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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, multidimensional and multiperspective modular modelling framework for analysing tourism's production and consumption systems. The framework aims to provide a common framework that allows for standardisation, structure, and flexibility in assessing and measuring tourism sustainability, with a particular focus on 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 standardized eco-labels in the tourism industry.

Keywords: Sustainable tourism; eco-efficiency; modularity; multiperspective; multidimension; ecolabel.

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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 CO_2-equivalent in 2019. This accounts for approximately 8.8% of total global greenhouse gas emissions (Y.-Y. Sun et al., 2024). In 2024, the tourism sector officially recovered to pre-COVID-19 levels of 2019, with 1.4 billion international tourist arrivals globally (UNWTO, 2025). 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 (2012), 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 (Asmelash & Kumar, 2019; Butler, 1999; Filimonau, 2016). 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 efficiency must continuously improve to keep tourism within planetary boundaries (Gössling et al., 2005a). 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 (Font, 2002), such as practice-based standards (Prag et al., 2016). 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 (Filimonau, 2016). 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) (Castellani & Sala, 2012; Filimonau et al., 2014)). Jere Jakulin (2017) 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. 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 centralized 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 that 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 standardizing and organizing 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 (2012), expanding tourism perspectives and evaluation tools to better address sustainability challenges.

While the focus of this paper is on eco-efficiency, it acknowledges the importance of other sustainability dimensions (e.g., social and cultural) for 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.

This paper begins with a literature review on the emergence and current application of ecoefficiency 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 LITERATURE REVIEW

2.1 Tourism eco-efficiency

Introduced in the 1990s, the eco-efficiency concept aims to strike a balance between compromises and continuous improvements, anticipating consumption alternatives based on environmental and economic data. Recognized by the World Business Council for Sustainable Development (2006), eco-efficiency aims to create equal or greater value to satisfy human needs with less environmental impact, adhering to the Earth's limits. While it underscores carrying capacity as a threshold for economic development, this notion of limits is politically unpopular (Butler, 2019) and context-dependent (Pásková et al., 2021). Gössling et al. (2005a) introduced the concept of eco-efficiency in the tourism literature, suggesting the benchmarking of tourism emissions per unit of value against the 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 (Gössling et al., 2005a).

Sun et al. (2020) identify three methods in the literature for measuring 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 (Y. Sun et al., 2020), have been applied in various scopes and contexts (Cadarso et al., 2016; Gössling et al., 2005a; Nguyen et al., 2020; Papargyropoulou et al., 2016; Thamagasorn & Pharino, 2019). Index system methods, created by indicators to measure eco-efficiency, can be applied at various scales (Gössling et al., 2005a). Model methods involve advanced nonparametric analysis models such as DEA (data envelopment analysis), which are suitable for regional-scale analysis to study spatial and temporal developments (Liu et al., 2017; Lu et al., 2021; Y. Sun et al., 2020).

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., CO2 eq. emissions and solid waste management). Index systems could support the evaluation of tourism package eco-efficiency, as they are well-suited to complex social, economic, and natural systems at regional scales. However, they are criticized for the subjective weighting in results evaluation (Peng et al., 2017).

2.2 Evaluation tools and tourism evaluation models

Despite advancements in evaluation tools in the tourism literature, proposed indicators (Asmelash & Kumar, 2019), and tourism impact evaluations, these remain disparate in their methods, scope, impact spectra, and tool combinations. The diversity complicates the comparisons and decision-making for stakeholders with varying objectives. Tourism studies employ a wide range of evaluation tools, from environmental sciences, engineering or social science, focusing on specific indicators (e.g., climate change, waste generation), tourism products and services or sectors (e.g., transportation and accommodation), types of tourism (e.g., ecotourism, urban, sports, events), scales of analysis (e.g., products and services, holiday packages, destinations and geographic scales), and perceptions (e.g., tourists, tour operators and governments) for different purposes (e.g., regulatory compliance, competitiveness, United Nations objectives, etc.). Authors have identified various sustainable tourism indicators tailored to specific stakeholder categories (Purwaningsih et al., 2020) and those suitable for different destinations, thereby aligning the academic and political realms for operationalization (Tanguay et al., 2011). Arzoumanidis et al. (2021) analyse potential life cycle-based sustainability and circularity indicators related to the hospitality sector, while Torres-Delgado and Saarinen (2013) investigate the role of indicators for a sustainable tourism transition and review the pros and cons of simple and combined indicators versus indexes at various scales. Despite the search for an ideal set of indicators, challenges such as data accessibility and subjective interpretation persist (Torres-Delgado & Saarinen, 2013). These studies indicate that multiple viewpoints are essential, as stakeholders both impact and are impacted by tourism sustainability.

Current models fail to capture the global complexity of tourism, and studies often remain incomparable unless disaggregated (Berners-Lee et al., 2011; Cadarso et al., 2016). On the other hand, studies mention the need to combine tools to enhance evaluation robustness and bypass limitations (Cadarso et al., 2016; Castellani & Sala, 2012; Schianetz et al., 2007); however, this increases the complexity of measuring tourism eco-efficiency. Various tools analyse different tourism aspects: Greenhouse Gas (GHG) Protocol for air transportation (Gössling et al., 2024), a hybrid multi-criteria approach for hotel chains' sustainability indicators (Míguez et al., 2023), Input-Output (I-O) approach for Japan's tourism carbon footprint (Kitamura et al., 2020), Material Flow Analysis (MFA) for food waste in-flight catering (Thamagasorn & Pharino, 2019), Ecological Footprint (EF) Analysis for ecotourism packages (Mancini et al., 2018), Data Envelope Analysis (DEA) for Chinese coastal cities' eco-efficiency (Liu et al., 2017), Life Cycle Assessment (LCA) for tourism components (Filimonau, 2016) and Sustainability Indicators (SI) at the municipal level (Torres-Delgado & Palomeque, 2014). Tool combinations such as LCA and I-O methods (Berners-Lee et al., 2011) and LCA and EF (Castellani & Sala, 2012). In the food supply chains, life cycle eco-efficiency has been applied to products and their sub-sectors to identify eco-efficiency improvements (Konstantas et al., 2020). Though insightful, tool applications remain limited due to methodological weaknesses and practical challenges (Filimonau, 2016).

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 (Candia & Pirlone, 2021; Castellani & Sala, 2012; Filimonau, 2016; Filimonau et al., 2013). These models serve different purposes and lack a standard consensus. More flexible and standardised evaluation models and ecolabels (Font, 2002) could improve data reuse across contexts, enhancing eco-efficiency measures within the tourism system's complexity.

Considering multiple perspectives and dimensions that define the context (scale, time, scope) while acknowledging the need to combine tools for comprehensive tourism eco-efficiency adds to the evaluation complexity, alongside considerations of carrying capacities. Although further development of carrying capacities is beyond the scope of this study, it acknowledges their critical role as the foundation of sustainable tourism, requiring joint consideration by all tourism stakeholders.

2.3 Tourism ecolabel

Ecolabels provide information about a product before the purchase decision (Buckley, 2002, 2011) and aim to enhance the environmental performance of the applicants, driven by market forces, peer pressure, or subsidies (Font, 2002). 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, including destinations, tour operators, hotels, and MICE tourism (which stands for meetings, incentives, conferences, and exhibitions), as guidelines for certifications. These guidelines specify what should be done but not how, nor what to measure or the suggested thresholds. Buckley (2002) notes that effective tourism ecolabels should be customizable to the context of different countries, ecosystems, and activities. Conversely, Font (2002) 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 (Font, 2002), impeding international standardisation (Buckley, 2011; Font, 2002; Gössling & Buckley, 2016). The International Organization for Standardization offers a family of standardised guidelines for applying ecolabels (ISO, 2022). Type III ecolabels inform buyers about the performance of a product or service's life cycle, for comparison purposes (ISO, 2006). 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

As briefly discussed, the concept of modularity could benefit the complex tourism system by providing a structured depth of analysis. The literature explores modularity in several contexts, addressing management (Campagnolo & Camuffo, 2010), innovation (Ethiraj & Levinthal, 2004), service design (Avlonitis & Hsuan, 2017) and organisational economic issues (Langlois, 2002). These studies decompose complex systems into so-called "modules", revealing their compositions, interactions or interdependencies (Langlois, 2002). Avlonitis et al. (2017) note that modularity research aligns with modularity multi-level analysis, and is cohesive when services are examined from a systems theory angle, as modularity is a general characteristic of systems.

The service sector has yet to fully exploit modularity for sustainability purposes, while two studies investigate the advantages of scaling and updating the life cycle model using reusable independent modules. One study integrates modularity (Buxmann et al., 2009), while the other applies object-oriented modelling (Gadre et al., 2017) to the life cycle approach, standardising modules for different applications and increasing flexibility and reusability. Object-oriented modelling methods reduce complexity by representing the structure of real-world systems in a simplified manner, originally used to structure software data and its behaviours (Rumbaugh et al., 1991). This method identifies and classifies system components and behaviours as general modules to reproduce and analyse real-world instances. Modularity is well-suited for examining the complexity of tourism, as it allows for the organization and definition of its components into distinct modules. For example, analyzing various tourism perspectives, such as those of supply chain actors, through modularity would involve scaling, mixing, and matching tourism resources or products and services modules based on environmental evaluation and labelling schemes.

2.5 Gaps' 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 (Candia & Pirlone, 2021; Filimonau et al., 2011, 2013; Gössling et al., 2005b; Miralles et al., 2024), 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.

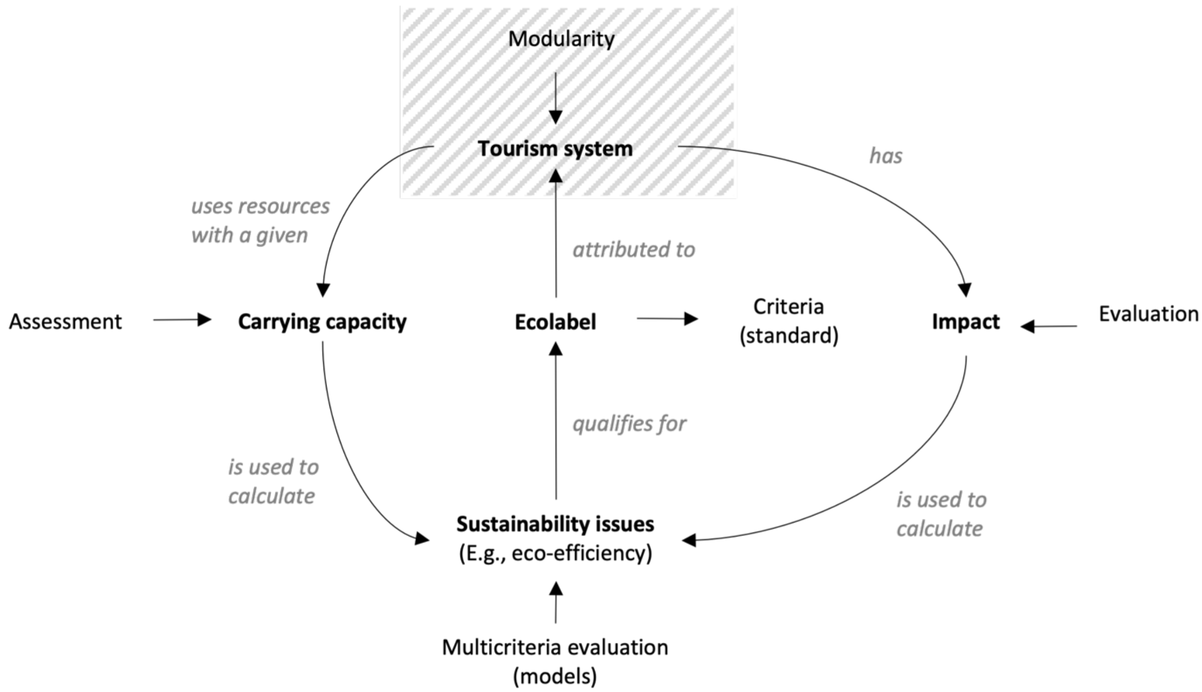


Figure 1 Literature review mapping illustrating how the concepts interconnect

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 eco-labels. 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 (Schianetz et al., 2007), 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.

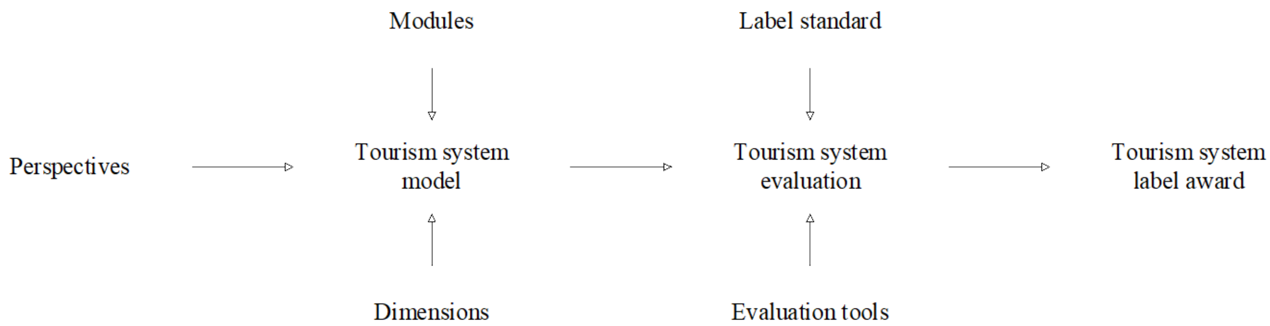


Figure 2 Logical sequence applied to the concepts' use

4 CONCEPTUAL MODELS TO MEASURE TOURISM ECO-EFFICIENCY

4.1 *Tourism multidimensional and multiperspective eco-efficiency framework*

4.1.1 *Concepts supporting the 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. The tourism system model in Figure 4 is inspired by the object-oriented modelling method to apply modularity.

Second, eco-efficiency aims to reduce environmental impact while fostering economic growth, also known as decoupling (Lonca et al., 2019). Despite criticism that index system methods limit the isolation of indirect influences (Y. Sun et al., 2020), they remain useful for evaluating impacts across scales (Gössling et al., 2005a). 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, eco-labels could be used to communicate eco-efficiency status or improvements. 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. (2012), 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. The framework has the potential to incorporate eco-labels from different perspectives to ensure coherence and uniformity.

*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, using the model to study inputs and outputs (resources) throughout the life cycle to offer competitive, 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, involving selecting service providers based on overall sustainable performance (supplier A versus B), choices among accommodations (hotel A, room 1 versus room 2), activities, restauration 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 (Sigala, 2008). They can integrate eco-efficient options of products and services into their packages. Although consumer values, preferences and social norms are not directly reflected in the framework, they may be considered through consumption patterns with the general equation by selecting as a preference by choosing certain 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 centers, etc.) at various spatial scales (e.g., municipal, regional, and national levels), or for specific impacts or resources that threaten carrying capacities.

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, periods covered (e.g., cumulative impacts or duration), or sustainability scope like the technosphere (e.g., technological change in resource efficiency), ecosphere (e.g., environmental changes) or even sociosphere aspects (e.g., human social interactions). Lastly, dynamic effects can be assessed using non-linear models or simulations with feedback loops.

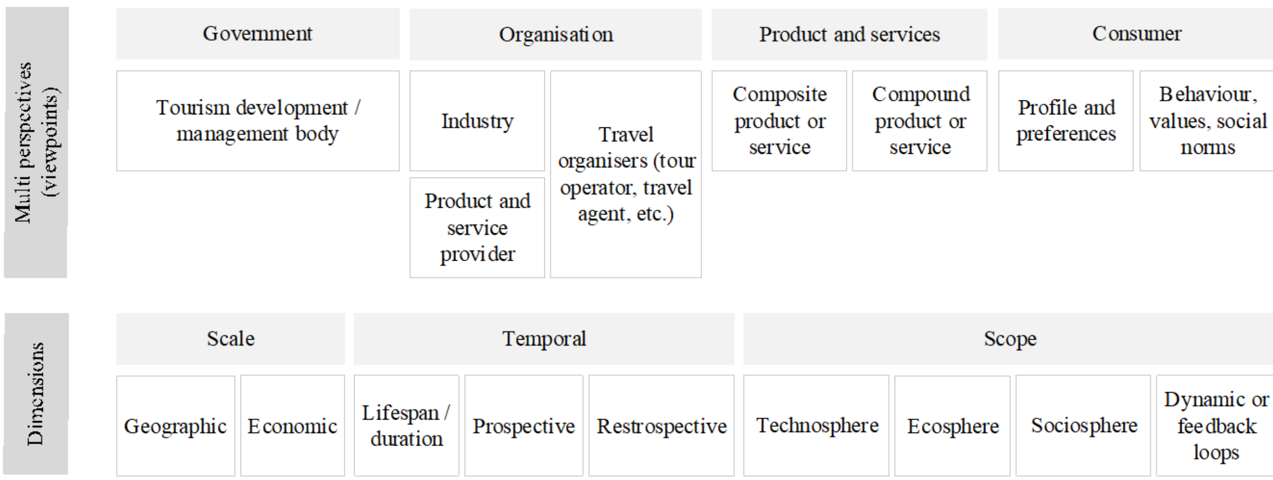


Figure 3 Multiple perspectives and dimensions

4.2.1 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. 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. The 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.

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, restauration, 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 (Camilleri, 2018), 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.

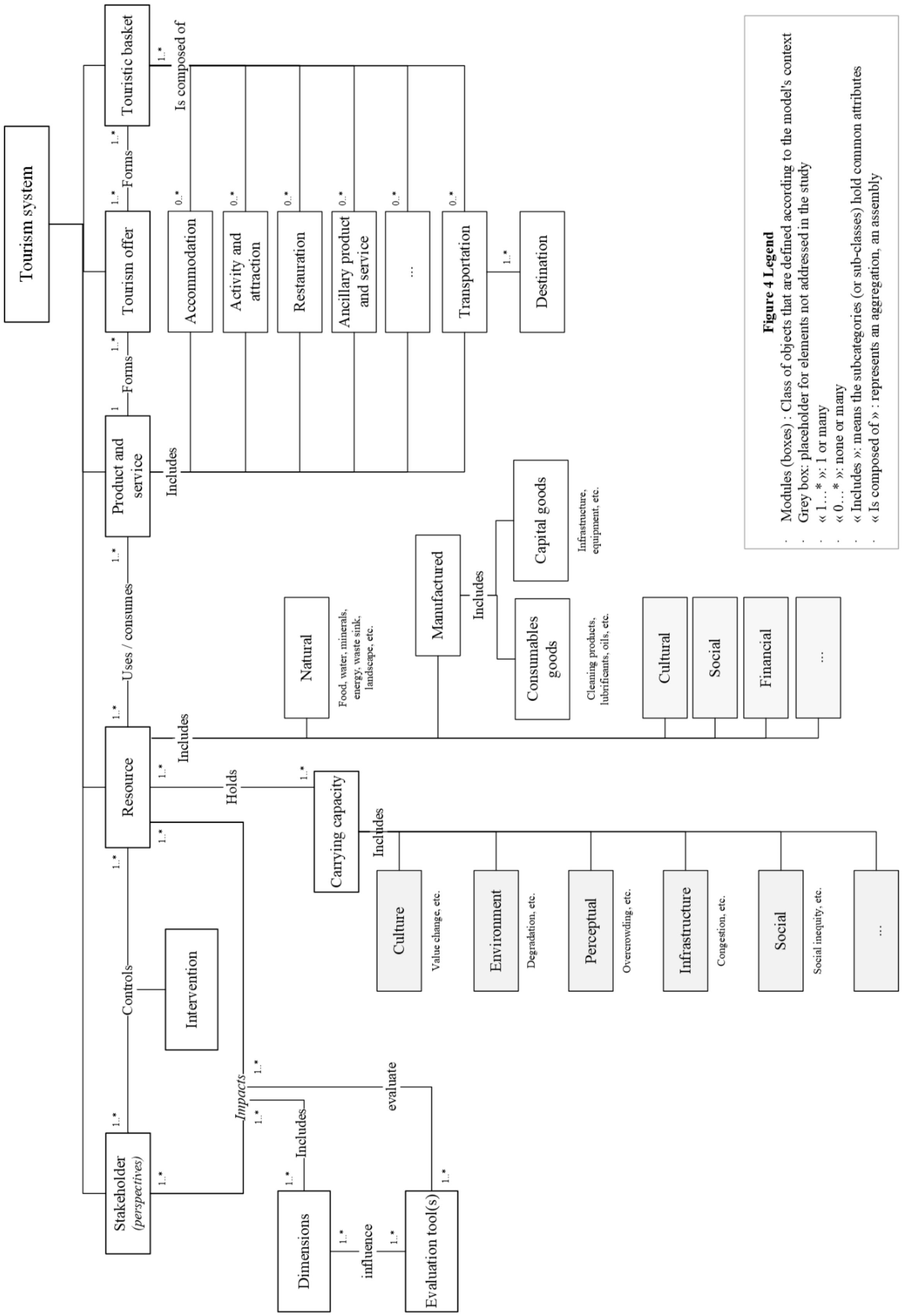


Figure 4 Modular tourism system model illustrates the tourism modules, their relationships (links)

4.2.2 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. This equation is then applied to two specific cases (Figure 5). 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 (Lonca et al., 2019). Lonca et al. (2019) 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. (2014) 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 the impacts on product and product systems' life cycles (Font Vivanco et al., 2014).

$$i = p * A * T \tag{1}$$

$$Impact = Population * Affluence * Technology \tag{2}$$

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

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

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, product and service 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 (Font Vivanco et al., 2014; Lonca et al., 2019). 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 (Y.-Y. Sun et al., 2020). 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 Table 1, 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.

$$Impact = VABPRF \tag{5}$$

Table 1 Tourism eco-efficiency drivers included in the matrix and their respective tourism factors associated (inspired by Sun et al. (2020)

Factors	Volume	Consumption level (affluence)		Resource efficiency (technology)		Characterisation factor (CF)
Matrix (or vector)	*V*	*A*	*B*	*P*	*R*	*F*
Parameters	*[1*1]*	*[1*q]*	*[q*a]*	*[a*d]*	*[d*b]*	*[b*j]*
Tourism factors	Tourists	Touristic baskets / Tourist	PSs / Touristic basket	Resources / PS	Impacts / Resource	Damage category CF / Impact

When studied from the supplier perspective, a *q* supplier touristic basket is a collection of products and services among the *a* market tourism offers made from a collection of *d* resources (manufactured or natural). The *j* impact category per product or service is *b* impacts per *d* resource. For example, the *d* resources consumed by *q* hotel, 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 *b* impacts or *j* damage categories 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.nights, 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 impacts 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.

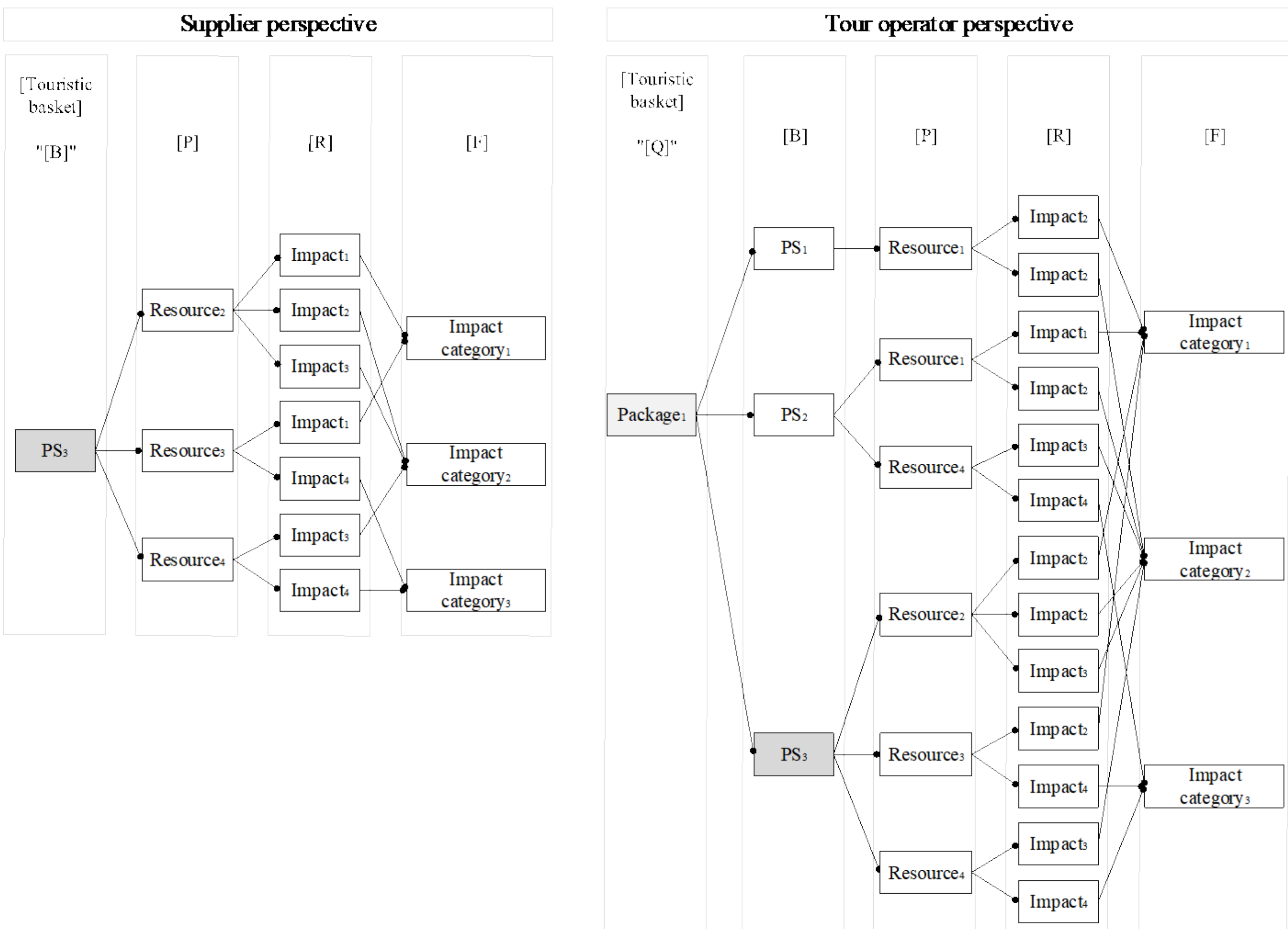
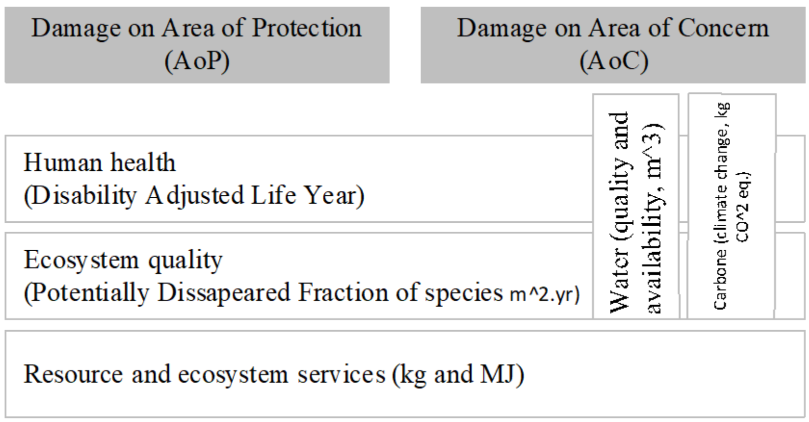


Figure 5 Tree nomenclatures for a supplier and a tour operator perspective

4.2.3 *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, such as 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 (Filimonau et al., 2013). The life cycle assessment method



IMPACT World+ (Figure 6) includes 21 types of damage indicators from the economic system's interactions with the environment, such as 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 (Bulle et al., 2019). 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. [2019])

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 (Filimonau et al., 2013) and the specific stages of a service at a destination site (Graedel, 1997). 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.

Graedel (1997)	Filimonau et al. (2013)	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

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.

Table 2 Adapted from Filimonau (2013) and Graedel (1997), the table presents 4 scopes and 5 life stages to evaluate the environmental impacts of the tourism sectorn

Then, integrating carrying capacities into the model would require a combination of tools, as demonstrated by Bjørn & Hauschild (2015) or Castellani & Sala (2012), 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, and its weight into the carrying capacity "inventories". To consider carrying capacities in the model, as outlined in equation (5), thresholds could be included in the impact matrix.

As done by Schianetz et al. (2007) 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 (Font Vivanco et al., 2014) from different perspectives through modularity (Buxmann et al., 2009; Gadre et al., 2017). It offers extensive environmental impact assessment (Schianetz et al., 2007) and provides an overview of environmental trade-offs (Buxmann et al., 2009). Additionally, the combination of assessment tools addresses shortcomings (Schianetz et al., 2007), benefiting the different perspectives addressed by the modular equation (5).

Economic tools	*Flow analysis*	*Environmental tools*	*Multipurpose tools*	*Reporting and compliance*
Input-Output (I-O)	*Substance Flow Analysis (SFA)*	*Ecological Footprint Analysis (EFA)*	*Agent-based modelling*	*Greenhouse Gas (GHG) Protocol*
Partial Equilibrium (PE)	*Material Flow Analysis (MFA)*	*Environmental Impact Assessment*	*System dynamics*	*Environmental Audits*
Computable General Equilibrium (CGE)	*Life cycle assessment (LCA)*	*Biocapacity method*	*Sustainability Indicators*	
Data Envelope Analysis (DEA)			*Multi-Criteria Analysis (MCA)*	
Eco-efficiency indicators/ratios			*Adaptive Environmental Assessment*	

Table 3 Evaluation tools categories (based on Schianetz et al. (2007) with modifications)

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. A potential modular ecolabelling scheme is then discussed, 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 3, 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.Following the modelling and the 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 (International Organization for Standardization, 2006). 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 standardizing 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. Example 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 recommendations systems, smart infrastructure, renewable energy), and evolving governance (e.g., policy and regulation) and scientific evaluation tools (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, accounting for these changes - reflected through increases, reductions, or substitutions in production and consumption in the general equation. The framework also supports 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.

Just as indicators used in tourism to evaluate its sustainability are influenced by specific socio-spatial context and scales (Torres-Delgado & Saarinen, 2013), the framework allows modelling different scales depending on the perspective considered 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 the industry stakeholders in future research, such as 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 (Fernandes Martins et al., 2022); 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 and combinations for tourism perspectives, as done by Schianetz et al. (2007) to assess tourism destinations.

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. Furthermore, improving eco-efficiency can positively impact environmental carrying capacity while also potentially exacerbating other carrying capacity issues simultaneously. 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 their reliability and credibility, as well as the impact on the industry's profitability and data accessibility.

Finally, integrating the proposed framework with a labelling scheme without overwhelming the industry is a challenge. 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 measurement tools to identify needed improvements and communicate progress robustly and accurately. 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 these measures. 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 around common grounds.

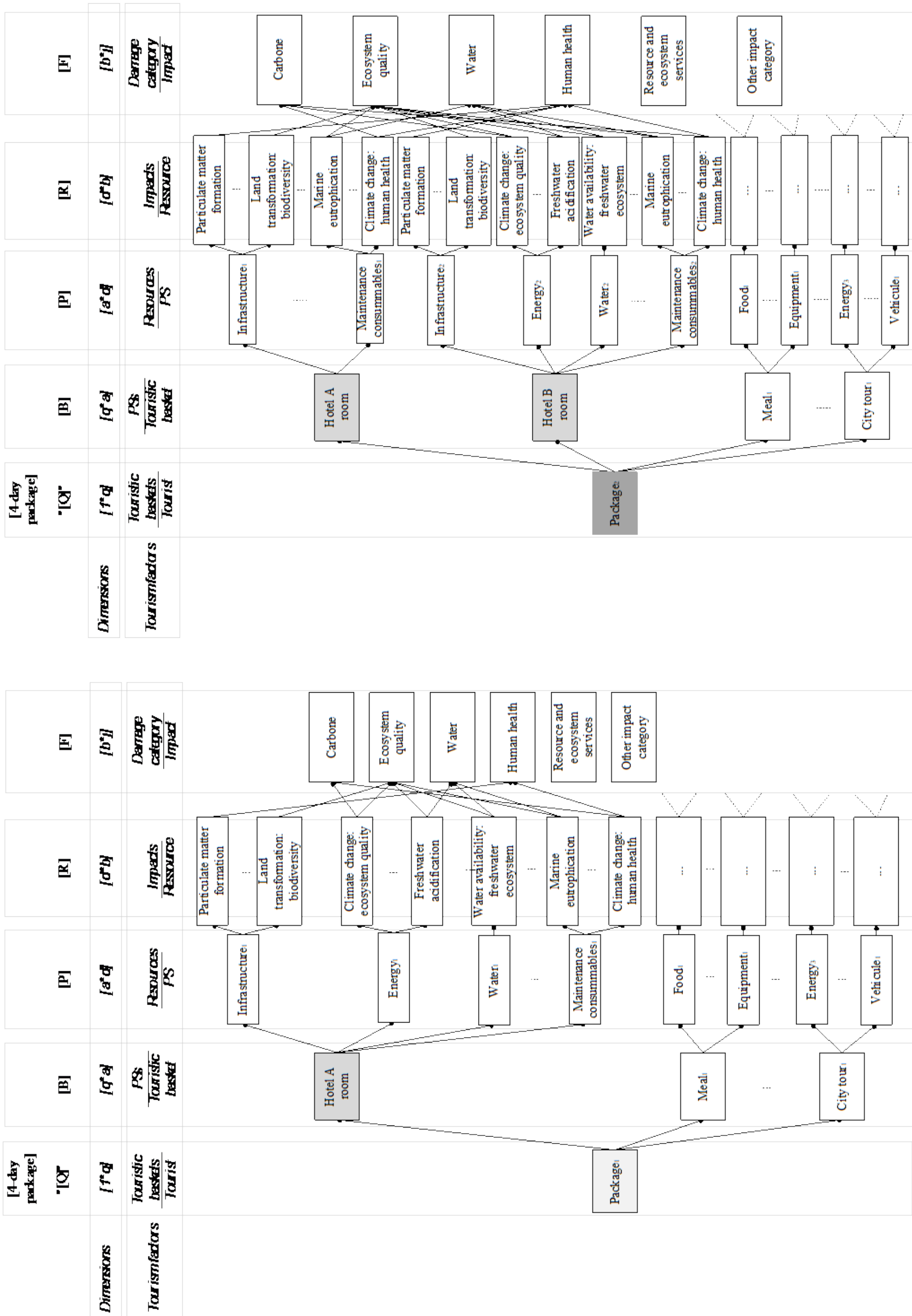


Figure 7 Example comparing two 4-day packages to demonstrate the use of modularity visually, and applied with the general equation (5)

6 CONCLUSION

The complex nature of tourism calls for adaptive sets of indicators tailored to destination characteristics, the 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. (2020), Torres-Delgado & Saarinen (2013), and Costa et al. (2024) 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 a variety of perspectives.

The need to adapt measurement to the application and context is essential in tourism. Consequently, this study proposes a modelling framework adaptable to tourism stakeholders (multiperspective) and context (dimensions) to study sustainable tourism performance in a holistic, structured, flexible, and systemic way 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. 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, such as ecolabel applications, with an appropriate architecture that enables the combination of modules, updates, and adaptation to new needs and contexts for different stakeholders or purposes.

7 DECLARATION OF INTEREST STATEMENT

The authors declare no competing interests.

8 AUTHOR CONTRIBUTIONS WITH CReDiT ROLES

Sarah Teigeiro, Sophie Bernard, Jean-Marc Frayret: Conceptualisation, Methodology, Formal analysis, Writing – Review & Editing, Visualisation, Sophie Bernard, Jean-Marc Frayret: Supervision, Sarah Teigeiro: Investigation, Resources, Data curation, Writing – Original Draft, Project administration, Funding acquisition. All authors approved the paper and agreed to its submission for publication.

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11 REFERENCES

Arzoumanidis, I., Walker, A. M., Petti, L., & Raggi, A. (2021). Life Cycle-Based Sustainability and Circularity Indicators for the Tourism Industry: A Literature Review. *Sustainability*, *13*(21), Article 21. https://doi.org/10.3390/su132111853

Asmelash, A. G., & Kumar, S. (2019). Assessing progress of tourism sustainability: Developing and validating sustainability indicators. *Tourism Management*, *71*, 67–83. https://doi.org/10.1016/j.tourman.2018.09.020

Avlonitis, V., & Hsuan, J. (2017). Exploring modularity in services: Cases from tourism. *International Journal of Operations & Production Management*, *37*(6), 771–790. https://doi.org/10.1108/ijopm-08-2015-0531

Berners-Lee, M., Howard, D. C., Moss, J., Kaivanto, K., & Scott, W. A. (2011). Greenhouse gas footprinting for small businesses—The use of input-output data. *The Science of the Total Environment*, *409*(5), 883–891. https://doi.org/10.1016/j.scitotenv.2010.11.023

Bjørn, A., & Hauschild, M. Z. (2015). Introducing carrying capacity-based normalisation in LCA: Framework and development of references at midpoint level. *The International Journal of Life Cycle Assessment*, *20*(7), 1005–1018. https://doi.org/10.1007/s11367-015-0899-2

Buckley, R. (2002). Tourism ecolabels. *Annals of Tourism Research*, *29*(1), 183–208. https://doi.org/10.1016/s0160-7383(01)00035-4

Buckley, R. (2011). Tourism and environment. *Annual Review of Environment and Resources*, *36*(1), 397–416. https://doi.org/10.1146/annurev-environ-041210-132637

Bulle, C., Margni, M., Patouillard, L., Boulay, A.-M., Bourgault, G., De Bruille, V., Cao, V., Hauschild, M., Henderson, A., Humbert, S., Kashef-Haghighi, S., Kounina, A., Laurent, A., Levasseur, A., Liard, G., Rosenbaum, R. K., Roy, P.-O., Shaked, S., Fantke, P., & Jolliet, O. (2019). IMPACT World+: A globally regionalized life cycle impact assessment method. *The International Journal of Life Cycle Assessment*, *24*(9), 1653–1674. https://doi.org/10.1007/s11367-019-01583-0

Butler, R. W. (1999). Sustainable tourism: A state-of-the-art review. *Tourism Geographies*, *1*(1), 7–25. https://doi.org/10.1080/14616689908721291

Butler, R. W. (2019). Tourism carrying capacity research: A perspective article. *Tourism Review*, *75*(1), 207–211. https://doi.org/10.1108/tr-05-2019-0194

Buxmann, K., Kistler, P., & Rebitzer, G. (2009). Independent information modules—A powerful approach for life cycle management. *The International Journal of Life Cycle Assessment*, *14*(Suppl 1), 92–100. https://doi.org/10.1007/s11367-009-0075-7

Cadarso, M. Á., Gómez, N., López, L. A., & Tobarra, M. Á. (2016). Calculating tourism's carbon footprint: Measuring the impact of investments. *Journal of Cleaner Production*, *111*, 529–537. https://doi.org/10.1016/j.jclepro.2014.09.019

Camilleri, M. A. (2018). The Tourism Industry: An Overview. In M. A. Camilleri (Ed.), *Travel Marketing, Tourism Economics and the Airline Product: An Introduction to Theory and Practice* (pp. 3–27). Springer international Publishing.

Campagnolo, D., & Camuffo, A. (2010). The concept of modularity in management studies: A literature review. *International Journal of Management Reviews*, *12*(3), 259–283. https://doi.org/10.1111/j.1468-2370.2009.00260.x

Candia, S., & Pirlone, F. (2021). Tourism Environmental Impacts Assessment to Guide Public Authorities towards Sustainable Choices for the Post-COVID Era. *Sustainability*, *14*(1), Article 1. https://doi.org/10.3390/su14010018

Castellani, V., & Sala, S. (2012). Ecological Footprint and Life Cycle Assessment in the sustainability assessment of tourism activities. *Ecological Indicators*, *16*, 135–147. https://doi.org/10.1016/j.ecolind.2011.08.002

Costa, M. de O., Proença, A. R. G. B., Solha, K. T., & Pinto, G. P. (2024). Turismo Responsável: Resultados que inspiram! In *Portal de Livros Abertos da USP*. Portal de Livros Abertos da USP. https://doi.org/10.11606/9788572052788

De Camillis, C., Peeters, P., Petti, L., & Raggi, A. (2012). Tourism Life Cycle Assessment (LCA): Proposal of a New Methodological Framework for Sustainable Consumption and Production. In M. Kasimoglu (Ed.), *Visions for Global Tourism Industry—Creating and Sustaining Competitive Strategies*. https://doi.org/10.5772/23550

Ethiraj, S. K., & Levinthal, D. (2004). Modularity and Innovation in Complex Systems. *Management Science*, *50*(2), 159–173. https://doi.org/10.1287/mnsc.1030.0145

Fernandes Martins, K., Teixeira, D., & De Oliveira Corrêa, R. (2022). Gains in sustainability using Voluntary Sustainability Standards: A systematic review. *Cleaner Logistics and Supply Chain*, *5*, 100084. https://doi.org/10.1016/j.clscn.2022.100084

Filimonau, V. (2016). *Life Cycle Assessment (LCA) and Life Cycle Analysis in Tourism. A Critical Review of Applications and Implications.* Springer, Cham. https://doi.org/10.1007/978-3-319-26224-6

Filimonau, V., Dickinson, J. E., Robbins, D., & Reddy, M. V. (2011). A critical review of methods for tourism climate change appraisal: Life cycle assessment as a new approach. *Journal of Sustainable Tourism*, *19*(3), 301–324. https://doi.org/10.1080/09669582.2010.527345

Filimonau, V., Dickinson, J., & Robbins, D. (2014). The carbon impact of short-haul tourism: A case study of UK travel to Southern France using life cycle analysis. *Journal of Cleaner Production*, *64*, 628–638. https://doi.org/10.1016/j.jclepro.2013.07.052

Filimonau, V., Dickinson, J., Robbins, D., & Reddy, M. V. (2013). The role of 'indirect' greenhouse gas emissions in tourism: Assessing the hidden carbon impacts from a holiday package tour. *Transportation Research Part A: Policy and Practice*, *54*, 78–91. https://doi.org/10.1016/j.tra.2013.07.002

Font Vivanco, D., Kemp, R., van der Voet, E., & Heijungs, R. (2014). Using LCA-based Decomposition Analysis to Study the Multidimensional Contribution of Technological Innovation to Environmental Pressures. *Journal of Industrial Ecology*, *18*(3), 380–392. https://doi.org/10.1111/jiec.12118

Font, X. (2002). Environmental certification in tourism and hospitality: Progress, process and prospects. *Tourism Management*, *23*(3), 197–205. https://doi.org/10.1016/S0261-5177(01)00084-X

Gadre, S., Esterman, M., & Thorn, B. K. (2017, November 3). *Implementation of an Object-Oriented Life Cycle Assessment Framework Using Functional Analysis and Systems Engineering Principles*. ASME 2017 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. https://doi.org/10.1115/DETC2017-68303

Gössling, S., & Buckley, R. (2016). Carbon labels in tourism: Persuasive communication? *Journal of Cleaner Production*, *111*, 358–369. https://doi.org/10.1016/j.jclepro.2014.08.067

Gössling, S., Humpe, A., & Sun, Y.-Y. (2024). Are emissions from global air transport significantly underestimated? *Current Issues in Tourism*, *0*(0), 1–14. https://doi.org/10.1080/13683500.2024.2337281

Gössling, S., Peeters, P., Ceron, J.-P., Dubois, G., Patterson, T., & Richardson, R. B. (2005a). The eco-efficiency of tourism. *Ecological Economics*, *54*(4), 417–434. https://doi.org/10.1016/j.ecolecon.2004.10.006

Gössling, S., Peeters, P., Ceron, J.-P., Dubois, G., Patterson, T., & Richardson, R. B. (2005b). The eco-efficiency of tourism. *Ecological Economics*, *54*(4), 417–434.

Graedel, T. E. (1997). Life-Cycle Assessment in the Service Industries. *Journal of Industrial Ecology*, *1*(4), 57–70. https://doi.org/10.1162/jiec.1997.1.4.57

International Organization for Standardization. (2006). *Environmental labels and declarations. Type III environmental declarations. Principles and procedures.* (ISO 14025). International Organization for Standardization. (Published)

International Organization for Standardization. (2022). *Environmental statements and programmes for products—Principles and general requirements.* (ISO 14020).

Jere Jakulin, T. (2017). Systems Approach to Tourism: A Methodology for Defining Complex Tourism System. *Organizacija*, *50*(3), 208–215. https://doi.org/10.1515/orga-2017-0015

Kitamura, Y., Ichisugi, Y., Karkour, S., & Itsubo, N. (2020). Carbon Footprint Evaluation Based on Tourist Consumption toward Sustainable Tourism in Japan. *Sustainability*, *12*(6), Article 6. https://doi.org/10.3390/su12062219

Konstantas, A., Stamford, L., & Azapagic, A. (2020). A framework for evaluating life cycle eco-efficiency and an application in the confectionary and frozen-desserts sectors. *Sustainable Production and Consumption*, *21*, 192–203. https://doi.org/10.1016/j.spc.2019.12.006

Langlois, R. N. (2002). Modularity in technology and organization. *Journal of Economic Behavior & Organization*, *49*(1), 19–37. https://doi.org/10.1016/S0167-2681(02)00056-2

Liu, J., Zhang, J., & Fu, Z. (2017). Tourism eco-efficiency of Chinese coastal cities – Analysis based on the DEA-Tobit model. *Ocean & Coastal Management*, *148*, 164–170. https://doi.org/10.1016/j.ocecoaman.2017.08.003

Lonca, G., Bernard, S., & Margni, M. (2019). A versatile approach to assess circularity: The case of decoupling. *Journal of Cleaner Production*, *240*, 118174. https://doi.org/10.1016/j.jclepro.2019.118174

Lu, F., Qin, W., & Wang, Y.-X. (2021). 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. *Scientific Programming*, *2021*, 1951264. https://doi.org/10.1155/2021/1951264

Madden, K., Young, R., Hall, J., & Brady, K. (2006). *Eco-efficiency Learning Module*. World Businesss Council for Sustainable Development (WCSD). https://www.wbcsd.org/gf6v

Mancini, M., Evans, M., Iha, K., Danelutti, C., & Galli, A. (2018). Assessing the Ecological Footprint of Ecotourism Packages: A Methodological Proposition. *Resources*, *7*(2), 1–28. https://doi.org/10.3390/resources7020038

Míguez, J. L., Rivo-López, E., Porteiro, J., & Pérez-Orozco, R. (2023). Selection of non-financial sustainability indicators as key elements for multi-criteria analysis of hotel chains. *Sustainable Production and Consumption*, *35*, 495–508. https://doi.org/10.1016/j.spc.2022.12.004

Miralles, C. C., Roura, M. B., Salas, S. P., Argelaguet, L. L., & Jordà, J. C. (2024). Assessing the socio-economic impacts of tourism packages: A methodological proposition. *The International Journal of Life Cycle Assessment*. https://doi.org/10.1007/s11367-024-02284-z

Nguyen, H. A. T., Gheewala, S. H., Sophea, T., Areerob, T., Hashimoto, K., Pimonsree, S., & Prueksakorn, K. (2020). Comparative carbon footprint assessment of agricultural and tourist locations in Thailand. *Journal of Cleaner Production*, *269*, 122407. https://doi.org/10.1016/j.jclepro.2020.122407

Papargyropoulou, E., Wright, N., Lozano, R., Steinberger, J., Padfield, R., & Ujang, Z. (2016). Conceptual framework for the study of food waste generation and prevention in the hospitality sector. *Waste Management*, *49*, 326–336. https://doi.org/10.1016/j.wasman.2016.01.017

Pásková, M., Wall, G., Zejda, D., & Zelenka, J. (2021). Tourism carrying capacity reconceptualization: Modelling and management of destinations. *Journal of Destination Marketing & Management*, *21*, 100638. https://doi.org/10.1016/j.jdmm.2021.100638

Peng, H., Zhang, J., Lu, L., Tang, G., Yan, B., Xiao, X., & Han, Y. (2017). Eco-efficiency and its determinants at a tourism destination: A case study of Huangshan National Park, China. *Tourism Management*, *60*, 201–211. https://doi.org/10.1016/j.tourman.2016.12.005

Prag, A., Lyon, T., & Russillo, A. (2016). *Multiplication of Environmental Labelling and Information Schemes (ELIS): Implications for Environment and Trade* (OECD Environment Working Papers 106; OECD Environment Working Papers, Vol. 106). https://doi.org/10.1787/5jm0p33z27wf-en

Purwaningsih, R., Agusti, F., Pranomo, S. N. W., Susanty, A., & Purwanggono, B. (2020). Assessment sustainable tourism: A literature review composite indicator. *E3S Web of Conferences*, *202*, 03001. https://doi.org/10.1051/e3sconf/202020203001

Rumbaugh, J., Blaha, M., Premerlani, W., Eddy, F., & Lorensen, B. (1991). *Object-oriented modeling and design*. Prentice Hall.

Schianetz, K., Kavanagh, L., & Lockington, D. (2007). Concepts and Tools for Comprehensive Sustainability Assessments for Tourism Destinations: A Comparative Review. *Journal of Sustainable Tourism*, *15*(4), 369–389. https://doi.org/10.2167/jost659.0

Sigala, M. (2008). A supply chain management approach for investigating the role of tour operators on sustainable tourism: The case of TUI. *Journal of Cleaner Production*, *16*(15), 1589–1599. https://doi.org/10.1016/j.jclepro.2008.04.021

Sun, Y., Hou, G., Huang, Z., & Zhong, Y. (2020). Spatial-Temporal Differences and Influencing Factors of Tourism Eco-Efficiency in China's Three Major Urban Agglomerations Based on the Super-EBM Model. *Sustainability*, *12*(10). https://doi.org/10.3390/su12104156

Sun, Y.-Y., Faturay, F., Lenzen, M., Gössling, S., & Higham, J. (2024). Drivers of global tourism carbon emissions. *Nature Communications*, *15*(1), 10384. https://doi.org/10.1038/s41467-024-54582-7

Sun, Y.-Y., Lin, P.-C., & Higham, J. (2020). Managing tourism emissions through optimizing the tourism demand mix: Concept and analysis. *Tourism Management*, *81*, 104161. https://doi.org/10.1016/j.tourman.2020.104161

Tanguay, G. A., Rajaonson, J., & Therrien, M.-C. (2011). Sustainable Tourism Indicators: Selection Criteria for Policy Implementation and Scientific Recognition. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.1948674

Thamagasorn, M., & Pharino, C. (2019). An analysis of food waste from a flight catering business for sustainable food waste management: A case study of halal food production process. *Journal of Cleaner Production*, *228*, 845–855. https://doi.org/10.1016/j.jclepro.2019.04.312

Torres-Delgado, A., & Palomeque, F. L. (2014). Measuring sustainable tourism at the municipal level. *Annals of Tourism Research*, *49*, 122–137. https://doi.org/10.1016/j.annals.2014.09.003

Torres-Delgado, A., & Saarinen, J. (2013). Using indicators to assess sustainable tourism development: A review. *Tourism Geographies*, *16*(1), 31–47. https://doi.org/10.1080/14616688.2013.867530

United Nations Environment Programme & World Tourism Organization. (2012). *Tourism in the Green Economy – Background Report*. UNWTO. https://www.unenvironment.org/explore-topics/resource-efficiency/what-we-do/responsible-industry/tourism

United Nations World Tourism Organization. (2025, January 21). *International tourism recovers pre-pandemic levels in 2024*. United Nations World Tourism Organization. https://www.unwto.org/news/international-tourism-recovers-pre-pandemic-levels-in-2024