
Facility operations (e.g., maintenance)	Maintenance/renovation		X	X	X
Site and service closure	Disposal/end-of-life		X	X	X

The life stages considered at the different scopes are indicated by X. Scope 1 represents operations from a travel package component, such as air travel, coach car, and hotel. Scope 2 encompasses the indirect impacts from the life cycle stages of travel package components from manufacturing to end-of-life, beyond scope 1 operations. Scope 3 includes the indirect impacts associated with the elements of travel package components (e.g., life cycle for air travel; fuel, vehicle, airport, air travel management). Finally, scope 4 considers the temporal dimensions, determining the lifespan of the direct and indirect impacts for each component of the travel package elements.

Then, integrating carrying capacities into the model would require a combination of tools, as demonstrated by Bjørn & Hauschild [62] or Castellani & Sala [10], but further development is necessary. The general equation addresses constant marginal impacts within ranges where the impact per additional tourism service provider, product, attraction, or tourist is hypothetically the same, as well as their weight in the carrying capacity “inventories”. To consider carrying capacities in the model, as outlined in Equation (5), thresholds could be included in the impact matrix. For example, a region with limited hydroelectric capacity may supply clean energy up to a given threshold. Once this threshold is exceeded, the resource shifts to another, such as natural gas. Consequently, during the organisation of spontaneous events or during peak seasons, increased tourism consumption may generate non-linear environmental impacts. Likewise, in an arid region, water restrictions may apply beyond a threshold level of consumption, thereby modifying the marginal impact of tourism on the local population. Concretely, these thresholds can be operationalised by acting on specific elements of the impact matrices P , R , or F . As an illustrative example, let r_{ij} denote a specific element of matrix R that varies due to carrying capacities, say the impact per electricity consumption. We may then define a tourism consumption threshold $\bar{Q}$ where the following rule applies:

$$r_{ij} = \begin{cases} \bar{r} & \text{if } Q \geq \bar{Q} \\ \underline{r} & \text{otherwise} \end{cases} \text{ where } \bar{r} > \underline{r},$$

and where Q is the sum of electricity consumption coming from VABP in Equation (5). Accordingly, two types of effects emerge as tourism consumption Q approaches or exceeds the carrying capacity threshold $\bar{Q}$: the first is the volume effect, which exists even in the absence of thresholds: higher consumption leads to greater total impacts (Impact in Equation (5)). The second is the impact effect, whereby each additional unit of consumption generates a larger marginal impact, reflected in changes in r_{ij} within R . This rule introduces a non-linearity while preserving its linear structure, below or above the thresholds. Additionally, rules need to be adjusted to different situations, as this reflects one example.

As done by Schianetz et al. [29] at the destination level, Table 3 identifies tools (not limited to) that could potentially evaluate, measure, or simulate eco-efficiency for tourism offers. This paper proposes using life cycle assessment methods to measure tourism eco-efficiency, as a growing number of life cycle assessment studies are employing this approach. It is compatible with the IPAT equation to measure eco-efficiency [57] from different perspectives through modularity [47,48]. It offers extensive environmental impact assessment [29] and provides an overview of environmental trade-offs [47]. Additionally, the combination of assessment tools addresses shortcomings [29], benefitting the different perspectives addressed by the modular Equation (5).

Table 3. Evaluation tools categories (based on Schianetz et al. [29] with modifications).

Category	Evaluation Tools
Economic tools	Input–Output (I–O)
	Partial Equilibrium (PE)
	Computable General Equilibrium (CGE)
	Data Envelope Analysis (DEA)
	Eco-efficiency indicators/ratios
Flow analysis	Substance Flow Analysis (SFA)
	Material Flow Analysis (MFA)
	Life cycle assessment (LCA)

Table 3. *Cont.*

Category	Evaluation Tools
Environmental tools	Ecological Footprint Analysis (EFA) Environmental Impact Assessment Biocapacity method
Multipurpose tools	Agent-based modelling System dynamics Sustainability Indicators Multi-Criteria Analysis (MCA) Adaptive Environmental Assessment
Reporting and compliance	Greenhouse Gas (GHG) Protocol Environmental Audits

5. Discussion

The framework application begins by establishing the constitutive parts that define and model the tourism system from various perspectives, thereby improving the structure of evaluation tools. This section presents the application of the framework from the perspectives of a supplier and a tour operator, serving as examples for evaluating two eco-efficiencies using the life cycle assessment approach. Then, an insight into the framework's suitability over time and changes in the ecosystem is followed by an outline of the framework's limitations.

First, defining the dimensions for the eco-efficiency measurement from a particular perspective initiates the application of the framework for an impact evaluation between the production and consumption of tourism activities. This includes considering scale, temporal, and scoping dimensions to be studied for alternative eco-efficiency solutions, such as for tourism suppliers in a specific city, for prospective scenarios over the technosphere and ecosphere scopes. Then, when modelling the supplier perspective, as depicted in Figure 4, the system's model perspective defines itself in a logical sequence. Generally, suppliers select resources to create tourism offers (products and services) which are eventually integrated into tourism packages. Their tourism offers are represented by touristic baskets (matrix B) that can be compared with other baskets comprising alternative resources (e.g., different energy source options for a hotel) before being offered on the market. The model enables suppliers to mix and match resources that best align with their eco-efficiency objectives. Stakeholders control the eco-efficiency performance of their touristic basket by modelling alternatives based on impacts per resource or resource per product or service. Matrices P and R in Table 1 and Figure 5 guide the selection of resources based on impacts with rigour and structure, specifying what is included for the alternatives. For instance, the proposed example compares two 3-night packages for a single tourist in a city. A hotel room is a service provided by a supplier, comprising resources such as infrastructure, energy (fossil or renewable), water, and maintenance consumables. The hotel selects the resources based on the eco-efficiency performance to compose its touristic basket (service) before commercialising it. Each offer consists of different resources and eco-efficiency performance.

From the tour operator's perspective, the eco-efficiency performance of accommodation options for two 4-day packages (touristic baskets) is compared (Figure 7). Other perspectives, such as the government's touristic basket, could include the impacts of government services or resources consumed by tourism industries. This framework offers a variety of applications and interventions at different geographic or economic scales to improve, for example, a destination's label performance.

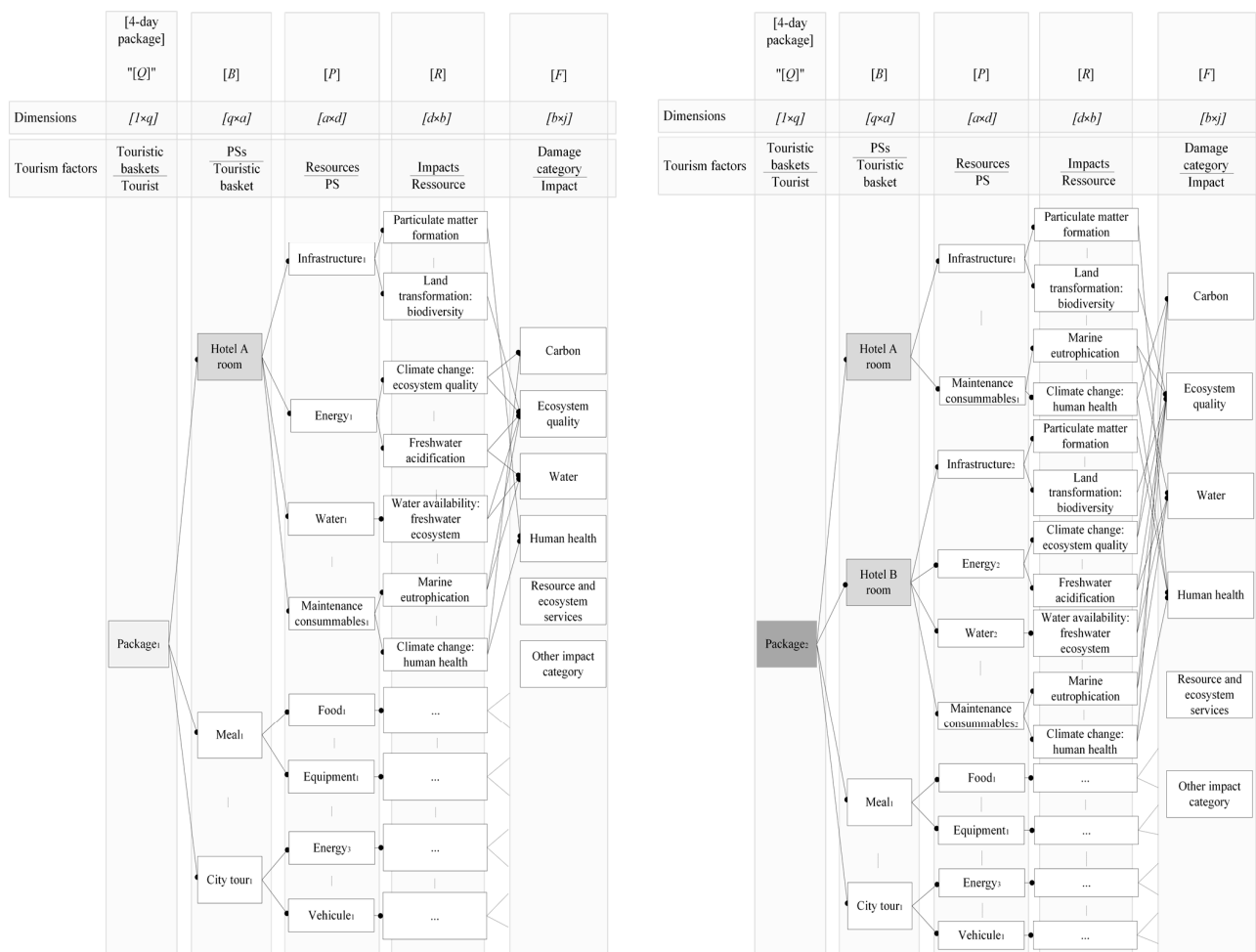


Figure 7. Example comparing two 4-day packages to visually demonstrate the use of modularity, applied with the general Equation (5) for two levels of modules (in grey).

Following the modelling and environmental impact assessment using life cycle assessment tools (appropriate for this example), Equation (5) is applied to obtain eco-efficiency performances per visitor for each impact category (Figure 7). The framework's modularity then structures information and adjusts the content of touristic baskets, facilitating the measurement of eco-efficiency. Each basket comprises products, services, or resource modules, each with specific attributes and characteristics that influence eco-efficiency measures.

From a practical standpoint, an individual label could be created for every module, aligning with the modularity concept proposed by ISO 14025:2006 [41]. This framework could thus serve certifying organisations across various markets by providing eco-efficiency performance information to improve decision-making from different perspectives. Existing labels tend to be modular, including levels of certification with compliance points (e.g., LEED) or reporting categories of specific impacts such as GHG emissions (GHG Protocol). By breaking down complex tourism systems and standardising the measurement approach, as formalized in Equation (5), modularity facilitates the assessment of eco-efficiency. Then, combining the LCA method with Equation (5) provides a structured basis for qualifying Type III ecolabels, thereby supporting informed choices by tourism stakeholders.

As the tourism industry transforms and evolves, the framework is meant to reflect these changes through its flexible and modular representation. Examples of changes over time or in the tourism ecosystem are the industry transformations (e.g., virtual tour, collaborative platforms), behaviours (e.g., longer stays), technological innovations (e.g., AI recommendation systems, smart infrastructure, renewable energy). They may also involve

evolving governance frameworks (e.g., policy and regulation) and new scientific evaluation tools (to provide precision or new ways to evaluate impacts). The framework enables the anticipation and measurement of outcomes from different perspectives, scales, and transformations by modelling the system and accounting for these changes, reflected through increases, reductions, or substitutions in production and consumption in the general equation. The framework offers the potential to support more informed, effective, flexible, and adaptive sustainable decision-making by structuring tourism ecosystem information; defining and measuring the impact of new trends on ecological, social, and economic outcomes; and developing methodology to measure impacts. For instance, currently, the measure of social impacts is limited and future tools developed could be considered within this framework. In fact, the general equation can consider cultural and human resources or even the attractiveness of touristic resources, which is aligned with work by Claude and Zaccour [63]. Those authors specifically mention that:

“As noted by Brown et al. (1997), the sustainability of tourism is [...] directly tied to maintaining the integrity of [the] attraction [landscape, wildlife and ecosystem, historical monument, or indigenous culture] and mediating the interaction between the tourists and the attraction over time, such that interest is maintained. Therefore, it is important to assess not only the nature of the motivations and attraction, but also the feedback among them.” [63] (p. 798)

Just as indicators used in tourism to evaluate its sustainability are influenced by specific socio-spatial contexts and scales [27], the framework allows modelling different scales depending on the considered perspective and defining various dimensions. From these models, building scenarios involves integrating diverse concerns and engaging with experts, tourism actors, and local communities. The framework identifies elements that require further development and consultation with industry stakeholders in future research, such as the comparison and selection of the proper evaluation tools, carrying capacity, stakeholder implications and social and cultural impacts. Although studies tend to focus on specific issues, in reality, they are often related or interdependent [64]; therefore, studies should consider evaluating multiple impacts for a comprehensive assessment. This framework anticipates this need. Operationalising the framework would benefit from real case studies to validate and improve its application across different perspectives and tools. The assessment tools presented in Table 3 should be reviewed to specifically guide their use for different combinations of tourism perspectives, as done by Schianetz et al. [28] to assess tourism destinations. As the framework is suitable to welcome several indicators and evaluation tools, consensus through a participatory approach should be envisioned. This would ensure standardisation of index system methods across perspectives and suitability with existing standards and norms, such as ISO 14025 and PCRs, which support reproducible and consensus-based declarations. This type of approach would also be suitable for stakeholder engagement to establish mechanisms for system and module boundary definitions, interdependence management, evaluation tool selection, impact aggregation rules, and the specifics of data collection for such a framework. In addition, further empirical applications operationalising the framework, building on Teigeiro et al. [59], which proposes a method of application, would help identifying the practical implications as well as trade-offs between model complexity and usability. It could also be worth studying the mechanisms used in other industries that are more advanced in setting standards or working towards standard ecolabels, such as working groups.

Regarding carrying capacities, this study is situated within a range of constant marginal impacts with thresholds. However, further research should consider the non-linearity of tourism systems, for example, examining how capacity levels influence environmental impact results, such as low impact offers entering a saturated market with

limited carrying capacities. The proposed framework also presents other limitations that require further research to demonstrate the different dimensions documented, such as assessing dynamic effects using nonlinear models and feedback loop simulation. Furthermore, improving eco-efficiency can positively impact environmental carrying capacity while simultaneously exacerbating other carrying capacity issues. This rebound or backfire phenomenon should be investigated to avoid impact displacements. Other questions remain, such as the effect of measured ecolabels on consumption habits while increasing the ecolabel's reliability and credibility, as well as their impact on the industry's profitability and data accessibility.

Finally, integrating the proposed framework with a labelling scheme without overwhelming the industry will be a challenge and should be addressed in future research. Tourism ecolabels are abundant in the market, and building on existing ecolabels to achieve greater sustainability in the tourism industry will require additional evaluation and integration of measurement tools to identify needed improvements and standardisation efforts and to communicate progress robustly and accurately. To achieve such a change, public interventions by governments and international consensus will be necessary, potentially reshaping how ecolabel markets organise themselves (e.g., through fusion, acquisition, and transformation of requirements). The Global Sustainable Tourism Council has been consolidating consulting efforts for the industry by establishing basic criteria for tourism stakeholders; however, further work is needed to evaluate and measure the effects of these initiatives. To meet these challenges, the framework seeks to offer the flexibility the tourism industry needs to achieve greater sustainability through modularity, one module at a time, as a tool to engage stakeholders and scholars on common ground.

6. Conclusions

The complex nature of tourism calls for adaptive sets of indicators tailored to destination characteristics, interactions shaping the tourism system, and stakeholders' scope of action to improve sustainability. This adaptability extends to eco-efficiency measures of resource production, consumption, and ecolabels, which vary based on the context and perspectives across the tourism supply chain. Each stakeholder (perspective) controls a scope of action and addresses issues proportional to their capacity to act. However, collectively, within the tourism system, each action contributes to a greater objective. Similarly, Purwaningsih et al. [25], Torres-Delgado & Saarinen [27], and Costa et al. [65] emphasise the necessity of involving a variety of stakeholders to implement actions at all levels for sustainable tourism. The modular approach was studied as an option to improve structure, standardisation, and robustness for modelling tourism sustainability evaluation and measurement. Modularity structures and breaks down tourism systems into standard modules that can be assembled on demand to fit each stakeholder's needs, enabling the study of the tourism system model according to evolving sustainability needs, characteristics, and appropriate evaluation tools, as well as various perspectives.

The need to adapt measurement to the application and context is essential in tourism. Consequently, this study proposes a modelling framework that is adaptable to tourism stakeholders (multiperspective) and contexts (dimensions), allowing for the study of sustainable tourism performance in a holistic, structured, flexible, and systemic manner through modular modelling. The application of two perspectives provides examples (scenarios) to construct a visual model and calculate its eco-efficiency based on a set of impact categories and variables. A study by Teigeiro et al. [59] also provides a real-world case study that applies the framework to two perspectives, thereby demonstrating its operation. Once established, a module structure can be reused in another scenario, allowing for the mixing and matching of modules to compare alternative tourism models with varying

resource consumption or production. The framework proposes a progressive and standardised approach for various purposes with an appropriate architecture that enables the combination of modules, updates, and adaptation to new needs and contexts for different stakeholders or purposes. The demonstration of the framework focuses on the environmental dimension of sustainability, and more research would be necessary to expand its application to other sustainability issues and how they contribute to eco-efficiency, that is, reducing impacts while creating economic growth and value. The study identifies ecolabels as a potential application, but more research is necessary to identify the practical challenges for integrating the framework into existing ecolabels schemes.

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Appendix A. Illustrative Application of Equation (5)

To illustrate the operationalisation of Equation (5), this appendix presents a simplified application from the supplier perspective. It compares a tourism basket of two 3-night energy technology scenarios for a small hotel, a fossil fuel baseline, and a renewable energy alternative. The matrices V , A , B , P , R , and F are populated with LCA values to compute comparative eco-efficiency indicators. This example demonstrates that the framework produces meaningful comparisons and isolates the contribution of individual matrix factors to eco-efficiency performance. A complete empirical application across multiple scenarios and perspectives is available in [59] for a halieutic outfitter.

Table A1. Matrix values by scenario.

Matrix	Tourism Factors	Parameters	Scenario A (Fossil) Values	Scenario B (Renewable) Values
V	Volume of tourists	$[1 \times 1]$	1	1
A	Touristic basket per tourist	$[1 \times q]$	1	1
B	Person.night per touristic basket	$[q \times a]$	3	3
P	Energy per person.night (MJ)	$[a \times d]$	120	45
R	CO ₂ eq per MJ (kg)	$[d \times b]$	0.15	0.07
F	Characterisation factor	$[b \times j]$	1	1

Values are illustrative only and do not correspond to a specific LCA dataset. $F = [1]$ because this example assesses a single midpoint impact category (climate change, kg CO₂eq) without aggregating into damage categories, as would be done using the characterisation factors of IMPACT World+.

Calculation

$$\text{Impact} = V \times A \times B \times P \times R \times F$$

$$\text{Scenario A: } 1 \times 1 \times 3 \times 120 \times 0.15 \times 1 = 54.0 \text{ kg CO}_2\text{eq per tourist}$$

$$\text{Scenario B: } 1 \times 1 \times 3 \times 45 \times 0.07 \times 1 = 9.5 \text{ kg CO}_2\text{eq per tourist}$$

Table A2. Eco-efficiency comparison.

	Scenario A (Fossil)	Scenario B (Renewable)
Impact per person.night (kg CO ₂ eq/person.night) = $P \times R \times F$	18.0	3.2
Impact per tourist (kg CO ₂ eq/tourist) = $A \times B \times P \times R \times F$	54.0	9.5

Interpretation

Eco-efficiency is measured here as the environmental impact per tourist, and the lower the value, the better the performance. Scenario B generates 3.2 kg CO₂eq per person.night compared to 18.0 kg CO₂eq for Scenario A, representing approximately six times less impact for the same night of service. Over the full 3-night stay, Scenario B emits 9.5 kg CO₂eq per tourist versus 54.0 kg CO₂eq for Scenario A.

The transition from fossil to renewable energy technology, reflected in matrices P and R, is the primary driver. It simultaneously reduces energy consumption per night (P from 120 to 45 MJ) and carbon intensity per MJ (R from 0.15 to 0.07 kg CO₂eq/MJ), improving eco-efficiency without altering the equation's structure or the level of service offered. For context, applying a carbon price of \$65/tonne CO₂eq would add \$3.51 per basket under Scenario A versus \$0.62 under Scenario B, illustrating that higher environmental impacts translate directly into greater economic exposure under carbon pricing mechanisms. Additional impact categories in matrix F and service modules, such as transportation or restauration, can be incorporated by expanding matrices R or B, without altering the equation's structure.

References

1. Sun, Y.-Y.; Faturay, F.; Lenzen, M.; Gössling, S.; Higham, J. Drivers of global tourism carbon emissions. *Nat. Commun.* **2024**, *15*, 10384. [CrossRef] [PubMed]
2. United Nations World Tourism Organization. International Tourism Recovers Pre-Pandemic Levels in 2024. Available online: <https://www.unwto.org/news/international-tourism-recovers-pre-pandemic-levels-in-2024> (accessed on 15 March 2026).
3. United Nations Environment Programme; World Tourism Organization. *Tourism in the Green Economy—Background Report*; UNWTO: Madrid, Spain, 2012. Available online: <https://www.unenvironment.org/explore-topics/resource-efficiency/what-we-do/responsible-industry/tourism> (accessed on 5 May 2024).
4. Butler, R.W. Sustainable tourism: A state-of-the-art review. *Tour. Geogr.* **1999**, *1*, 7–25. [CrossRef]
5. Filimonau, V. *Life Cycle Assessment (LCA) and Life Cycle Analysis in Tourism. A Critical Review of Applications and Implications*; Springer: Cham, Switzerland, 2016. [CrossRef]
6. Asmelash, A.G.; Kumar, S. Assessing progress of tourism sustainability: Developing and validating sustainability indicators. *Tour. Manag.* **2019**, *71*, 67–83, Erratum in *Tour. Manag.* **2019**, *74*, 438. [CrossRef]
7. Gössling, S.; Peeters, P.; Ceron, J.-P.; Dubois, G.; Patterson, T.; Richardson, R.B. The eco-efficiency of tourism. *Ecol. Econ.* **2005**, *54*, 417–434. [CrossRef]
8. Font, X. Environmental certification in tourism and hospitality: Progress, process and prospects. *Tour. Manag.* **2002**, *23*, 197–205. [CrossRef]
9. Prag, A.; Lyon, T.; Russillo, A. *Multiplication of Environmental Labelling and Information Schemes (ELIS): Implications for Environment and Trade*; OECD Environment Working Papers 106; OECD: Paris, France, 2016. [CrossRef]
10. Castellani, V.; Sala, S. Ecological Footprint and Life Cycle Assessment in the sustainability assessment of tourism activities. *Ecol. Indic.* **2012**, *16*, 135–147. [CrossRef]
11. Filimonau, V.; Dickinson, J.; Robbins, D. The carbon impact of short-haul tourism: A case study of UK travel to Southern France using life cycle analysis. *J. Clean. Prod.* **2014**, *64*, 628–638. [CrossRef]
12. Jere Jakulin, T. Systems Approach to Tourism: A Methodology for Defining Complex Tourism System. *Organizacija* **2017**, *50*, 208–215. [CrossRef]

13. De Camillis, C.; Peeters, P.; Petti, L.; Raggi, A. Tourism Life Cycle Assessment (LCA): Proposal of a New Methodological Framework for Sustainable Consumption and Production. In *Visions for Global Tourism Industry—Creating and Sustaining Competitive Strategies*; Kasimoglu, M., Ed.; InTech: Houston, TX, USA, 2012. [\[CrossRef\]](#) [\[PubMed\]](#)
14. World Business Council for Sustainable Development (WBCSD). Eco-Efficiency Learning Module. 2006. Available online: <https://docs.wbcsd.org/2006/08/EfficiencyLearningModule.pdf> (accessed on 9 February 2022).
15. Butler, R.W. Tourism carrying capacity research: A perspective article. *Tour. Rev.* **2019**, *75*, 207–211. [\[CrossRef\]](#)
16. Pásková, M.; Wall, G.; Zejda, D.; Zelenka, J. Tourism carrying capacity reconceptualization: Modelling and management of destinations. *J. Destin. Mark. Manag.* **2021**, *21*, 100638. [\[CrossRef\]](#)
17. Sun, Y.; Hou, G.; Huang, Z.; Zhong, Y. Spatial-Temporal Differences and Influencing Factors of Tourism Eco-Efficiency in China's Three Major Urban Agglomerations Based on the Super-EBM Model. *Sustainability* **2020**, *12*, 4156. [\[CrossRef\]](#)
18. Cadarso, M.Á.; Gómez, N.; López, L.A.; Tobarra, M.Á. Calculating tourism's carbon footprint: Measuring the impact of investments. *J. Clean. Prod.* **2016**, *111*, 529–537. [\[CrossRef\]](#)
19. Nguyen, H.A.T.; Gheewala, S.H.; Sophea, T.; Areerob, T.; Hashimoto, K.; Pimonsree, S.; Prueksakorn, K. Comparative carbon footprint assessment of agricultural and tourist locations in Thailand. *J. Clean. Prod.* **2020**, *269*, 122407. [\[CrossRef\]](#)
20. Papargyropoulou, E.; Wright, N.; Lozano, R.; Steinberger, J.; Padfield, R.; Ujang, Z. Conceptual framework for the study of food waste generation and prevention in the hospitality sector. *Waste Manag.* **2016**, *49*, 326–336. [\[CrossRef\]](#) [\[PubMed\]](#)
21. Thamagasorn, M.; Pharino, C. An analysis of food waste from a flight catering business for sustainable food waste management: A case study of halal food production process. *J. Clean. Prod.* **2019**, *228*, 845–855. [\[CrossRef\]](#)
22. Liu, J.; Zhang, J.; Fu, Z. Tourism eco-efficiency of Chinese coastal cities—Analysis based on the DEA-Tobit model. *Ocean Coast. Manag.* **2017**, *148*, 164–170. [\[CrossRef\]](#)
23. Lu, F.; Qin, W.; Wang, Y.-X. Research on Spatial Pattern Dynamic Evolution Algorithm and Optimization Model Construction and Driving Mechanism of Provincial Tourism Eco-Efficiency in China under the Background of Cloud Computing. *Sci. Program.* **2021**, *2021*, 1951264. [\[CrossRef\]](#)
24. Peng, H.; Zhang, J.; Lu, L.; Tang, G.; Yan, B.; Xiao, X.; Han, Y. Eco-efficiency and its determinants at a tourism destination: A case study of Huangshan National Park, China. *Tour. Manag.* **2017**, *60*, 201–211. [\[CrossRef\]](#)
25. Purwaningsih, R.; Agusti, F.; Pranomo, S.N.W.; Susanty, A.; Purwanggono, B. Assessment sustainable tourism: A literature review composite indicator. *E3S Web Conf.* **2020**, *202*, 03001. [\[CrossRef\]](#)
26. Tanguay, G.A.; Rajaonson, J.; Therrien, M.-C. Sustainable Tourism Indicators: Selection Criteria for Policy Implementation and Scientific Recognition. *SSRN Electron. J.* **2011**. [\[CrossRef\]](#)
27. Torres-Delgado, A.; Saarinen, J. Using indicators to assess sustainable tourism development: A review. *Tour. Geogr.* **2013**, *16*, 31–47. [\[CrossRef\]](#)
28. Berners-Lee, M.; Howard, D.C.; Moss, J.; Kaivanto, K.; Scott, W.A. Greenhouse gas footprinting for small businesses—The use of input-output data. *Sci. Total Environ.* **2011**, *409*, 883–891. [\[CrossRef\]](#) [\[PubMed\]](#)
29. Schianetz, K.; Kavanagh, L.; Lockington, D. Concepts and Tools for Comprehensive Sustainability Assessments for Tourism Destinations: A Comparative Review. *J. Sustain. Tour.* **2007**, *15*, 369–389. [\[CrossRef\]](#)
30. Gössling, S.; Humpe, A.; Sun, Y.-Y. Are emissions from global air transport significantly underestimated? *Curr. Issues Tour.* **2025**, *28*, 695–708. [\[CrossRef\]](#)
31. Míguez, J.L.; Rivo-López, E.; Porteiro, J.; Pérez-Orozco, R. Selection of non-financial sustainability indicators as key elements for multi-criteria analysis of hotel chains. *Sustain. Prod. Consum.* **2023**, *35*, 495–508. [\[CrossRef\]](#)
32. Kitamura, Y.; Ichisugi, Y.; Karkour, S.; Itsubo, N. Carbon Footprint Evaluation Based on Tourist Consumption toward Sustainable Tourism in Japan. *Sustainability* **2020**, *12*, 2219. [\[CrossRef\]](#)
33. Mancini, M.; Evans, M.; Iha, K.; Danelutti, C.; Galli, A. Assessing the Ecological Footprint of Ecotourism Packages: A Methodological Proposition. *Resources* **2018**, *7*, 38. [\[CrossRef\]](#)
34. Torres-Delgado, A.; Palomeque, F.L. Measuring sustainable tourism at the municipal level. *Ann. Tour. Res.* **2014**, *49*, 122–137. [\[CrossRef\]](#)
35. Candia, S.; Pirlone, F. Tourism Environmental Impacts Assessment to Guide Public Authorities towards Sustainable Choices for the Post-COVID Era. *Sustainability* **2021**, *14*, 18. [\[CrossRef\]](#)
36. Filimonau, V.; Dickinson, J.; Robbins, D.; Reddy, M.V. The role of 'indirect' greenhouse gas emissions in tourism: Assessing the hidden carbon impacts from a holiday package tour. *Transp. Res. Part Policy Pract.* **2013**, *54*, 78–91. [\[CrossRef\]](#)
37. Buckley, R. Tourism ecolabels. *Ann. Tour. Res.* **2002**, *29*, 183–208. [\[CrossRef\]](#)
38. Buckley, R. Tourism and environment. *Annu. Rev. Environ. Resour.* **2011**, *36*, 397–416. [\[CrossRef\]](#)
39. Gössling, S.; Buckley, R. Carbon labels in tourism: Persuasive communication? *J. Clean. Prod.* **2016**, *111*, 358–369. [\[CrossRef\]](#)
40. ISO 14020:2022; Environmental Statements and Programmes for Products—Principles and General Requirements. International Organization for Standardization: Geneva, Switzerland, 2022.

41. ISO 14025:2006; Environmental Labels and Declarations—Type III Environmental Declarations—Principles and Procedures. International Organization for Standardization: Geneva, Switzerland, 2006.
42. Campagnolo, D.; Camuffo, A. The concept of modularity in management studies: A literature review. *Int. J. Manag. Rev.* **2010**, *12*, 259–283. [\[CrossRef\]](#)
43. Ethiraj, S.K.; Levinthal, D. Modularity and Innovation in Complex Systems. *Manag. Sci.* **2004**, *50*, 159–173. [\[CrossRef\]](#)
44. Avlonitis, V.; Hsuan, J. Exploring modularity in services: Cases from tourism. *Int. J. Oper. Prod. Manag.* **2017**, *37*, 771–790. [\[CrossRef\]](#)
45. Langlois, R.N. Modularity in technology and organization. *J. Econ. Behav. Organ.* **2002**, *49*, 19–37. [\[CrossRef\]](#)
46. Rumbaugh, J.; Blaha, M.; Premerlani, W.; Eddy, F.; Lorensen, B. *Object-Oriented Modeling And Design*; Prentice-Hall International Editions; Prentice Hall: Englewood Cliffs, NJ, USA, 1991.
47. Buxmann, K.; Kistler, P.; Rebitzer, G. Independent information modules—A powerful approach for life cycle management. *Int. J. Life Cycle Assess.* **2009**, *14*, 92–100. [\[CrossRef\]](#)
48. Gadre, S.; Esterman, M.; Thorn, B.K. Implementation of an Object-Oriented Life Cycle Assessment Framework Using Functional Analysis and Systems Engineering Principles. In *ASME 2017 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*; American Society of Mechanical Engineers Digital Collection: Rochester, NY, USA, 2017. [\[CrossRef\]](#)
49. Groetsch, T.; Creighton, C.; Varley, R.; Kaluza, A.; Dér, A.; Cerdas, F.; Herrmann, C. A modular LCA/LCC-modelling concept for evaluating material and process innovations in carbon fibre manufacturing. *Procedia CIRP* **2021**, *98*, 529–534. [\[CrossRef\]](#)
50. Gu, P.; Hashemian, M.; Sosale, S.; Rivin, E. An Integrated Modular Design Methodology for Life-Cycle Engineering. *CIRP Ann.* **1997**, *46*, 71–74. [\[CrossRef\]](#)
51. Spykman, R.; Hossaini, S.M.; Peguero, D.A.; Green, A.; Heinz, V.; Smetana, S. A modular environmental and economic assessment applied to the production of *Hermetia illucens* larvae as a protein source for food and feed. *Int. J. Life Cycle Assess.* **2021**, *26*, 1959–1976. [\[CrossRef\]](#)
52. Filimonau, V.; Dickinson, J.E.; Robbins, D.; Reddy, M.V. A critical review of methods for tourism climate change appraisal: Life cycle assessment as a new approach. *J. Sustain. Tour.* **2011**, *19*, 301–324. [\[CrossRef\]](#)
53. Miralles, C.C.; Roura, M.B.; Salas, S.P.; Argelaguet, L.L.; Jordà, J.C. Assessing the socio-economic impacts of tourism packages: A methodological proposition. *Int. J. Life Cycle Assess.* **2024**, *29*, 1096–1115. [\[CrossRef\]](#)
54. Lonca, G.; Bernard, S.; Margni, M. A versatile approach to assess circularity: The case of decoupling. *J. Clean. Prod.* **2019**, *240*, 118174. [\[CrossRef\]](#)
55. Sigala, M. A supply chain management approach for investigating the role of tour operators on sustainable tourism: The case of TUI. *J. Clean. Prod.* **2008**, *16*, 1589–1599. [\[CrossRef\]](#)
56. Camilleri, M.A. The Tourism Industry: An Overview. In *Travel Marketing, Tourism Economics and the Airline Product: An Introduction to Theory and Practice*; Camilleri, M.A., Ed.; Springer international Publishing: Cham, Switzerland, 2018.
57. Font Vivanco, D.; Kemp, R.; van der Voet, E.; Heijungs, R. Using LCA-based Decomposition Analysis to Study the Multidimensional Contribution of Technological Innovation to Environmental Pressures. *J. Ind. Ecol.* **2014**, *18*, 380–392. [\[CrossRef\]](#)
58. Sun, Y.-Y.; Lin, P.-C.; Higham, J. Managing tourism emissions through optimizing the tourism demand mix: Concept and analysis. *Tour. Manag.* **2020**, *81*, 104161. [\[CrossRef\]](#) [\[PubMed\]](#)
59. Teigeiro, S.; Bernard, S.; Frayret, J.-M. *Tourism Eco-Efficiency Through a Modular Lens 2026*; CIRANO Working Papers 2026s-09; CIRANO: Montreal, QC, Canada, 2026. [\[CrossRef\]](#)
60. Bulle, C.; Margni, M.; Patouillard, L.; Boulay, A.-M.; Bourgault, G.; De Bruille, V.; Cao, V.; Hauschild, M.; Henderson, A.; Humbert, S.; et al. IMPACT World+: A globally regionalized life cycle impact assessment method. *Int. J. Life Cycle Assess.* **2019**, *24*, 1653–1674. [\[CrossRef\]](#)
61. Graedel, T.E. Life-Cycle Assessment in the Service Industries. *J. Ind. Ecol.* **1997**, *1*, 57–70. [\[CrossRef\]](#)
62. Bjørn, A.; Hauschild, M.Z. Introducing carrying capacity-based normalisation in LCA: Framework and development of references at midpoint level. *Int. J. Life Cycle Assess.* **2015**, *20*, 1005–1018. [\[CrossRef\]](#)
63. Claude, D.; Zaccour, G. Investment in tourism market and reputation. *J. Public Econ. Theory* **2009**, *11*, 797–817. [\[CrossRef\]](#)
64. Fernandes Martins, K.; Teixeira, D.; De Oliveira Corrêa, R. Gains in sustainability using Voluntary Sustainability Standards: A systematic review. *Clean. Logist. Supply Chain* **2022**, *5*, 100084. [\[CrossRef\]](#)
65. Costa, M.d.O.; Proença, A.R.G.B.; Solha, K.T.; Pinto, G.P. *Turismo Responsável: Resultados que Inspiram!*; Portal de Livros Abertos da USP: São Paulo, Brazil, 2024. [\[CrossRef\]](#)

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