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The green logistics maturity model for evaluating sustainable logistics practices

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ABSTRACT

The growing concern about the environmental impact of industrial processes highlights the need for sustainable practices in supply chain management and logistics. Maturity Models (MMs) are widely used to evaluate the development of entities through continuous improvement, addressing sustainability assessment and enhancements. Literature proposes MMs for evaluating green practices in logistics. However, the MMs available do not follow systematic design, and they lack proper validation and application. This study introduces the Green Logistics Maturity (GreLoM) model to evaluate and improve green logistics practices within organizations. Using structured methodologies for maturity modeling, the five-level GreLoM model is based on four dimensions of resource management, process management, network management, and sustainable reporting, each one with relevant sub-dimensions and items. The model was developed using a hybrid approach that combines analysis of existing logistics MMs and semi-structured interviews with expert practitioners. The GreLoM model was validated through content validity and reliability analysis, assessed by a balanced pool of industry experts and academic researchers. After validation, the GreLoM model was applied descriptively, comparatively, and prescriptively in two case studies using a structured questionnaire weighing respondents' feedback by their knowledge with the process and years of experience. The results demonstrate the utility and practicality of the GreLoM model, suggesting that its adoption can support the transition to a low-emission industry, aligning with global sustainability goals. The model assesses the maturity of green logistics practices and promotes a culture of continuous improvement by comparing model application results with practitioners' perceptions of improvement areas. Thus, the GreLoM model can be a valuable tool for practitioners aiming for low emissions and for researchers focused on green logistics assessment and sustainable maturity modeling.

1. Introduction

TheI environmental impact of industrial processes is a growing concern, as increasing resource consumption and emissions contribute to climate change and environmental degradation with a requests of 90 billion tons of material per year (Ramírez-Rodríguez et al., 2024). Supply chain management and logistics are critical components of these industrial processes, contributing to resource depletion and environmental issues (Govindan et al., 2014). Manufacturing activities generate approximately 50 % of global greenhouse gas emissions due to energy-intensive production technologies and methods also contributing to air quality and pollution (Manco et al., 2023). Similarly, the transportation of products, often through multimodal approaches, impacts greenhouse gas emissions with an increasing trend of 45 % by 2045 only from truck freight transportation (Ellram and Murfield, 2017). Warehousing significantly affects energy consumption due to the use of lighting, heating, cooling, and handling equipment within distribution centers (Perotti and Colicchia, 2023). Other processes, such as packaging and disposal, lead to material losses, which are sometimes non-recyclable, requiring appropriate solid waste management systems

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(Di Foggia and Beccarello, 2022).

To address the environmental drawbacks of logistics it is crucial to integrate sustainable practices like reverse logistics (Weber et al., 2023), closed-loop supply chains (Ferraro et al., 2024), and green logistics (Karaman et al., 2020). Some authors assess the effectiveness of optimizing route planning (Lou et al., 2024), investing in eco-friendly packaging (Del Borghi et al., 2018) and adopting electric vehicles (Chun et al., 2023) as strategies to reduce the impact of logistics operations. In this context, green logistics can be defined as "*the study of practices that aim to reduce the environmental externalities*" (Dekker et al., 2012). However, these practices are not always easily applicable in industrial contexts (Nikseresht et al., 2023) and it remains unclear which should be prioritized for implementation (Guimarães et al., 2022). These considerations highlight the need for tools that facilitate the introduction and effectiveness of green practices in industrial processes, including logistics, starting with the assessment of the current state and identifying areas for improvement.

In this context, MMs are valuable tools that provide a structured approach to evaluate the growth and development of specific entities through a continuous improvement approach (Cuenca et al., 2013). Given the rising trends in emissions and consumption, some researchers argue that these MMs could be valuable for assessing the sustainability of processes and organizations (Correia et al., 2017). However, their application in supply chain and logistics management remains relatively underexplored (Ferraro et al., 2023c), particularly in assessing green logistics maturity. From a methodological standpoint, several structured modeling approaches facilitate the development of MMs (Becker et al., 2009; Mettler, 2011; Otto et al., 2020). However, many MMs do not rigorously follow key phases of maturity modeling, making them difficult to replicate and raising concerns about their methodological rigor (García-Mireles et al., 2012). In particular, most MMs focus heavily on the development and application phases, often overlooking the crucial validation step. When it comes to applying, MMs can be deployed thorough descriptive, comparative, and prescriptive approaches (De Carolis et al., 2017). In logistics and supply chain management, most MMs rely on descriptive and comparative approaches. For MMs that claim to be prescriptive, clear guidelines, actionable methods, and prioritized lists of improvements for achieving continuous improvement are often lacking, making it difficult to implement effectively (Correia et al., 2017).

To address these gaps, this paper introduces a novel tool for evaluating green logistics maturity, building on the general model developed by Ferraro et al. (2023b). The proposed GreLoM model adheres closely to the modeling approach outlined by De Bruin et al. (2005), which encompasses the phases of scope, design, populate, test, deploy, and maintain. This revised model is designed to provide a thorough assessment of green logistics practices, incorporating key dimensions such as resource management, process management, network management, and sustainable reporting. The proposed GreLoM model has been validated through collaboration with both academics and industry professionals and applied to five case studies, reporting the results of the two most relevant case studies to demonstrate its practical applicability. The application of the GreLoM model goes beyond merely showcasing its applicability: it also provides a descriptive, comparative, and prescriptive analysis. GreLoM model allows organizations to assess the maturity level of their logistics processes, compare their performance, and identify improvement area based on the scores of maturity measurements. This prioritization integrates both the adoption urgency and adoption priority of green practices for the overall maturity enhancement. However, it is important to note that the present study does not cover the maintain phase of the modeling cycle, which involves the continuous revision of the model through repeated applications to assess the long-term impact and effectiveness of the improvement strategies adopted in order to address dynamic sustainability challenges. Moreover, the GreLoM model is limited exclusively to the pillar of environmental sustainability, excluding those of economic and social sustainability.

This paper aims to provide several contributions as follows. Theoretically, it proposes the new GreLoM model based on one of the most widely used modeling approaches of De Bruin et al. (2005). Compared to many existing MMs, this work provides a detailed validation of the GreLoM model by engaging both industry experts and academic researchers, thus advancing scientific research. The GreLoM model's validation is conducted through an analysis of validity and reliability, employing techniques for measuring constructs. Practically, this paper presents a structured model integrated into a green logistics maturity assessment tool, implemented via a questionnaire. For instance, the tool is demonstrated through its application to two case studies, illustrating how it can be used to describe and compare the current maturity state and identify critical areas for improvement to enhance overall process maturity.

The structure of this paper is as follows. Section 2 provides a detailed theoretical background on MMs (Section 2.1) and highlights the most widely used MMs in logistics identifying existing gaps (Section 2.2). Section 3 describes the methodology for proposing, validating, and applying the proposed GreLoM model. Section 4 presents the GreLoM model (Section 4.1), its validation process (Section 4.2), and its application to two case studies (Section 4.3), discussing the results in Section 5. Finally, Section 6 offers theoretical and practical implications (Section 6.1) along with limitations and suggestions for future research and development (Section 6.2).

2. Literature review

2.1. Theoretical background on maturity models

The concept of continuous improvement is well established within industrial processes (Fantozzi et al., 2022). Various approaches and methodologies, including the use of MMs, can be considered in this context. These tools support entities through various stages -introduction, growth, and maturity-by evaluating key attributes and providing actionable insights (Çınar et al., 2021). The origin of MM can be traced back to quality management with the development of the Quality Management Maturity Grid (Crosby, 1979). However, their widespread adoption is largely attributed to the significant impact of the Capability Maturity Model in software engineering (Paulk et al., 1991). Since the early 21st century, the use of MMs has expanded to several disciplines, including business process management, project management, and knowledge management. Similarly, disciplines related to supply chain and logistics management have also adopted these tools, albeit to a lesser extent (Lockamy and McCormack, 2004). Furthermore, MMs have facilitated the introduction of various paradigms, such as Industry 4.0 (De Carolis et al., 2017), circular economy (Kayikci et al., 2022), and the emerging Industry 5.0 (Hein-Pensel et al., 2023).

The adoption of MMs has been facilitated by their ease of application and their significant potential in defining improvement guidelines and roadmaps (Radosavljevic et al., 2016). These models enable the assessment of an entity according to various attributes and objectives, using a set of essential elements as outlined by Battista and Schiraldi (2013). These essential elements include a modeling framework, a maturity framework, a performance framework, and an improvement system. The modeling framework provides the structural basis of the MM, outlining the key components and their interactions. This includes defining the dimensions, sub-dimensions, and elements of the model, as well as their primary relationships. The maturity framework establishes the levels of maturity, specifying both the number of levels and, in some cases, providing detailed descriptions and labels for each level. The performance framework outlines the measurement system, and the tools used for assessment. Finally, the improvement system details the steps, priorities, and actions required to progress from one maturity level to the next, based on best practices, real-life examples, and improvement metrics. Improvement system also includes structured proposals for guidelines or roadmaps to facilitate continuous improvement.

From a design standpoint, MMs can also be differentiated based on the actors involved in their development and the definition of their modeling frameworks. This classification includes: i) theory-based models, which define dimensions, sub-dimensions, and items based on literature research—whether systematic or not—that pertains to the application context or similar MMs addressing that context; ii) practitioner-based models, which rely on expert judgment to establish dimensions, sub-dimensions, and items; and iii) hybrid models, which combine expert input with insights from literature analysis to define the elements of the modeling framework. Theory-based models have the benefit of offering a solid theoretical foundation for model elements but may risk being overly academic and disconnected from practical applications. Practitioner-based models, on the other hand, may be limited by the perspectives of experts, potentially resulting in a less generalizable model and lacking of theoretical foundations. Hybrid models capture the advantages of both approaches, making them the preferred option. Additionally, from an application perspective, MMs can be classified into several types based on their underlying methodologies and complexities (Vance et al., 2023). These include: i) CMM-based models, which are derived from the original Capability Maturity Model, which assess each item based on a series of practices and techniques with incremental and measurable operational levels; ii) Likert-like based models, which use a linguistic Likert scale for the evaluation of each item; and iii) maturity grid-based models, which use a grid format to assess maturity levels. CMM-based models typically adopt a continuous maturity framework, allowing for more granular progression, whereas Likert-like and maturity grid-based models tend to follow stage-based frameworks, characterized by a discrete number of maturity levels usually aligned with the structure of the performance framework being used (Mendes Jr et al., 2016). MMs can also be distinguished based on the entity to which they are applied, the considered attribute, and the intended use. Commonly considered attributes include readiness, capability, and maturity. Readiness assesses the preparedness for the introduction or adoption of a new process or technology, facilitating the introductory phase (Caiado et al., 2021). Capability evaluates the use of available resources to support the growth phase, ensuring that processes are effective and efficient (Lookman et al., 2022). Maturity assesses the ability of the entity to improve continuously, enabling advancement to higher levels of performance (Correia et al., 2017). These tools can also be viewed in terms of their intended use. MMs can be utilized through descriptive, comparative, and prescriptive approaches (De Carolis et al., 2017). Descriptive approaches focus on describing the current state of processes, providing a baseline for improvement. Comparative approaches facilitate benchmarking against other entities or best practices, identifying gaps and areas for enhancement. Finally, prescriptive approaches offer guidelines and recommendations for achieving higher maturity levels, providing recommendations for prioritized actions and roadmaps for continuous improvement.

2.2. Logistics maturity models

Among the various scopes for which MMs are applied, logistics is an area with limited development of such models. Indeed, according to Ferraro et al. (2023c), this subject is not thoroughly explored in the literature. A summary of the MMs for logistics is presented in Table 1. From the perspective of their application scope, logistics MMs can be grouped into three categories: i) logistics 4.0, ii) process management, and iii) sustainable and green logistics. Within the logistics 4.0 category, the work of Asdecker and Felch (2018) stands out for evaluating the digitalization maturity of the delivery process under the concept of Industry 4.0. Similarly, Boullauazan et al. (2022) focuses on Industry 4.0 but assesses the maturity of smart ports. Krowas and Riedel (2019)'s work diverges slightly by specifically evaluating the maturity of intralogistics 4.0, particularly for small and medium enterprises. Other MMs proposing Logistics 4.0 concepts include those by Modica et al. (2021) for freight transportation, and by Zoubek et al. (2022) and Zoubek and Simon (2021) both for internal logistics. The first and third MMs are limited to the design phase, while the second explores comparative applications across different sectors, such as automotive, manufacturing, and electronics. Some MMs evaluate logistics maturity purely from a process perspective. Within the process management category, the work of Tetik et al. (2022) measures the maturity level of logistics practices within the construction sector. In the service industry sector, Werner-Lewandowska and Kosacka-Olejnik (2020) proposes an MM to enhance logistics maturity. In contrast, the study of Márquez-Gutiérrez et al. (2020) measures logistics process immaturity. Lastly, Peña-Montoya et al. (2020) and Olejnik and Werner-Lewandowska (2018) propose MMs to evaluate the reverse logistics process. While the first two categories feature several contributions, those focusing on sustainable and green logistics are less developed. Notable examples include the Sustainable Logistics Management Model by Werner-Lewandowska and Golinska-Dawson (2021) maturity model for the sustainable development of logistics service providers of Wehner et al. (2021) and the Green Logistics Maturity Model (GLMM) of Ferraro et al. (2023b). The model of Werner-Lewandowska and Golinska-Dawson (2021) assesses the logistics process across five levels, the three dimensions—i) economy, ii) environment, and iii) social— and 36 sub-dimensions. The model proposed by Wehner et al. (2021) evaluates process maturity from an energy efficiency perspective across five levels, three dimensions—i) actions, ii) processes, iii) services—and 14 sub-dimensions. Finally, the model of Ferraro et al. (2023b) provides a detailed assessment of green logistics maturity using five levels, three dimensions—i) resource management, ii) process management, and iii) network management—and six sub-dimensions.

From a design approach perspective, most existing logistics MMs adopt a theory-based perspective (Tetik et al., 2022; Modica et al., 2021; Olejnik and Werner-Lewandowska, 2018), with only the model of Werner-Lewandowska and Golinska-Dawson (2021) incorporates solo practitioner-based insights. In contrast, the works of Boullauazan et al. (2022), Wehner et al. (2021), Zoubek and Simon (2021), Peña-Montoya et al. (2020), and Asdecker and Felch (2018) employ a hybrid modeling approach, integrating both theoretical foundations from the academic literature and practical knowledge from industry experts.

Considering the modeling phases, among the three MMs addressing sustainable and green logistics, only the model by Werner-Lewandowska and Golinska-Dawson (2021) includes both the design and application phases. In contrast, the models by Wehner et al. (2021) and Ferraro et al. (2023b) are limited to the design phase. However, none of the three models consider the validation phase, which raises concerns about the reliability of the models and the accuracy of the results obtained from their application (Wendler, 2012). Similar observations apply to logistics MMs in the other two categories, with only the models by Boullauazan et al. (2022) and Asdecker and Felch (2018) integrating both design and validation phases. Among the models that advance to the application phase, most are divided between descriptive (4 MMs) and comparative (3 MMs) uses, while only one MM follows a prescriptive application approach. Specifically, within the Industry 4.0 category, the models by Krowas and Riedel (2019) and Boullauazan et al. (2022) adopt a descriptive approach, while Zoubek et al. (2022) applies a comparative one. For process management MMs, the models by Peña-Montoya et al. (2020) and Tetik et al. (2022) are descriptive, Márquez-Gutiérrez et al. (2020) is comparative, and Werner-Lewandowska and Kosacka-Olejnik (2020) is prescriptive. Finally, among sustainable and green logistics MMs, only the model by Werner-Lewandowska and Golinska-Dawson (2021) adopts a comparative application. In addition to the scarcity of prescriptive models, none of the existing MMs propose an integrated application of descriptive, comparative, and prescriptive approaches.

The new MM aims to advance the cluster of models related to green logistics, distinguishing itself not only in terms of its modeling

Table 1

More relevant MMs for logistics practices based on research topic (1 = Logistics 4.0, 2 = Process management, 3 = Sustainable and green logistics) indicating the essential elements of modeling framework (dimensions and number of sub-dimensions (#S)), maturity framework (type and levels), performance framework (type), improvement system (descriptive (D), comparative (C), prescriptive (P) use and type), modeling approach (theory-based (TB) and practitioners-based (PB)), main modeling phase, and number of case studies.

MM	Research topic			Modeling framework		Maturity framework		Performance framework	Improvement system		Modeling approach		Modeling phase	# of case studies				
	1	2	3	Dimensions	#S	Type	Levels	Type	Use	Type	TB	PB		No	1	2	3	>4
Delivery Process Maturity Model 4.0 (Asdecker and Felch, 2018)	X			D1) Order processing D2) Warehousing D3) Shipping	15	Staged	L1) Basic digitization L2) Cross-department digitization L3) Horizontal and vertical digitization L4) Full digitization L5) Optimized full digitization	Likert-like scale	D	–	X	X	Design Validation	X				
Maturity Model for Intralogistics 4.0 (Krowas and Riedel, 2019)	X			D1) Data D2) Communication D3) Processes D4) Intellectual capital	12	Staged	L1) Outsider L2) Beginner L3) Advanced L4) Experienced L5) Expert	Maturity grid	D	–	X	–	Design Application		X			
Maturity model for the Logistics 4.0 transportation process (Modica et al., 2021)	X			D1) Application D2) Decision Scope D3) Decision Level D4) Network Span D5) Level of Automation D6) Frequency of Acquisition D7) Level of Autonomy	22	Staged	L1) Level 1 L2) Level 2 L3) Level 3 L4) Level 4	–	–	–	X	–	Design	X				
Framework for Logistics 4.0 Maturity Model (Zoubek and Simon, 2021)	X			D1) Manipulation D2) Storage D3) Packaging D4) Supply D5) Material identification	14	Staged	L0) Level 0 L1) Level 1 L2) Level 2 L3) Level 3 L4) Level 4 L5) Level 5	Likert-like scale	D	–	X	X	Design	X				
Smart Port Maturity Model (Boullauazan et al., 2022)	X			D1) Port operation D2) Synchromodality D3) Safety and Security D4) Energy and Environment D5) Capability	–	Staged	L1) Silo focus L2) Integration focus L3) Supply-chain focus L4) Port-wide focus L5) Inter-port focus	Maturity grid	D	Action list	X	X	Design Validation Application		X			
Readiness model of Internal Logistics for Industry 4.0 (Zoubek et al., 2022)	X			D1) Handling D2) Storage D3) Packaging D4) Supply D5) Material identification	14	Staged	L0) Level 0 L1) Level 1 L2) Level 2 L3) Level 3 L4) Level 4 L5) Level 5	Likert-like scale	C	Action list	–	–	Application					X
Reverse Logistics Maturity Model (Olejnik and Werner-Lewandowska, 2018)		X		D1) Physical network D2) Formalization D3) Structuration D4) Information flow & data exchange D5) Optimization D6) Stakeholder's relations & engagement	25	Staged	L1) Level 1 L2) Level 2 L3) Level 3 L4) Level 4 L5) Level 5	Maturity grid	D	–	X	–	Design	X				

(*continued on next page*)

Table 1 (*continued*)

MM	Research topic			Modeling framework		Maturity framework		Performance framework	Improvement system		Modeling approach		Modeling phase	# of case studies				
	1	2	3	Dimensions	#S	Type	Levels	Type	Use	Type	TB	PB		No	1	2	3	>4
Logistics Maturity Model for Service Industry (Werner-Lewandowska and Kosacka-Olejnik, 2020)		X		D1) Warehouse management D2) Transport management D3) Supply and inventory management D4) Supply chain and distribution D5) IT support	65	Staged	L1) Level 1 L2) Level 2 L3) Level 3 L4) Level 4 L5) Level 5 L6) Level 6	Likert-like scale	P	Roadmap	X	–	Design Application					X
Logistic immaturity model (Márquez-Gutiérrez et al., 2020)		X		D1) Warehouse management and control D2) Inventory management and control D3) Production control D4) Customer relationship management D5) Supply and procurement management D6) Logistic and production planning D7) Organizational and human resource management D8) Sales and internationalization D9) Technological appropriation and logistics 4.0	–	Staged	L1) Negligent L2) Obstructive L3) Contemptuous	Likert-like scale	C	Action list	X	–	Design Application		X			
Maturity model for reverse logistics (Peña-Montoya et al., 2020)		X		D1) Business strategy D2) Strategy and objectives of the reverse supply chain D3) Sustainability	8	Staged	L1) Immature L2) Naïve L3) Semi-mature L4) Mature	Maturity grid	D	–	X	X	Design Application					X
Logistics maturity model for the construction industry (Tetik et al., 2022)		X		D1) Planning D2) Organizing D3) Operations D4) Use of technology D5) Information flow	–	Staged	L1) Basic, unmanaged L2) Advanced, toward integrated L3) Optimized, industrialized	Maturity grid	C	Guidelines	X	–	Design Application				X	
Sustainable Logistics Management Maturity assessment framework (Werner-Lewandowska and Golinska-Dawson, 2021)			X	D1) Economy D2) Environment D3) Social	36	Continuous	L1) SLMML1 L2) SLMML2 L3) SLMML3 L4) SLMML4 L5) SLMML5	Likert-like scale	C	–	–	X	Design Application					X
Maturity model for the sustainable development of logistics service providers (Wehner et al., 2021)			X	D1) Actions D2) Processes D3) Services	14	Staged	L1) Initial L2) Ad Hoc L3) Manage in isolation L4) Internal institutionalization L5) External institutionalization	Maturity grid	D	–	X	X	Design	X				

(*continued on next page*)

Table 1 (*continued*)

MM	Research topic			Modeling framework		Maturity framework		Performance framework	Improvement system		Modeling approach		Modeling phase	# of case studies				
	1	2	3	Dimensions	#S	Type	Levels	Type	Use	Type	TB	PB		No	1	2	3	>4
Green Logistics Maturity Model (Ferraro et al., 2023b)			X	D1) Resource management D2) Process management D3) Network management	6	Staged	L1) Level 1 L2) Level 2 L3) Level 3 L4) Level 4 L5) Level 5	–	D	–	X	–	Design	X				
GreLoM model (This study)			X	D1) Resource management D2) Process management D3) Network management D4) Sustainable reporting	31	Staged	L1) Completely Immature L2) Partially Immature L3) Neither Immature nor Mature L4) Partially Mature L5) Completely Mature	Likert-like scale	C, D, P	Priority matrix	X	X	Design Validation Application					X

framework components but also through its structured modeling phases and its improvement system. Moreover, the proposed model extends previous models focused on sustainable and green logistics. In fact, both the models developed by Wehner et al. (2021) and Ferraro et al. (2023b) address only the design phase, discussing their potential application from a qualitative perspective. Conversely, the MM proposed by Werner-Lewandowska and Golinska-Dawson (2021) focuses on service and 3PL providers. This focus limits the generalizability of the tool's application to other contexts. Furthermore, the same model by Werner-Lewandowska and Golinska-Dawson (2021) adopts a modeling approach that relies solely on practitioners' input, without incorporating scientific evidence. In contrast, our work integrates both practitioners' insights and contributions from the literature, while deliberately maintaining a broad scope of application without a specific focus. As an extension of Ferraro et al. (2023b), the proposed GreLoM model enhances the framework by adding the sustainability reporting dimension—based on practitioners' feedback—to the existing dimensions of resource, process, and network management. By systematically following the modeling phases—design, validation, and application—this proposal offers a comprehensive model. It further differentiates itself in the application phase through the adoption of a comprehensive improvement system. In particular, it aims to demonstrate the model's use in descriptive, comparative, and prescriptive terms, facilitated by the adoption of a priority matrix. The application of the GreLoM model was conducted on a broad sample, whereas most maturity models that reach the application phase are typically tested on a single case study (Boullauazan et al., 2022; Márquez-Gutiérrez et al., 2020; Krowas and Riedel, 2019) or a limited number of cases (Tetik et al., 2022), thus limiting the model applicability.

3. Methodology

The development of the GreLoM model necessitates a suitable design methodology to ensure the tool's replicability and validity. Generally, the modeling of MMs follows an iterative and collaborative approach between academics and practitioners, resulting in a model with a robust scientific foundation and tangible industrial applicability. Various modeling approaches have been proposed in the literature and are used qualitatively for model design, validation, and application (Becker et al., 2009; Mettler, 2011; Otto et al., 2020). To ensure broad applicability, this work adapted the modeling approach of De Bruin et al. (2005)—which consists of the macro phases: scope, design, populate, test, deploy, and maintain— following the three phases of model proposal, validation and application (see Fig. 1). The modeling approach was deployed starting from the general Green Logistics Maturity Model (GLMM) proposed by (Ferraro et al., 2023b) to propose the novel GreLoM model.

The first modeling phase (Scope phase) identifies the model's purpose and the stakeholders involved in its design. The scope of this study addresses the maturity of green logistics from an industrial process perspective, involving academics and industry experts familiar with logistics processes.

The second modeling phase (Design phase) identifies the practical need for the model, emphasizing the reasons for its application, how it should be applied, the entities involved, and the intended outcomes. Based on the literature gaps identified in Section 2, there is a practical need for a MM to assess and improve sustainable approaches within industrial processes, specifically focusing on logistics to meet medium- and long-term environmental goals. The model will be applied using a 5-point Likert scale questionnaire, evaluating various items (I). The entities involved include industrial personnel from manufacturing and service companies interested in assessing the maturity of their logistics processes. Each model item is evaluated using a weighted mean aggregation approach, assessing specific sub-dimensions (S) and, in turn, the dimensions (D) that ultimately determine the maturity level (L). For the application of the GreLoM model, weighting criteria were used to

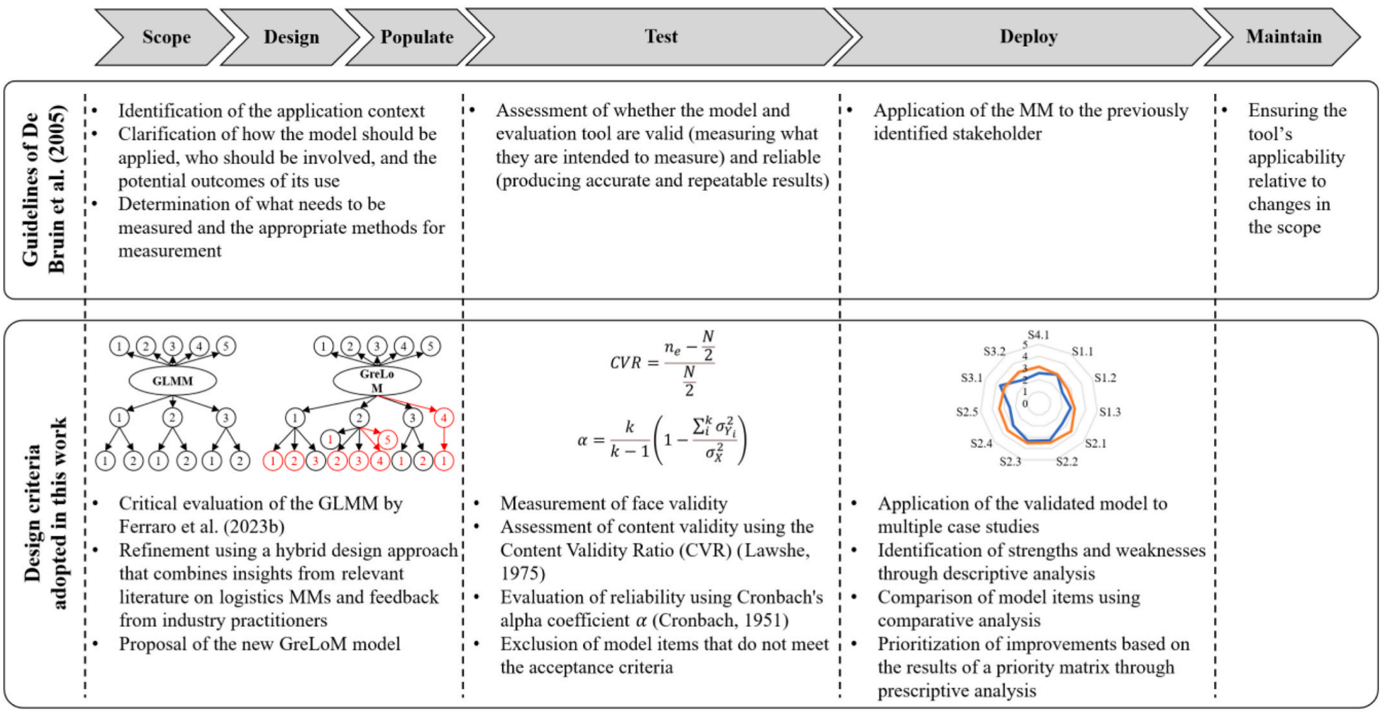


Fig. 1. Methodology proposed in this work following the approach of De Bruin et al. (2005) for maturity modeling.

mediate the scores from the respondents regarding the novel measurement of sub-dimensions and dimensions and the levels of maturity. Additionally, the evaluation of items by multiple respondents from the same company, whose assessments are aggregated according to weighting criteria, helps reduce subjectivity and mitigate potential response bias. This practice is quite common in literature where multiple respondents have to provide their expertise (Caiado et al., 2021). In this study, the weighting criteria, presented in Table 2, evaluate the respondent's knowledge with the logistics process and their years of experience. The measurement system structure is highlighted by the formulas in Equations (1)–(3).

$$S_{s,d} = \frac{1}{P}\sum_{p}^{P}\frac{1}{I}\frac{\sum_{i}^{I} x_{p,i,s} * \sum_{c}^{C} w_{p,c}}{\sum_{p}^{P}\sum_{c}^{C} w_{p,c}} \tag{1}$$

$$D_d = \frac{1}{S}\sum_{s}^{S} S_{s,d} \tag{2}$$

$$L = \left\lfloor \frac{1}{D}\sum_{d}^{D} D_d \right\rfloor \tag{3}$$

Let I be the number of evaluated items, P be the number of respondents evaluating the items, C be the number of evaluation criteria, S be the number of sub-dimensions, and D be the number of dimensions. Within the equations, $x_{p,i,s}$ represents the score given by respondent p for model item i within sub-dimension s, $w_{p,c}$ represents the weight based on the respondent's profile p regarding criterion c, $S_{s,d}$ represents the score for sub-dimension s within dimension d based on score of the model items within the sub-dimensions s, D_d the score for dimension d based on score of the model sub-dimensions within the dimension d, and L the maturity level assessment based on score of the model dimensions. For simplicity, the notations of the measurement system used are provided in Table 3. By measuring the elements of the model at the level, dimension, and sub-dimension, the GreLoM model can be used for descriptive, comparative, and prescriptive intended use. More in detail, the prescriptive use is achieved through radar charts and a priority matrix as proposed by Mendoza and Pigosso (2023). The priority matrix evaluates the model sub-dimensions based on adoption urgency and adoption priority. Adoption urgency refers to the immediate necessity to implement specific practices due to pressing factors such as regulatory changes, emerging environmental concerns, or urgent customer demands. It captures how quickly practices need to be adopted

Table 2
Weighting criteria of experts' judgements.

Criteria	Classification	w_p
Process knowledge	Extremely familiar	10
	Very familiar	8
	Moderately familiar	6
	Slightly familiar	4
	Not all familiar	2
Years of experience	≥ 30	10
	20–29	8
	10–19	6
	6–9	4
	≤ 5	2

Table 3
Description of parameters of the measurement system.

Parameter	Description
C, c	Number of evaluation criteria ($c = 1, \ldots, C$)
P, p	Number of respondents ($p = 1, \ldots, P$)
I, i	Number of evaluated items ($i = 1, \ldots, I$)
S, s	Number of sub-dimensions ($s = 1, \ldots, S$)
D, d	Number of dimensions ($d = 1, \ldots, D$)
$x_{p,i,s}$	Score given by respondents p for the model item i within sub-dimension s
$w_{p,c}$	Weight of respondents p regarding criteria c
$S_{s,d}$	Score of the sub-dimension s within the dimension d based on score of the model items within the sub-dimension s
D_d	Score of the dimension d based on score of the model sub-dimensions within the dimension d
L	Level of maturity for the assessment of the proposed MM based on score of the model dimensions

to address short-term challenges or to leverage immediate opportunities. For instance, if new regulations require compliance within a tight deadline, the urgency to adopt related sustainable practices will be high. Conversely, adoption priority evaluates the strategic importance of implementing these practices relative to other ongoing or planned initiatives. It considers factors such as long-term strategic goals, resource allocation, and overall impact on organizational performance. Adoption priority is concerned with how critical it is to integrate these practices into the business strategy, regardless of the immediate time frame. For example, a company might prioritize practices that align with its long-term sustainability goals even if they are not immediately necessary.

In the third modeling phase (Populate phase), elements to measure the intended attributes are gathered, which can be achieved through theory-based approaches such as critical or systematic literature reviews, practitioner-based contributions from experts and potential model users, or a combination of both. This phase results in a preliminary model, which must then be validated in the test phase. Regarding this phase, the novel GreLoM model builds upon the previous one GLMM and extends it using a mixed approach. This approach combines critical literature reviews with feedback from companies, gathered through semi-structured interviews with industrial managers dealing with supply chain and logistics management.

During the fourth modeling phase (Test phase), it is crucial to verify the validity (accuracy) and reliability (consistency) of the GreLoM model's elements and the corresponding measurement tool. In this study, the validity of the GreLoM model elements was assessed using both face validity and content validity, including both academics and practitioners. Lawshe's Content Validity Ratio (CVR) was utilized (Lawshe, 1975) as in the work of Ho et al. (2020) and it can be measured as depicted in Equation (4):

$$CVR = \frac{n_e - \frac{N}{2}}{\frac{N}{2}} \tag{4}$$

where n_e represents the number of respondents who deem the element or question they are evaluating as essential, and N represents the total number of respondents. A 5-level Likert scale was used, where scores of 4 and 5 are considered essential for CVR measurement. Based on the results and using the thresholds provided by Almanasreh et al. (2019), the minimum CVR value can be obtained based on the respondent sample to consider that model item valid. If a model item is considered valid, it is retained within the validated model; otherwise, it is excluded. Regarding the measurement of reliability, following the work of Srai et al. (2013), only the evaluation of internal consistency was considered through the calculation of Cronbach's alpha coefficient (Cronbach, 1951), expressed in Equation (5):

$$\alpha = \frac{k}{k-1}\left(1 - \frac{\sum_{i}^{k} \sigma_{Y_i}^2}{\sigma_X^2}\right) \tag{5}$$

where σ_X^2 is the variance of the total score, and $\sigma_{Y_i}^2$ is the variance of item i for the sample of individuals under examination. The theoretical value of alpha ranges from zero to one, as it is the ratio of two variances. However, estimates of alpha can take any value less than or equal to 1, including negative values, although only positive values make sense. Assessments can be made based on the coefficient, where a value greater than 0.9 is excellent, between 0.9 and 0.8 is good, between 0.8 and 0.7 is acceptable, between 0.7 and 0.6 is questionable, between 0.6 and 0.5 is poor, and below 0.5 is unacceptable. In the study by Susanty et al. (2020), an acceptability threshold of 0.6 was established for reliable constructs. This threshold was also adopted as the reference value in the present work. For both evaluations regarding the model's items, a sample of respondents from both academic and industrial backgrounds was utilized.

Once validated, the GreLoM model can be implemented in the fifth modeling phase (Deploy phase) from an industrial perspective. In this study, the GreLoM model will be applied using a multiple case study approach to compare the results and provide potential guidelines for each case study to improve its maturity level. Specifically, three primary objectives will be pursued. Firstly, the GreLoM model will provide a descriptive overview of the current maturity level among the companies involved in the multiple case studies. Secondly, these results will not only illustrate the current state but also compare companies across case studies for insights from a comparative standpoint. Thirdly, a prescriptive approach will be taken, enriching the practical value of the GreLoM model by proposing a prioritized list of improvements based on practitioners' experiences that can be derived in two perspectives and consequently compared. The first perspective (model's perspective) considers the results consistent with the model items defined from the hybrid design approach. This allows for the definition of improvement guidelines based on aggregated scores for sub-dimensions and dimensions, prioritizing those with lower scores. The second perspective (practitioners' perspective) gathers the results from the priority matrix directly indicating the respondents' interest regarding sub-dimensions that are more or less relevant concerning their adoption priority and adoption urgency. However, experts may prefer, based on the priority matrix results, to improve sub-dimensions not favored by the model's application. To evaluate this discrepancy of judgments for each case study, a discrepancy index (δ_l) was calculated for three groups (high, medium, low), defined by Equation (6):

$$\delta_l = 1 - \frac{n_{m,p}}{s} \tag{6}$$

where l defines the group (high, medium, low), s identifies the number of sub-dimensions within each group l, and $n_{m,p}$ indicates the number of relevant sub-dimensions for improvement within each group l common to both the model's application (model's perspective) and the priority matrix (practitioners' perspective). For example, if within the group $l = high$ (indicating sub-dimensions requiring improvement to reach a higher maturity level), there are three sub-dimensions ($s = 3$), and only one ($n_{m,p} = 1$) is specified both by the model application and the priority matrix results, the discrepancy index is $\delta_{high} = 0.66$ ($\delta_{high} = \left(1 - \frac{1}{3}\right) * 100 = 0.66$).

Lastly, although often overlooked in the literature, the last modeling phase (Maintain phase) is critical for updating and improving the model to ensure its relevance and utility over time and to prevent obsolescence of a MM. Addressing it would require longitudinal studies involving extended observation periods, which are resource-intensive and time-consuming (Bass et al., 2018; Franzè et al., 2024). In this regard, maintain phase is beyond the scope of this work and is not explicitly addressed.

4. Green logistics maturity model

Starting from the previous MMs, this work aims to extend the literature for evaluating the maturity of logistics proposing a novel model for evaluating green logistics practices. This study originates from a collaborative research project with two Italian companies involved in emissions-reduction initiatives, both seeking an evaluation tool to assess their performance in adopting green logistics practices and identify potential areas for improvement. In the following sections, the GreLoM model is presented as a new proposed MM (Section 4.1), its validation is discussed (Section 4.2), and finally, its application to two case studies is detailed (Section 4.3).

4.1. Maturity model proposal

Following the methodology outlined in Section 3, the proposal for the new GreLoM model was developed based on the previous GLMM of Ferraro et al. (2023b) and integrating the existing literature on logistics MMs (Table 1). Additionally, the GreLoM model was assessed through semi-structured interviews with a group of corporate practitioners in supply chain and logistics management. These practitioners, who have extensive knowledge of logistics processes and expertise in green practices, provided insights and comments into the model's completeness and practicality. Specifically, the interviews aimed to refine and update the elements of the previous MM and, combined with evidence from the literature, to propose the new GreLoM model.

From a conceptual standpoint, the GreLoM model retains the widely used maturity and performance frameworks of the GLMM and employs a stage-based evaluation structure using a 5-level Likert scale questionnaire as the measurement tool. However, feedback from experts who evaluated the previous model indicated that GLMM was "*too broad, with the risk of losing industrial applicability*." One expert noted that "*while the model provides a good overview, its general nature makes it hard to apply to specific industries where more tailored solutions are needed*". Moreover, the dimensions and sub-dimensions of the previous model were described as "*lacking clarity and requiring more detailed descriptions*". Another expert pointed out that "*the sub-dimensions are not always well-defined, which makes it difficult for practitioners to accurately assess different areas of logistics performance. A more precise breakdown would make the model more user-friendly and applicable*". In particular, the term resources was considered as "*too generic, as assessments vary significantly depending on the type and use of resources within different processes*". An expert explained, "*Resources can refer to anything from labor to equipment and packaging materials, and each of these has a very different impact on logistics processes. Without clear distinctions, it's hard to ensure consistency in evaluations across different areas*" Additionally, in the process management dimension, experts pointed out that "*the (GLMM) model lacked a specific section for evaluating the operating conditions of various resources*". Another comment emphasized that "*operating conditions are critical, especially for machinery and IT systems. Without assessing how these resources function under different conditions, the model misses key factors that affect operational efficiency and reliability*". Another point raised was the model's "*limited focus on inventory execution activities and their impact on the overall process, such as space utilization, low inventory turnover, and discrepancies between physical stock and digital records*". One expert noted, "*inventory management directly affects logistics performance. Issues like stock inaccuracies or inefficient use of space can cause disruptions in the entire supply chain, leading to delays, increased costs and emissions*". Experts also suggested the need to include an additional dimension to address "*process defects that can lead to inefficiencies and additional corrective actions, which compromise overall operations*". It was pointed out that "*process defects are a major source of operational waste. If the model does not account for these, it fails to capture the true drivers of inefficiency in logistics systems*". Within the network management dimension, experts observed that "*some high-level operational concepts were not sufficiently clear, particularly regarding supply chain network reconfiguration*". Furthermore, although the model effectively addressed horizontal and vertical collaboration, it was noted that "*lateral collaboration lacked practical relevance*". Finally, while the previous model was seen as "*fairly comprehensive from a management perspective, it overlooked the increasingly regulated area of sustainability reporting*". One expert concluded, "*with stricter regulations and growing expectations around sustainability, the model should include provisions for assessing sustainability performance and reporting*". Therefore, the new model proposal needs to integrate additional elements to address these gaps and align with current industry requirements.

To address the general scope of the previous MMs and integrate the evaluated GLMM by experts' insights, GreLoM model revises the modeling framework's elements, incorporating four dimensions and eleven sub-dimensions (see Table 4). Building on the initial dimensions of resource management (D1), process management (D2), and network management (D3), the proposed model adds the fourth dimension of sustainable reporting (D4). This addition is based on the experience and insights of the practitioners involved in the design phase.

The first dimension (D1), resource management, encompasses three sub-dimensions:

- Emission assessment (S1.1) evaluates how companies measure emissions from resources used in logistics activities. These resources can be divided into capital resources (e.g., technologies, equipment, and machinery), and consumable resources, including support materials for capital resources and packaging materials for transported products. This sub-dimension considers both the extent of adoption and the comprehensiveness of these assessment strategies. The following model items are proposed for measuring this sub-dimension: Capital resource emission assessment adoption (I1), Consumable resource emission assessment adoption (I2), Capital resource emission assessment completeness (I3), and Consumable resource emission assessment completeness (I4).
- Emission prediction (S1.2) also considers both capital and consumable resources but focuses on assessing future emissions rather than current or past ones. This sub-dimension can be measured through the following model items: Capital resource emission prediction adoption (I5), Consumable resource emission prediction adoption (I6), Capital resource emission prediction completeness (I7), and Consumable resource emission prediction completeness (I8).
- Useful life condition evaluation (S1.3) examines the lifespan of resources used in logistics practices and the recovery strategies that revalue resources typically considered obsolete or at the end of their life cycle through circular economy business models. This sub-dimension is measured using the following model items: Resource useful life condition evaluation (I9), Capital resource recovery strategy adoption (I10), and Consumable resource recovery strategy adoption (I11).

The second dimension, process management, has undergone substantial changes compared with the previous GLMM with the definition of five new sub-dimensions:

- Process evaluation (S2.1) examines logistics processes for their planning and optimization. This evaluation assesses how well organizations can plan, implement, review, and improve their strategies. This sub-dimension is measured through the model items: Process planning (I12) and Process optimization (I13).
- Capital operating condition evaluation (S2.2) exclusively evaluates capital resources, focusing on their operational aspects and the organization's ability to measure specific parameters. These parameters include utilization rate, availability, and saturation within the logistics system. Additionally, load capacity estimates and reliability can impact the management of processes within green logistics practices. The model items used to measure this sub-dimension: Capital resource utilization (I14), Capital resource availability (I15), Capital resource saturation (I16), Capital resource capacity (I17), and Capital resource reliability (I18).
- Consumable operating condition evaluation (S2.3), analogous to the previous sub-dimension, focuses on consumable resources and their performance within the logistics process. Considerations include availability, capacity, and waste generation, measured by the model items: Consumable resource availability (I19), Consumable resource capacity (I20), and Consumable resource waste generation (I21).
- Inventory condition evaluation (S2.4) focuses on process activities within inventory management flows, assessing how effectively and efficiently these activities and systems are managed. Specifically, it considers warehouse space utilization, the rate of slow-moving inventory, and the discrepancy between actual and recorded

Table 4
Items for the evaluation of the new green logistics maturity model within the relevant sub-dimensions.

Sub-dimension	Item	Item description
Emission assessment (S1.1)	Capital resource emission assessment adoption (I1)	Capital resource emission assessment adoption refers to the extent to which organizations assess the emissions associated with their capital resources used in logistics activities
	Consumable resource emission assessment adoption (I2)	Consumable resource emission assessment adoption refers to the extent to which organizations assess the emissions associated with their consumable resources used in logistics activities
	Capital resource emission assessment completeness (I3)	Capital resource emission assessment completeness refers to the comprehensiveness of the information included in the actual emission produced by the capital resources in logistics activities (es. operating conditions, degradation, efficiency, …)
	Consumable resource emission assessment completeness (I4)	Consumable resource emission assessment completeness refers to the comprehensiveness of the information included in the actual emission produced by the consumable resources in logistics activities (es. operating conditions, degradation, efficiency, …)
Emission prediction (S1.2)	Capital resource emission prediction adoption (I5)	Capital resource emission prediction adoption refers to the extent to which organizations predict the emissions associated with their capital resources used in logistics activities
	Consumable resource emission prediction adoption (I6)	Consumable resource emission prediction adoption refers to the extent to which organizations predict the emissions associated with their consumable resources used in logistics activities
	Capital resource emission prediction completeness (I7)	Capital resource emission prediction completeness refers to the comprehensiveness of the information included in the future emission produced by the capital resources in logistics activities (es. operating conditions, degradation, efficiency, …)
	Consumable resource emission prediction completeness (I8)	Consumable resource emission prediction completeness refers to the comprehensiveness of the information included in the future emission produced by the consumable resources in logistics activities (es. operating conditions, degradation, efficiency, …)
Useful life condition evaluation (S1.3)	Resource useful life condition evaluation (I9)	Resource useful life condition evaluation refers to the extent to which organizations assess the overall condition and lifespan of their resources used in logistics activities
	Capital resource recovery strategy adoption (I10)	Capital resource recovery strategy adoption refers to the extent to which organizations implement strategies to recover and reuse capital resources in their logistics activities (es. reuse, repair, remanufacture, recycle, …)
	Consumable resource recovery strategy adoption (I11)	Consumable resource recovery strategy adoption refers to the extent to which organizations implement strategies to recover and reuse consumable resources in their logistics activities (es. reuse, repair, remanufacture, recycle, …)
Process evaluation (S2.1)	Process planning (I12)	Process planning refers to the extent to which structured plans and strategies are developed and implemented for logistics activities
	Process optimization (I13)	Process optimization refers to the extent to which logistics activities are refined and improved to achieve maximum efficiency and effectiveness
Capital operating condition evaluation (S2.2)	Capital resource utilization (I14)	Capital resource utilization refers to the actual time resources are used compared to the total available time for logistics activities
	Capital resource availability (I15)	Capital resource availability refers to the actual time resources are utilized, excluding breakdowns and maintenance, compared to the total actual utilization time
	Capital resource saturation (I16)	Capital resource saturation refers to the actual utilization time of resources, net of both empty trips and loading/unloading times, compared to the utilization time of resources net of breakdowns and maintenance
	Capital resource capacity (I17)	Capital resource capacity refers to the actual loading capacity of resources compared to the nominal loading capacity of resources
	Capital resource reliability (I18)	Capital resource reliability refers to the probability that operational resources retain their functional capacities after a predetermined period of time for which they were designed
Consumable operating condition evaluation (S2.3)	Consumable resource availability (I19)	Consumable resource availability refers to the available amount of consumable resources, such as packaging materials, fuel, and other supplies, necessary for your logistics activities
	Consumable resource capacity (I20)	Consumable resource capacity refers to the capacity of consumable resources, such as packaging materials, fuels, and other supplies, to be utilized in comparison to their nominal or expected quantity
	Consumable resource waste generation (I21)	Consumable resource waste generation refers to the amount of waste produced from consumable resources, such as packaging materials, fuel, and other supplies, during your logistics activities
Inventory condition evaluation (S2.4)	Inventory space utilization (I22)	Inventory space utilization refers to the efficiency with which storage space is used for inventory within your logistics activities

(continued on next page)

Table 4 (*continued*)

Sub-dimension	Item	Item description
	Slow-moving inventory (I23)	Slow-moving inventory refers to items in your inventory that have a low turnover rate and remain in storage for an extended period
	Inventory inaccuracy refers (I24)	Inventory inaccuracy refers to the discrepancy between recorded and actual inventory levels
Process defects evaluation (S2.5)	Process defects generation (I25)	Process defects generation refers to the frequency and extent to which nonconformities, errors, and inefficiencies occur in your logistics processes
	Process defects identification (I26)	Process defects identification refers to the extent to which nonconformities, errors, and inefficiencies in logistics processes are recognized and documented
Network collaboration (S3.1)	Horizontal collaboration (I27)	Horizontal collaboration refers to the degree of cooperation and partnership among multiple players or entities within the same level of supply chain networks
	Vertical collaboration (I28)	Vertical collaboration refers to the degree of cooperation and partnership among multiple players or entities within different levels of supply chain networks
Information sharing (S3.2)	Environmental footprints sharing (I29)	Environmental footprints sharing refers to the extent to which various stakeholders involved in logistics activities, such as suppliers, manufacturers, distributors, and retailers, exchange and communicate information regarding their environmental impact (e.g., carbon footprint, water footprint, resource footprint, …)
	Current practices sharing (I30)	Current practices sharing refers to the extent to which various stakeholders involved in logistics activities, such as suppliers, manufacturers, distributors, and retailers, exchange and communicate their existing methods, processes, and practices
	Improvement strategies sharing (I31)	Improvement strategies sharing refers to the extent to which various stakeholders involved in logistics activities, such as suppliers, manufacturers, distributors, and retailers, exchange and communicate strategies aimed at enhancing green logistics
Sustainable reporting (S4.1)	Sustainability reporting adoption (I32)	Sustainability reporting adoption refers to the extent to which organizations integrate sustainability practices into their logistics activities and disclose related information through structured frameworks (es. Global Reporting Initiatives, Sustainability Accounting Standards Boards, Carbon Disclosure Project, …)
	Sustainability reporting completeness (I33)	Sustainability reporting completeness refers to the comprehensiveness of the information included in your sustainable reporting specifically related to logistics activity (es. energy use, water use, material and resource use, …)

inventory. The model items for measuring this sub-dimension: Inventory space utilization (I22), Slow-moving inventory (I23), and Inventory inaccuracy (I24).

- Process defects evaluation (S2.5) addresses issues related to process errors and product defects, evaluating how well companies can control the process based on the generation and identification of errors. This is measured through the model items: Process defects generation (I25) and Process defects identification (I26).

Within the third dimension, network management, the sub-dimensions have been revised and are now defined as:

- Network collaboration (S3.1) evaluates the organization's positioning relative to other actors in the supply chain. It assesses the extent to which the company collaborates with actors at the same level of the supply chain (horizontal collaboration) and with actors at different levels of the supply chain (vertical collaboration). This sub-dimension is measured through the model items: Horizontal collaboration (I27) and Vertical collaboration (I28).
- Information sharing (S3.2) considers the sharing of relevant information to ensure the improvement of green practices within business processes. The relevant information includes environmental footprints, current practices, and improvement strategies. This sub-dimension is evaluated through the model items: Environmental footprints (I29), Current practices sharing (I30), and Improvement strategies (I31).

Finally, the fourth dimension of sustainable reporting is described by a single sub-dimension:

- Sustainable reporting (S4.1) draws on the increasing demand for both internal and external sustainability reporting and awareness efforts. This sub-dimension evaluates whether organizations adopt these activities and the level of detail in their analysis. Consequently, this fourth sub-dimension is measured through the model items: Sustainability reporting adoption (I32) and Sustainability reporting completeness (I33).

Fig. 2 presents a conceptual framework of the revised GreLoM model described in this work. In the new proposal, compared to the preliminary GLMM of Ferraro et al. (2023b), modifications are highlighted in red. Elements with only red text represent partial content modifications compared to the elements in the preliminary MM. Elements with both red text and red outlines indicate substantial content modifications. Newly added elements are represented by connections illustrated with red lines.

Considering the maturity framework, the new GreLoM model evaluates the maturity level of green logistics based on Equations (1)–(3) through a structured questionnaire, which measures specific items for each sub-dimension. These items are detailed in Table 4, and the associated questions for the GreLoM model application are provided in Appendix A (see Table A1). Although the questionnaire adopts a qualitative approach, the use of quantitative evidence can improve the reliability and consistency of the responses. Companies are therefore encouraged to support their answers by referring to quantitative data extracted from internal information systems or by leveraging external industrial

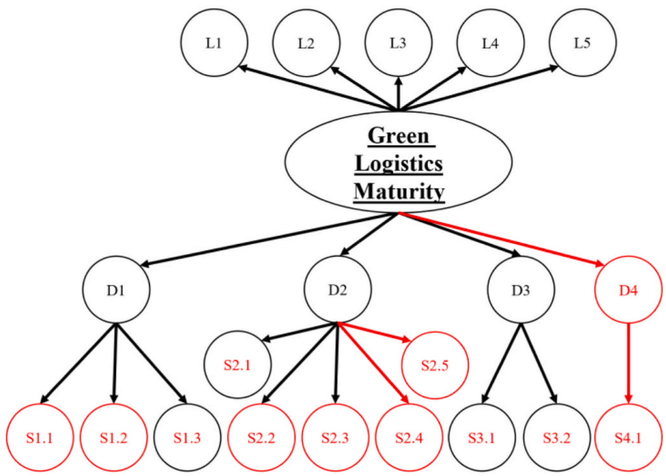


Fig. 2. Conceptual framework of the proposed GreLoM model representing the identified levels (L), dimensions (D), and sub-dimensions (S).

references and benchmarks, including national and international reports and databases (OECD, 2025; World Bank Group, 2022; Shukla et al., 2022). This triangulation between qualitative perception and quantitative data enhances the validity of the model output and supports a more robust maturity assessment. The maturity level evaluation is structured across the following five levels, considering a stage-based approach:

- Level 1 "Completely Immature": The analyzed process is deemed completely immature, as the evaluation reveals no adoption of the elements across the four dimensions identified by the GreLoM model. At this level, the company has no awareness of the environmental impact of its logistics processes, which are considered harmful.
- Level 2 "Partially Immature": The process is classified as partially immature, with the evaluation showing minimal adoption of the elements from the four dimensions of the GreLoM model. The company demonstrates limited awareness of the environmental impact of its logistics processes at this stage.
- Level 3 "Neither Immature nor Mature": The process falls between immaturity and maturity in terms of green logistics. At this level, the company has some awareness of the environmental impacts of its processes and has begun to adopt a few practices outlined in the four dimensions.
- Level 4 "Partially Mature": The process is considered partially mature, as the evaluation reflects a good level of adoption of the elements from the four dimensions. The company is aware of its environmental impacts and has implemented sustainable practices as defined by the GreLoM model, though not comprehensively.
- Level 5 "Completely Mature": The process is regarded as completely mature, as the evaluation shows full or near-complete adoption of the elements in the four dimensions of the model. At this level, the company is fully aware of its environmental impacts and has implemented strategies to assess and continuously improve its processes to monitor and reduce emissions.

4.2. Maturity model validation

With the proposed GreLoM model, it is possible to proceed with the test phase. In this study, the validity and reliability of the model were conducted by measuring the CVR (Equation (4)) of the elements of the new MM and Cronbach's alpha coefficient (Equation (5)). Measurements of these indicators were conducted by gathering responses from 26 participants using a structured questionnaire employing a 5-point Likert scale. The respondent sample included 15 practitioners from manufacturing and logistics service companies in senior managerial positions (senior managers, junior managers, specialists) and 11 academics from various levels. Table 5 provides detailed information regarding their organizational/academic roles. As shown, the sample of respondents is both balanced and sufficient to conduct the model's validation effectively.

Based on the number of participants, the minimum CVR value to assume an element is valid is 0.385 (Ayre and Scally, 2014). The measure is calculated considering the number of experts indicating whether an element is relevant (n_e) for evaluating the maturity of green logistics. For 5-point Likert scale questionnaires, this includes all experts who score the item above 3. With an acceptable minimum CVR value, the minimum required n_e is 18. Table 6 presents the results of the analysis. Out of the 33 identified items based on the preliminary model of Ferraro et al. (2023b) and expert contributions, only two were deemed unacceptable. The not valid items are "Slow-moving inventory" (I23) and "Horizontal collaboration" (I27), indicated in the table in italics and red text. The first item achieved consensus on relevance from 15 respondents, while the second from 14 respondents, thus resulting in CVR values of 0.154 and 0.077, respectively. Since these CVR values are below the acceptable minimum, they were excluded from the GreLoM model. Therefore, the new MM is described with 4 dimensions, 11 sub-dimensions, and 31 items.

The revised model underwent reliability testing using Cronbach's alpha measure of 0.97, indicating excellent reliability. Similarly, all dimensions demonstrated acceptable levels of internal consistency. Specifically, the dimensions "Resource Management" (D1), "Process Management" (D2), and "Sustainability Reporting" (D4) exhibited excellent reliability, with Cronbach's alpha coefficients of 0.958, 0.916, and 0.930, respectively. The "Network Management" dimension (D3) showed a slightly lower, yet still satisfactory, level of internal consistency, with an alpha of 0.829. Therefore, it can be concluded that both the model and the dimensions results are accurate and repeatable. The sub-dimensions also showed appropriate Cronbach's alpha level, considering the threshold value of 0.6 reported by Susanty et al. (2020). Considering the first dimension (i.e., Resource Management), the Cronbach's alpha of "Emission Assessment" (S1.1), "Emission Prediction" (S1.2), and "Useful life condition evaluation" (S1.3) were estimated at 0.946, 0.679, and 0.962 respectively. Regarding the second dimension (i.e., "Process Management"), the Cronbach's alpha of the sub-dimension are as follows: 0.905 for "Process Evaluation" (S2.1), 0.871 for "Capital operating condition evaluation" (S2.2), 0.675 for "Consumable operating condition evaluation" (S2.3), 0.860 for "Inventory condition evaluation" (S2.4), and 0.883 for "Process defects evaluation" (S2.5). The third dimension (i.e., "Network Management") has only one sub-dimension for which the Cronbach's alpha can be estimated since the other sub-dimension is composed of a single item. The sub-dimension "Information sharing" (S3.2) has an estimated Cronbach's alpha of 0.777. Finally, the Cronbach's alpha of the sub-dimension "Sustainable reporting" (S4.1) was computed ad 0.930.

4.3. Maturity model application

Once validated, the proposed GreLoM model was applied to five case studies of companies engaged daily in logistics activities. However, this paper presents the results of the two most relevant cases. These two case studies were selected based on their participation in a research project aimed at developing a green logistics assessment tool and, compared to

Table 5
Biographic information regarding respondents for the validation of the GreLoM model.

Position by practitioners	Occurrences	Position by academics	Occurrences
Senior manager	4	Associate professor	5
Junior manager	4	Assistant professor	2
Specialist	7	PhD student	4
Total	**15**	**Total**	**11**

Table 6
Statistics for the validation of the GreLoM model items.

I-ID	Item	μ	SD	n_e	*CVR*
I1	Capital resource emission assessment adoption	4.077	0.628	22	0.692
I2	Consumable resource emission assessment adoption	4.154	0.675	22	0.692
I3	Capital resource emission assessment completeness	4.000	0.748	19	0.462
I4	Consumable resource emission assessment completeness	4.115	0.766	20	0.538
I5	Capital resource emission prediction adoption	3.885	0.588	20	0.538
I6	Consumable resource emission prediction adoption	3.923	0.628	20	0.538
I7	Capital resource emission prediction completeness	3.962	0.599	21	0.615
I8	Consumable resource emission prediction completeness	3.923	0.628	20	0.538
I9	Resource useful life condition evaluation	4.154	0.732	21	0.615
I10	Capital resource recovery strategy adoption	4.038	0.774	19	0.462
I11	Consumable resource recovery strategy adoption	4.077	0.796	19	0.462
I12	Process planning	4.269	0.724	22	0.692
I13	Process optimization	4.308	0.788	21	0.615
I14	Capital resource utilization	4.077	0.688	21	0.615
I15	Capital resource availability	3.923	0.744	18	0.385
I16	Capital resource saturation	4.077	0.796	19	0.462
I17	Capital resource capacity	4.000	0.693	20	0.538
I18	Capital resource reliability	4.154	0.732	21	0.615
I19	Consumable resource availability	4.038	0.824	20	0.538
I20	Consumable resource capacity	4.038	0.774	19	0.462
I21	Consumable resource waste generation	4.423	0.703	23	0.769
I22	Inventory space utilization	3.846	0.834	19	0.462
I23	*Slow-moving inventory*	*3.692*	*0.884*	*15*	*0.154*
I24	Inventory inaccuracy	3.846	0.967	18	0.385
I25	Process defects generation	4.192	0.849	21	0.615
I26	Process defects identification	3.962	0.958	18	0.385
I27	*Horizontal collaboration*	*3.808*	*0.939*	*14*	*0.077*
I28	Vertical collaboration	4.115	0.864	20	0.538
I29	Environmental footprints sharing	4.000	0.800	18	0.385
I30	Current practices sharing	4.077	0.796	19	0.462
I31	Improvement strategies sharing	4.231	0.710	22	0.692
I32	Sustainability reporting adoption	4.077	0.628	22	0.692
I33	Sustainability reporting completeness	4.115	0.711	21	0.615

other cases, involved a larger number of participants. The comprehensive analysis of all five case studies is reported in Appendix B (see Table B1 and Table B2). Additionally, Figure B1 illustrates the logical application process of the tool through a flowchart representation, outlining the necessary steps to assess green logistics maturity and identifying the strategies to be introduced in model areas where sub-dimensions show low scores. It is essential to emphasize that the model application aims not to demonstrate the model's versatility but rather to verify its applicability. Specifically, the application addresses the descriptive, comparative, and prescriptive objectives of the GreLoM model. From a descriptive perspective, the application enables an assessment of the current state of the case studies based on the values of sub-dimensions, dimensions, and the overall maturity level. From a comparative standpoint, the GreLoM model is employed to compare the cases, identifying gaps across the various elements of the model. Finally, from a prescriptive perspective, the model is intended to provide a prioritized list of improvement areas, comparing the model's recommendations with those proposed by practitioners. From the analysis of the results, it will be possible to identify and improve critical areas from both the model and practitioners' perspectives. For reasons of non-disclosure agreements, the companies will henceforth be referred to as Company Alpha and Company Beta (with Company Gamma, Company Delta, and Company Epsilon included in Appendix B). Both companies operate in Italy, each with its own specificities. Company Alpha is classified as a small-sized logistics service provider, while Company Beta operates as a manufacturing enterprise in the oil and gas sector (with Company Gamma as a manufacturing enterprise in the automotive sector, Company Delta as a medium-sized organization in the telecommunication industry, and Company Epsilon as a small-sized manufacturing company for industrial and automation systems). Both are united by their focus on energy efficiency and reducing the environmental impact of their industrial processes. For each case study, key managers, engineers, and technicians responsible for logistics activities were consulted. This defined a sample of 4 respondents for Company Alpha and 11 experts for Company Beta (with 1 expert for Company Gamma, 1 for Company Delta, and 2 for Company Epsilon). The experts were consulted, and each of them completed a questionnaire to evaluate the level of green logistics maturity. To facilitate completion, the questionnaire was administered in person to respondents from both organizations. Initially, an introduction was provided on the concept of green logistics—defined as the adoption of practices and techniques to reduce environmental externalities—as well as on the significance of MMs, and how they can be structured and measured. Additionally, based on literature evidence and expert opinions, green logistics was presented as measurable through practices across the four areas in the GreLoM model: resource management, process management, network management, and sustainability reporting. Subsequently, each participant from the company of each case study was asked to complete the questionnaire, rating each element of every sub-dimension on a 5-point Likert scale. This scale allowed the participants to assess not only how mature they consider the company to be for each element (model's perspective) but also how urgent and prioritized they perceive each sub-dimension to be for the adoption of improvement plans (practitioners' perspective). During this phase, practitioners were also encouraged—wherever applicable and for quantitatively measurable items—to align the Likert scale ratings with available data from internal company reports and databases, ensuring consistency between subjective assessments and objective measures. For completeness, Table A1 in Appendix A provides the questionnaire used to apply the validated model.

Applying Equations (1)–(3) of the performance framework revealed that Company Alpha has a maturity level of 3, while Company Beta has a level of 4 (with Company Gamma 3, Company Delta 4, and Company Epsilon 3). For more detailed information, Figs. 3 and 4 present the weighted results of the dimensions and sub-dimensions for both case studies, while Figure B2 and Figure B3 in Appendix B report the results for all the five case studies.

Regarding dimensions, Company Alpha achieved the highest score for Network Management (D3) at 3.00, followed by Process Management (D2) and Resource Management (D1) with scores of 2.92 and 2.60, respectively. Sustainable Reporting (D4) scored the lowest at 2.56. In contrast, Company Beta, which achieved a higher maturity level of 4,

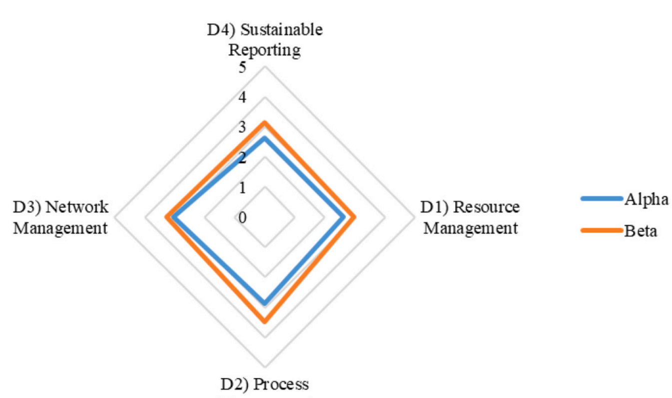


Fig. 3. Scoring of GreLoM model dimensions in the application to two case studies.

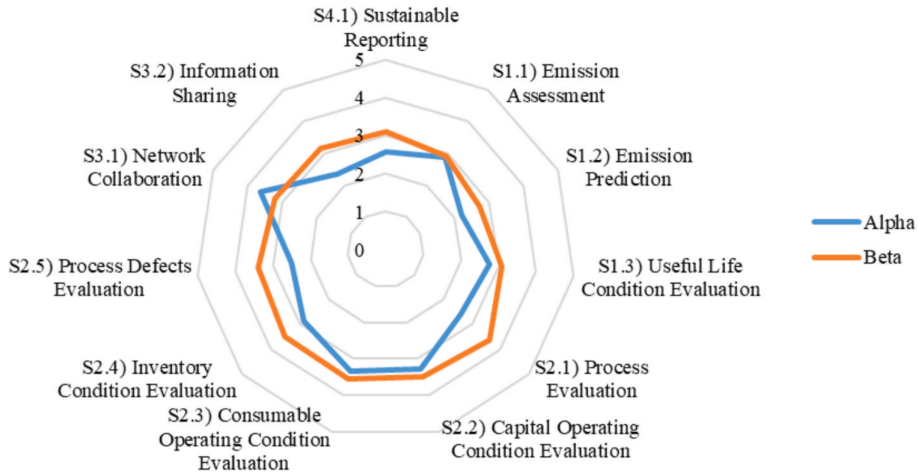


Fig. 4. Scoring of GreLoM model sub-dimensions in the application to two case studies.

scored highest for Process Management (D2) at 3.51, followed by Network Management (D3) and Sustainable Reporting (D4) with scores of 3.19 and 3.10, respectively. Resource Management (D1) scored the lowest at 2.91. From a comparative perspective, Company Alpha scored lower on each GreLoM model dimension compared to Company Beta, indicating a higher current inclination towards green logistics practices by the latter.

The results for dimensions can be further elaborated based on the scores obtained for each sub-dimension. Sub-dimensions can be clustered into three groups indicating those with the highest scores suggesting less need for improvement (low), those with intermediate scores and a non-priority need for improvement (medium), and those with the lowest scores thus requiring organizational focus to improve associated practices within the relevant sub-dimensions (high). Descriptively, Company Alpha scored highest for the sub-dimensions of Network Collaboration (S3.1), Consumable Operating Condition Evaluation (S2.3), and Capital Operating Condition Evaluation (S2.2) with scores of 3.63, 3.33, and 3.28, respectively. In the intermediate range are the sub-dimensions of Inventory Condition Evaluation (S2.4), Emission Assessment (S1.1), Useful Life Condition Evaluation (S1.3), Process Evaluation (S2.1), and Sustainable Reporting (S4.1) with scores of 2.88, 2.88, 2.75, 2.63, and 2.56, respectively. Finally, within the last group are the sub-dimensions of Process Defects Evaluation (S2.5), Information Sharing (S3.2), and Emission Prediction (S1.2) with scores of 2.5, 2.38, and 2.19. Based on aggregated and weighted scores for each element, these sub-dimensions indicate starting points for improving green logistics maturity. In contrast, Company Beta shows results, albeit with higher scores of different model elements, considering sub-dimensions within the three groups for which the model recommends improvement. Indeed, the three sub-dimensions with the highest scores for Company Beta are Process Evaluation (S2.1), Consumable Operating Condition Evaluation (S2.3), and Inventory Condition Evaluation (S2.4) with scores of 3.63, 3.54, and 3.51, respectively. The second group that does not need urgent improvement includes sub-dimensions Capital Operating Condition Evaluation (S2.2), Process Defects Evaluation (S2.5), Network Collaboration (S3.1), Information Sharing (S3.2), and Sustainable Reporting (S4.1) with scores of 3.49, 3.39, 3.21, 3.16, and 3.10, respectively. Finally, the model's most critical sub-dimensions that score lowest for Company Beta are Useful Life Condition Evaluation (S1.3), Emission Assessment (S1.1), and Emission Prediction (S1.2) with scores of 3.09, 2.92, and 2.72, respectively. Descriptively, Company Alpha shows almost all sub-dimensions with a lower score, except for Network Collaboration (S3.1) and Emission Prediction (S1.1), for which both companies achieve nearly the same score. The companies are also closely related in terms of Capital Operating Condition Evaluation (S2.2) and Consumable Operating Condition Evaluation (S2.3). The highest difference between companies is recorded from Process Evaluation (S2.1), followed by Process Defects Evaluation (S2.5) and Information Sharing (S3.2).

From the above results, the GreLoM model allows analysis of companies through a descriptive, comparative, and partially prescriptive approach. Indeed, from the results of the sub-dimensions and their clustering into three priority improvement areas, it is possible to recommend which sub-dimensions can be prioritized for improving green logistics maturity. To further analyze this within the questionnaire, respondents from both companies further provided their judgments on the improvement of each sub-dimension, assessing them based on adoption priority and adoption urgency. As outlined in Section 3, adoption priority reflects the importance of a sub-dimension in supporting long-term strategic goals, while adoption urgency highlights the need for immediate adoption of a sub-dimension to address short-term challenges. From the aggregated and weighted scores, Fig. 5 reports the results by representing them through a priority matrix, indicating on the left Company Alpha and on the right Company Beta (while Figure B4 reports the priority map for Company Gamma, Company Delta, and Company Epsilon). More specifically, sub-dimensions in the upper-right quadrant of the matrix exhibit high values in both adoption priority and adoption urgency, indicating their critical role in both short-term and long-term improvements. Conversely, sub-dimensions in the lower-left quadrant show low values for both adoption urgency and adoption priority. The remaining two quadrants reflect sub-dimensions with opposite values for the two criteria of adoption.

As shown in Fig. 5, both companies consider sub-dimensions with a high score of adoption urgency identifying the interest of both companies to introduce the short-term improvement of the model items of each sub-dimension. However, Company Alpha distinguishes some sub-dimensions with higher adoption priority than others, such as the ones of Process Defect (S2.5) and Network Collaboration (S3.1). Company Alpha also considers the sub-dimension of Information Sharing (S3.2) the most urgent despite this being considered the least prioritized. In a

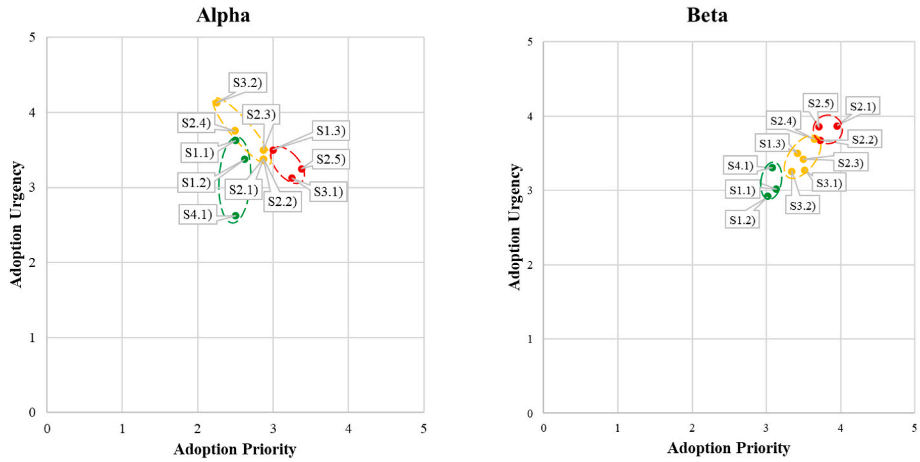


Fig. 5. Priority matrix of the GreLoM model based on respondents' perspective to two case studies.

different way, Company Beta shown through the right of Fig. 5 reports sub-dimensions ordered towards a portion of the chart indicating high adoption urgency and adoption priority. Company Alpha identifies the least urgent and prioritized sub-dimension related to Emission Prediction (S1.2) and the most urgent and prioritized sub-dimension of Process Evaluation (S2.1). By multiplying the scores for each sub-dimension regarding adoption priority and adoption urgency, it is possible to classify in an ordered manner how the respondents indicate which sub-dimensions of the GreLoM model consider more relevant for improving the green logistics maturity level. This method enables the classification of sub-dimensions based on their improvement needs from the practitioners' perspective. For Company Alpha, Emission Assessment (S1.1), Emission Prediction (S1.2), and Sustainable Reporting (S4.1) are marked in green with low need of improvement. Similarly, for Company Beta these sub-dimensions can be clustered in the group less need for improvement (low). In contrast, sub-dimensions rated as medium need for improvement in Company Alpha include Consumable Operating Condition Evaluation (S2.3), Process Evaluation (S2.1), Capital Operating Condition Evaluation (S2.2), Inventory Condition Evaluation (S2.4), and Information Sharing (S3.2). For Company Beta, the medium group sub-dimensions are Inventory Condition Evaluation (S2.4), Useful Life Condition Evaluation (S1.3), Consumable Operating Condition Evaluation (S2.3), Network Collaboration (S3.1), and Information Sharing (S3.2), indicated in orange. The most critical sub-dimensions for improvement (high), marked in red, for Company Alpha are Process Defects Evaluation (S2.5), Useful Life Condition Evaluation (S1.3), and Network Collaboration (S3.1). For Company Beta, they include Process Evaluation (S2.1), Process Defects Evaluation (S2.5), and Capital Operating Condition Evaluation (S2.2).

Table 7
Results of discrepancy index from model's perspective e practitioner's perspective on sub-dimensions enhancement for green logistics maturity levelling to two case studies.

Alpha					
l	Model's perspective sub-dimensions	Practitioners' perspective sub-dimensions	$n_{m,p}$	s	δ_l
High	S1.2, S3.2, S2.5	S2.5, S1.3, S3.1	1	3	0.66
Medium	S4.1, S2.1, S1.3, S1.1, S2.4	S2.3, S2.1, S2.2, S2.4, S3.2	2	5	0.60
Low	S2.2, S2.3, S3.1	S1.1, S1.2, S4.1	0	3	1.00
Beta					
l	**Model's perspective sub-dimensions**	**Practitioners' perspective sub-dimensions**	$n_{m,p}$	s	δ_l
High	S1.2, S1.1, S1.3	S2.1, S2.5, S2.2	0	3	1.00
Medium	S4.1, S3.2, S3.1, S2.5, S2.2	S2.4, S1.3, S2.3, S3.1, S3.2	2	5	0.60
Low	S2.4, S2.3, S2.1	S4.1, S1.1, S1.2	0	3	1.00

These results can be compared with those obtained from the application of the GreLoM model, thereby calculating how much the perception of the sub-dimension most important for improvement (practitioners' perspective) is actually consistent with sub-dimensions that obtained low values from the model application (model's perspective). Table 7 shows the results considering the three groups for calculating the discrepancy index δ_l (Equation (6)). As shown by the results, both companies have high discrepancy values for all three groups. Among the two, Company Beta records the highest discrepancy for both the group of sub-dimensions rated as high priority ($\delta_{high} = 1.00$) and the group of sub-dimensions with low priority for improvement ($\delta_{low} = 1.00$). Company Alpha, on the other hand, finds partial alignment for the sub-dimensions within the highly prioritized ($\delta_{high} = 0.66$) and medium prioritized ($\delta_{medium} = 0.60$) group while it has no maximum discrepancy for the sub-dimensions within the group from the low priority to improvement ($\delta_{low} = 1.00$). Based on the results of the discrepancy index analysis, it is evident that while companies are interested in improving green logistics maturity, they differ in which sub-dimensions they prioritize for improvement. These companies tend to focus on sub-dimensions with relatively high scores, overlooking those with lower scores. This discrepancy is critical as companies may improve only the practices they are familiar with, neglecting other important aspects for measuring and enhancing green logistics maturity. Therefore, by prioritizing sub-dimensions with lower scores for improvement, a comprehensive enhancement can be achieved, addressing not only the practices already of interest to companies but also those that are less developed.

5. Discussion

Compared to existing literature, the GreLoM model follows a well-known modeling approach based on the methodology of De Bruin et al. (2005), which is not presented in other MMs concerning green logistics. Following this methodology, GreLoM model was proposed, validated, and applied, allowing the assessment of green logistics maturity from descriptive, comparative, and partially prescriptive perspectives. The proposed MM, developed through practitioners' insights and expanded dimensions and sub-dimensions of the previous model proposed by Ferraro et al. (2023b), addresses previous limitations and enhances practical utility within the scope of green logistics. Moreover, the validation of the GreLoM model confirmed the validity and reliability of the model elements. The structured design and application approach along with the rigorous testing phase ensure that the GreLoM model is both theoretically robust and practically applicable.

The GreLoM model is structured around four main dimensions: resource management (D1), process management (D2), network management (D3), and sustainable reporting (D4). Each dimension is further detailed with respective sub-dimensions and items for assessing the level of green logistics maturity. Evaluating how resources are managed is crucial for reducing resource consumption. Many works in the literature provide significant contributions to assessing the lifecycle impacts of logistics resources and multi-criteria analyses on sustainable technologies and strategies (Ferraro et al., 2023a), as well as recovery strategies to extend their useful life through the well-known concepts of circular economy (Mancusi et al., 2023). This concept, not thoroughly discussed in previous logistics MMs, is explored in this work through the first dimension of resource management (D1).

The concept of green logistics involves the application of practices and techniques to reduce environmental externalities, considering all logistics activities and related material flows (inbound, internal, and outbound logistics) (Dekker et al., 2012). These practices are highlighted within MMs for logistics, primarily focusing on process management to make them more efficient and sustainably managed. As indicated in Section 2.1, most authors attempt to describe the involved logistics activities as comprehensively as possible. However, this specificity is often limited to the scope and the company involved, describing only a portion of the logistics processes accurately. In this context, the resource management dimension (D2) generally considers logistics processes, allowing respondents to describe their processes and apply the model to various logistics activities. This facilitates comparative evaluations of their green logistics maturity levels.

Considering the complexity of supply chains, it is also essential to establish collaborative relationships among supply chain actors, benefiting not only individual companies economically but also the entire value chain environmentally. These concepts, increasingly evident in both practice and research (Akhtar et al., 2023), are addressed within the network management dimension (D3), which is rarely covered in previous logistics MMs. Finally, the addition of the sustainable reporting dimension (D4) meets the increasing demand for transparency and accountability in environmental performance. This enables organizations to better align their green initiatives with overall business strategies and effectively communicate their progress to stakeholders (Zhu et al., 2024).

Based on the findings, the application of the GreLoM model has enabled the extension of research in the field of logistics MMs by concretely addressing the main research streams for evaluating and managing green practices within logistics processes. This approach overcomes both methodological limitations and scope constraints. By applying the GreLoM model to two case studies, we identified each company's maturity level, allowing for a comparative assessment that notably revealed Company Beta to be more mature. The model ultimately prescribed priority intervention areas for each company, positioning it as a valuable decision-making tool. For Company Alpha, the GreLoM model recommended enhancing the sub-dimensions of Emission Prediction (S1.2) related to resource management, Information Sharing (S3.2) concerning network management, and Process Defects Evaluation (S2.5) regarding process management. Similarly, for Company Beta, suggested improvements included Emission Prediction (S1.2), Emission Assessment (S1.1), and Useful Life Condition Evaluation (S1.3), all focused on resource management. However, the model's recommendations do not fully align with what respondents perceive as urgent for short-term goals and prioritized for long-term objectives. From the practitioners' perspective, Company Alpha mainly aims to improve Process Defects Evaluation (S2.5) for process management, Useful Life Condition Evaluation (S1.3) for resource management, and Network Collaboration (S3.1) for network management. In contrast, Company Beta emphasizes Process Evaluation (S2.1), Process Defects Evaluation (S2.5), and Capital Operating Condition Evaluation (S2.2), all within the framework of process management. This discrepancy highlights a concerning tendency for companies to focus on improving familiar dimensions and elements, often neglecting those recommended by decision-support tools. This tendency can be attributed to internal biases and the specific contexts in which companies operate. To address this, using assessment tools grounded in scientific evidence and applicable beyond individual company contexts becomes increasingly valuable. The GreLoM model integrates both scientific insights and expert judgments, acting as a tool to reduce internal biases and promote awareness of current maturity levels and improvement areas. Additionally, by weighting evaluations of respondents, the model emphasizes insights from those with a deeper understanding of the processes, leading to a more balanced and insightful assessment.

6. Conclusion

This study proposes a new GreLoM model based on identified gaps in the existing literature and expert judgment. The GreLoM model assesses maturity across five levels using a structured questionnaire with a 5-point Likert scale. Following validation, the model identified four dimensions—resource management, process management, network management, and sustainable reporting—along with 11 sub-dimensions and 31 items. Furthermore, the GreLoM model was applied through descriptive, comparative, and prescriptive approaches reporting the results of two case studies. This section discusses the significant theoretical and practical implications of the work, as well as its main limitations and directions for future research.

6.1. Theoretical and practical implications

From a theoretical perspective, the GreLoM model advances the literature on green logistics by offering a more detailed and validated framework compared to previous MMs. The GreLoM model is a validated, multi-purpose tool that captures the often-overlooked tension between model-based and practitioner-led improvement priorities. Unlike other MMs that often stop at the design or application stages with limited or omitted validation, the GreLoM model addresses the gap by incorporating both content validity and reliability assessment. Practically, the GreLoM model provides a valuable tool for organizations seeking to assess and enhance their green logistics practices. Specifically, while the GreLoM model does not directly evaluate logistics process improvements, it does assess the organization's current state, enabling recommendations toward higher green logistics maturity. The proposed model integrates descriptive, comparative, and prescriptive approaches, overcoming the limitations of many existing MMs that typically focus only on descriptive and comparative methods. In contrast, the GreLoM model not only provides a descriptive overview and comparative benchmarks but also offers prescriptive recommendations through a priority matrix. Lastly, despite their differences in size and sector, neither Company Alpha nor Company Beta encountered difficulties in using the GreLoM model. This ease of application and the model's effectiveness in identifying areas for improvement were also confirmed in the additional three case studies presented in Appendix B.

6.2. Limitations and future developments

Despite its strengths, the study has several limitations that could serve as starting points for future developments. These limitations primarily concern the GreLoM model's scope, elements, and application. Firstly, from a scope perspective, the model assesses green logistics maturity in a general sense, without considering specific analyses of material flow types and their management. Starting from the proposed model, future studies can develop context-specific tools by performing the required amendments. Indeed, depending on the context, the relevance of items, sub-dimensions, and dimensions can vary. This can lead to remove or add model elements. Additionally, the GreLoM model focuses exclusively on green practices, overlooking economic and social sustainability. Future research could address this limitation by incorporating assessments of both economic analyses and social impacts Secondly, regarding the model's elements, the GreLoM model employs a Likert-like scale via a structured questionnaire. A potential development could involve refining the evaluation of green logistics maturity combining self-assessment with data from external sources. This would further enhance the GreLoM model's reliability by cross-validating the data obtained through the questionnaire with objective assessments. Moreover, integrating external data would enable a more operational approach to green logistics by outlining practices associated with maturity level for every item and sub-dimension. This approach would not only enhance the model's practical applicability but also align it with best practices and international guidelines for emission reduction goals. Thirdly, notable limitations pertain to the application of the GreLoM model. The first is the limited application of the model to only five case studies. Expanding the GreLoM model's application to a broader range of companies within the same industry, as well as across different sectors, could provide a more comparative view of the current state of various contexts. Such expansion would allow for testing the model's true versatility and generalizability. The second limitation lies in the model's application being limited to an initial one-time assessment. While this evaluation allows for the identification of priority areas for improvement, it does not extend to any form of periodic and dynamic reassessment. Additionally, although the tool effectively highlights areas requiring improvement, it does not provide specific guidance on which green strategies should be adopted based on the scores of maturity measurements. Moreover, the tracking of performance indicators before and after the identification of improvement strategies was not within the scope of this study. Future research could address this by conducting longitudinal pilot studies to test the model's effectiveness through repeated applications to address dynamic challenges. Furthermore, integrating quantitative performance metrics into the model (e.g., carbon emission reduction, energy consumption reduction, or cost savings) could strengthen the framework by evaluating the effectiveness of the strategies implemented. Lastly, the GreLoM model's guidance on improvements is based on sub-dimension evaluations and a priority matrix, which may be too general for organizations with low scores across all dimensions. To enhance the specificity of maturity level improvement, more structured approaches could be employed. In this regard, the development of an operational toolkit, informed by empirical studies of highly mature companies, could significantly strengthen the model's applicability. Furthermore, it could offer tailored suggestions based on company, size, industry sector, and geographic context. This enhancement would help bridge the gap between theoretical maturity assessment of GreLoM model and the effective implementation of green practices.

CRediT authorship contribution statement

Saverio Ferraro: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Leonardo Leoni:** Writing – review & editing, Visualization, Validation, Methodology, Conceptualization. **Alessandra Cantini:** Writing – review & editing, Visualization, Validation, Methodology, Conceptualization. **Valentina Di Pasquale:** Writing – review & editing, Methodology, Conceptualization. **Filippo De Carlo:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to proofread the manuscript. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

Table A1
Questionnaire designed to measure the maturity of green logistics practices. Responses are recorded using a Likert scale.

D1) Resource management

S1.1) Emission assessment

Based on the literature and confirmed by experts, we have seen that emission assessment might affect the maturity of a firm to adopt green logistics practices. More in detail, we have identified the following 4 items:

1. The item "Capital resource emission assessment adoption" refers to the extent to which organizations assess the emissions associated with their capital resources used in logistics activities.
2. The item "Consumable resource emission assessment adoption" refers to the extent to which organizations assess the emissions associated with their consumable resources used in logistics activities.
3. The item "Capital resource emission assessment completeness" refers to the comprehensiveness of the information included in the actual emission produced by the capital resources in logistics activities (es. operating conditions, degradation, efficiency, …).
4. The item "Consumable resource emission assessment completeness" refers to the comprehensiveness of the information included in the actual emission produced by the consumable resources in logistics activities (es. operating conditions, degradation, efficiency, …).

We would like you to state how well your company operates regarding each item of emission assessment.

Question	**1**	**2**	**3**	**4**	**5**
On a scale from 1 (Extremely low) to 5 (Extremely high) for your logistics activities, which is the level of adoption of emission assessment of your capital resources?					

(*continued on next page*)

Table A1 (*continued*)

D1) Resource management

On a scale from 1 (Extremely low) to 5 (Extremely high) for your logistics activities, which is the level of adoption of emission assessment of your consumable resources?
On a scale from 1 (Extremely low) to 5 (Extremely high) for your logistics activities, how complete is the emission assessment of your capital resources?
On a scale from 1 (Extremely low) to 5 (Extremely high) for your logistics activities, how complete is the emission assessment of your consumable resources?

S1.2) Emission prediction

Based on the literature and confirmed by experts, we have seen that emission prediction might affect the maturity of a firm to adopt green logistics practices. More in detail, we have identified the following 4 items:
1. The item "Capital resource emission prediction adoption" refers to the extent to which organizations predict the emissions associated with their capital resources used in logistics activities.
2. The item "Consumable resource emission prediction adoption" refers to the extent to which organizations predict the emissions associated with their consumable resources used in logistics activities.
3. The item "Capital resource emission prediction completeness" refers to the comprehensiveness of the information included in the future emission produced by the capital resources in logistics activities (es. operating conditions, degradation, efficiency, …).
4. The item "Consumable resource emission prediction completeness" refers to the comprehensiveness of the information included in the future emission produced by the consumable resources in logistics activities (es. operating conditions, degradation, efficiency, …).
We would like you to state how well your company operates regarding each item of emission prediction.

Question	**1**	**2**	**3**	**4**	**5**
On a scale from 1 (Extremely low) to 5 (Extremely high) for your logistics activities, which is the level of adoption of emission prediction of your capital resources?					
On a scale from 1 (Extremely low) to 5 (Extremely high) for your logistics activities, which is the level of adoption of emission prediction of your consumable resources?					
On a scale from 1 (Extremely low) to 5 (Extremely high) for your logistics activities, how complete is the emission prediction of your capital resources?					
On a scale from 1 (Extremely low) to 5 (Extremely high) for your logistics activities, how complete is the emission prediction of your consumable resources?					

S1.3) Useful life condition evaluation

Based on the literature and confirmed by experts, we have seen that useful life condition evaluation might affect the maturity of a firm to adopt green logistics practices. More in detail, we have identified the following 3 items:
1. The item "Resource useful life condition evaluation" refers to the extent to which organizations assess the overall condition and lifespan of their resources used in logistics activities.
2. The item "Capital resource recovery strategy adoption" refers to the extent to which organizations implement strategies to recover and reuse capital resources in their logistics activities (es. reuse, repair, remanufacture, recycle, …).
3. The item "Consumable resource recovery strategy adoption" refers to the extent to which organizations implement strategies to recover and reuse consumable resources in their logistics activities (es. reuse, repair, remanufacture, recycle, …).
We would like you to state how well your company operates regarding each item of useful life condition evaluation.

Question	**1**	**2**	**3**	**4**	**5**
On a scale from 1 (Extremely low) to 5 (Extremely high) for your logistics activities, which is the level of useful life condition evaluation of your resources?					
On a scale from 1 (Extremely low) to 5 (Extremely high) for your logistics activities, which is the level of adoption of recovery strategy of your capital resources?					
On a scale from 1 (Extremely low) to 5 (Extremely high) for your logistics activities, which is the level of adoption of recovery strategy of your consumable resources?					

D2) Process management

S2.1) Process evaluation

Based on the literature and confirmed by experts, we have seen that process evaluation might affect the maturity of a firm to adopt green logistics practices. More in detail, we have identified the following 2 items:

1. The item "Process planning" refers to the extent to which structured plans and strategies are developed and implemented for logistics activities.
2. The item "Process optimization" refers to the extent to which logistics activities are refined and improved to achieve maximum efficiency and effectiveness.

We would like you to state how well your company operates regarding each item of process evaluation.

Question	**1**	**2**	**3**	**4**	**5**
On a scale from 1 (Extremely low) to 5 (Extremely high) for your logistics activities, which is the level of process planning?					
On a scale from 1 (Extremely low) to 5 (Extremely high) for your logistics activities, which is the level of process optimization?					

S2.2) Capital operating condition evaluation

Based on the literature and confirmed by experts, we have seen that capital operating condition evaluation might affect the maturity of a firm to adopt green logistics practices. More in detail, we have identified the following 5 items:
1. The item "Capital resource utilization" refers to the actual time resources are used compared to the total available time for logistics activities.
2. The item "Capital resource availability" refers to the actual time resources are utilized, excluding breakdowns and maintenance, compared to the total actual utilization time.
3. The item "Capital resource saturation" refers to the actual utilization time of resources, net of both empty trips and loading/unloading times, compared to the utilization time of resources net of breakdowns and maintenance.
4. The item "Capital resource capacity" refers to the actual loading capacity of resources compared to the nominal loading capacity of resources.
5. The item "Capital resource reliability" refers to the probability that operational resources retain their functional capacities after a predetermined period of time for which they were designed.
We would like you to state how well your company operates regarding each item of capital operating condition evaluation.

Question	**1**	**2**	**3**	**4**	**5**
On a scale from 1 (Extremely low) to 5 (Extremely high) for your logistics activities, which is the level of utilization of your capital resources?					
On a scale from 1 (Extremely low) to 5 (Extremely high) for your logistics activities, which is the level of availability of your capital resources?					
On a scale from 1 (Extremely low) to 5 (Extremely high) for your logistics activities, which is the level of saturation of your capital resources?					
On a scale from 1 (Extremely low) to 5 (Extremely high) for your logistics activities, which is the level of capacity of your capital resources?					
On a scale from 1 (Extremely low) to 5 (Extremely high) for your logistics activities, which is the level of reliability of your capital resources?					

S2.3) Consumable operating condition evaluation

Based on the literature and confirmed by experts, we have seen that consumable operating condition evaluation might affect the maturity of a firm to adopt green logistics practices. More in detail, we have identified the following 3 items:

(*continued on next page*)

Table A1 (*continued*)

D1) Resource management

1. The item "Consumable resource availability" refers to the available amount of consumable resources, such as packaging materials, fuel, and other supplies, necessary for your logistics activities.
2. The item "Consumable resource capacity" refers to the capacity of consumable resources, such as packaging materials, fuels, and other supplies, to be utilized in comparison to their nominal or expected quantity.
3. The item "Consumable resource waste generation" refers to the amount of waste produced from consumable resources, such as packaging materials, fuel, and other supplies, during your logistics activities.

We would like you to state how well your company operates regarding each item of consumable operating condition evaluation.

Question					
1	**2**	**3**	**4**	**5**	
On a scale from 1 (Extremely low) to 5 (Extremely high) for your logistics activities, which is the level of availability of your consumable resources?					
On a scale from 1 (Extremely low) to 5 (Extremely high) for your logistics activities, which is the level of capacity of your consumable resources?					
On a scale from 1 (Extremely low) to 5 (Extremely high) for your logistics activities, which is the level of waste generation of your consumable resources?					

S2.4) Inventory condition evaluation

Based on the literature and confirmed by experts, we have seen that inventory condition evaluation might affect the maturity of a firm to adopt green logistics practices. More in detail, we have identified the following 2 items:

1. The item "Inventory space utilization" refers to the efficiency with which storage space is used for inventory within your logistics activities.
2. The item "Inventory inaccuracy" refers to the discrepancy between recorded and actual inventory levels.

We would like you to state how well your company operates regarding each item of inventory condition evaluation.

Question	**1**	**2**	**3**	**4**	**5**
On a scale from 1 (Extremely low) to 5 (Extremely high) for your logistics activities, which is the level of space utilization of your inventory?					
On a scale from 1 (Extremely low) to 5 (Extremely high) for your logistics activities, which is the level of inaccuracy of your inventory?					

S2.5) Process defects evaluation

Based on the literature and confirmed by experts, we have seen that process defects evaluation might affect the maturity of a firm to adopt green logistics practices. More in detail, we have identified the following 2 items:

1. The item "Process defects generation" refers to the frequency and extent to which nonconformities, errors, and inefficiencies occur in your logistics processes.
2. The item "Process defects identification" refers to the extent to which nonconformities, errors, and inefficiencies in logistics processes are recognized and documented.

We would like you to state how well your company operates regarding each item of process defects evaluation.

Question	**1**	**2**	**3**	**4**	**5**
On a scale from 1 (Extremely low) to 5 (Extremely high) for your logistics activities, which is the level of defects generation of your process?					
On a scale from 1 (Extremely low) to 5 (Extremely high) for your logistics activities, which is the level of defects identification of your process?					

D3) Network management

S3.1) Network collaboration

Based on the literature and confirmed by experts, we have seen that network collaboration might affect the maturity of a firm to adopt green logistics practices. More in detail, we have identified the following item:

1. The item "Vertical collaboration" refers to the degree of cooperation and partnership among multiple players or entities within different levels of supply chain networks.

We would like you to state how well your company operates regarding the item of network collaboration.

Question	**1**	**2**	**3**	**4**	**5**
On a scale form 1 (Extremely low) to 5 (Extremely high) for your logistics activities, which is your level of vertical collaboration between players?					

S3.2) Information sharing

Based on the literature and confirmed by experts, we have seen that information sharing might affect the maturity of a firm to adopt green logistics practices. More in detail, we have identified the following 3 items:

1. The item "Environmental footprints sharing" refers to the extent to which various stakeholders involved in logistics activities, such as suppliers, manufacturers, distributors, and retailers, exchange and communicate information regarding their environmental impact (e.g., carbon footprint, water footprint, resource footprint, …).
2. The item "Current practices sharing" refers to the extent to which various stakeholders involved in logistics activities, such as suppliers, manufacturers, distributors, and retailers, exchange and communicate their existing methods, processes, and practices.
3. The item "Improvement strategies sharing" refers to the extent to which various stakeholders involved in logistics activities, such as suppliers, manufacturers, distributors, and retailers, exchange and communicate strategies aimed at enhancing green logistics.

We would like you to state how well your company operates regarding each item of information sharing.

Question	**1**	**2**	**3**	**4**	**5**
On a scale form 1 (Extremely low) to 5 (Extremely high) for your logistics activities, which is the level of sharing of environmental footprints between players?					
On a scale form 1 (Extremely low) to 5 (Extremely high) for your logistics activities, which is the level of sharing of current practices between players?					
On a scale form 1 (Extremely low) to 5 (Extremely high) for your logistics activities, which is the level of sharing of improvement strategies between players?					

D4) Sustainable reporting

S4.1) Sustainable reporting

Based on the literature and confirmed by experts, we have seen that sustainable reporting might affect the maturity of a firm to adopt green logistics practices. More in detail, we have identified the following 2 items:

1. The item "Sustainable reporting adoption" refers to the extent to which organizations integrate sustainability practices into their logistics activities and disclose related information through structured frameworks (es. Global Reporting Initiatives, Sustainability Accounting Standards Boards, Carbon Disclosure Project, …).
2. The item "Sustainable reporting completeness" refers to the comprehensiveness of the information included in your sustainable reporting specifically related to logistics activity (es. energy use, water use, material and resource use, …).

We would like you to state how well your company operates regarding each item of sustainable reporting.

Question	**1**	**2**	**3**	**4**	**5**
On a scale from 1 (Extremely low) to 5 (Extremely high) for your logistics activities, which is the level of adoption of sustainable reporting?					
On a scale from 1 (Extremely low) to 5 (Extremely high) for your logistics activities, how complete is your sustainable reporting?					

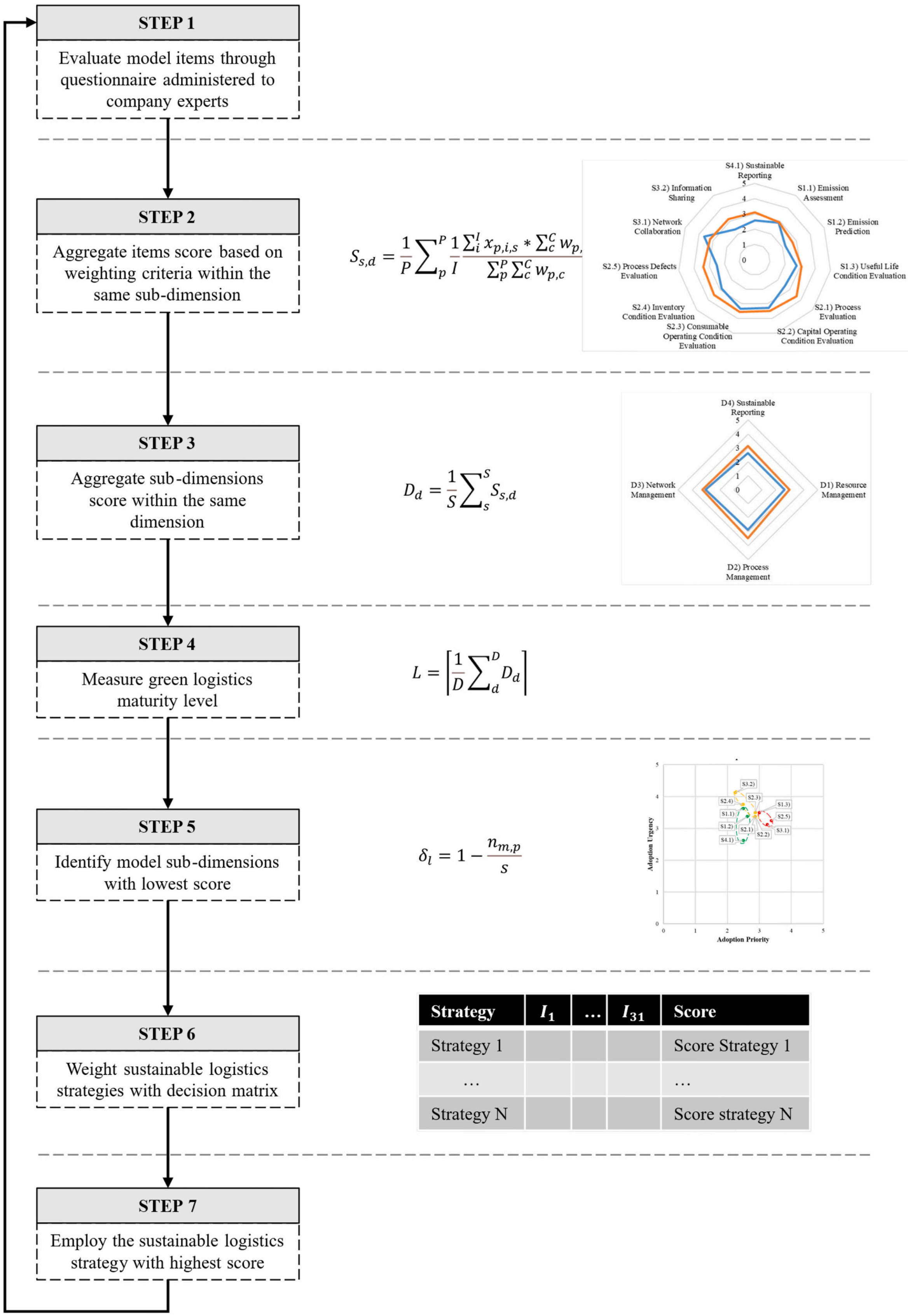
Appendix B

Table B1
Results of GreLoM model application.

General information	Company Alpha	Company Beta	Company Gamma	Company Delta	Company Epsilon
Company size classification	Small	Enterprise	Enterprise	Medium	Small
Type of industry	Logistics service provider	Manufacturing	Manufacturing	Manufacturing	Manufacturing
Number of participants	4	11	1	1	2
Sum of weights for "Process knowledge" criteria	22	66	6	10	12
Sum of weights for "Years experience" criteria	26	58	6	2	16
Scoring of GreLoM model	**Company Alpha**	**Company Beta**	**Company Gamma**	**Company Delta**	**Company Epsilon**
Maturity level	3	4	3	4	3
D1) Resource Management	2.60	2.91	2.25	2.25	2.35
D2) Process Management	2.92	3.51	3.22	3.64	3.25
D3) Network Management	3.00	3.19	3.00	3.17	2.50
D4) Sustainable Reporting	2.56	3.10	2.00	4.00	1.29
S1.1) Emission Assessment	2.88	2.92	2.75	2.75	2.00
S1.2) Emission Prediction	2.19	2.72	2.00	2.00	1.89
S1.3) Useful Life Condition Evaluation	2.75	3.09	2.00	2.00	3.14
S2.1) Process Evaluation	2.63	3.63	3.50	4.00	3.21
S2.2) Capital Operating Condition Evaluation	3.28	3.49	3.60	4.20	3.37
S2.3) Consumable Operating Condition Evaluation	3.33	3.54	3.00	4.00	3.38
S2.4) Inventory Condition Evaluation	2.88	3.51	3.00	3.50	2.79
S2.5) Process Defects Evaluation	2.50	3.39	3.00	2.50	3.50
S3.1) Network Collaboration	3.63	3.21	3.00	3.00	3.00
S3.2) Information Sharing	2.38	3.16	3.00	3.33	2.00
S4.1) Sustainable Reporting	2.56	3.10	2.00	4.00	1.29

Table B2
Results of discrepancy index from model's perspective e practitioner's perspective on sub-dimensions enhancement for green logistics maturity levelling.

Alpha					
l	Model's perspective sub-dimensions	Practitioners' perspective sub-dimensions	$n_{m,p}$	s	δ_l
High	S1.2, S3.2, S2.5	S2.5, S1.3, S3.1	1	3	0.66
Medium	S4.1, S2.1, S1.3, S1.1, S2.4	S2.3, S2.1, S2.2, S2.4, S3.2	2	5	0.60
Low	S2.2, S2.3, S3.1	S1.1, S1.2, S4.1	0	3	1.00
Beta					
l	**Model's perspective sub-dimensions**	**Practitioners' perspective sub-dimensions**	$n_{m,p}$	s	δ_l
High	S1.2, S1.1, S1.3	S2.1, S2.5, S2.2	0	3	1.00
Medium	S4.1, S3.2, S3.1, S2.5, S2.2	S2.4, S1.3, S2.3, S3.1, S3.2	2	5	0.60
Low	S2.4, S2.3, S2.1	S4.1, S1.1, S1.2	0	3	1.00
Gamma					
l	**Model's perspective sub-dimensions**	**Practitioners' perspective sub-dimensions**	$n_{m,p}$	s	δ_l
High	S1.2, S1.3, S4.1	S2.2, S2.3, S2.1	0	3	1.00
Medium	S1.1, S3.2, S3.1, S2.5, S2.4	S2.4, S2.5, S3.1, S3.2, S1.2	4	5	0.20
Low	S2.3, S2.1, S2.2	S1.1, S4.1, S1.3	0	3	1.00
Delta					
l	**Model's perspective sub-dimensions**	**Practitioners' perspective sub-dimensions**	$n_{m,p}$	s	δ_l
High	S1.2, S1.3, S2.5	S2.3, S2.5, S1.1	1	3	0.66
Medium	S1.1, S3.1, S3.2, S2.4, S2.1	S1.2, S2.2, S3.2, S1.3, S2.4	2	5	0.60
Low	S2.3, S4.1, S2.2	S3.1, S4.1, S2.1	1	3	0.66
Epsilon					
l	**Model's perspective sub-dimensions**	**Practitioners' perspective sub-dimensions**	$n_{m,p}$	s	δ_l
High	S4.1, S1.2, S1.1	S2.4, S2.5, S2.2	0	3	1.00
Medium	S3.2, S2.3, S3.1, S1.3, S2.1	S2.1, S1.2, S3.1, S1.1, S2.3	2	5	0.60
Low	S2.2, S2.3, S2.5	S1.3, S3.2, S4.1	0	3	1.00



$$S_{s,d} = \frac{1}{P}\sum_{p}^{P}\frac{1}{I}\frac{\sum_i^I x_{p,i,s} * \sum_c^C w_{p,c}}{\sum_p^P \sum_c^C w_{p,c}}$$

$$D_d = \frac{1}{S}\sum_{s}^{S} S_{s,d}$$

$$L = \left[\frac{1}{D}\sum_{d}^{D} D_d\right]$$

$$\delta_l = 1 - \frac{n_{m,p}}{s}$$

Strategy	I_1	…	I_{31}	Score
Strategy 1				Score Strategy 1
…				…
Strategy N				Score strategy N

Fig. B1. Flowchart representing the steps required to apply the GreLoM model.

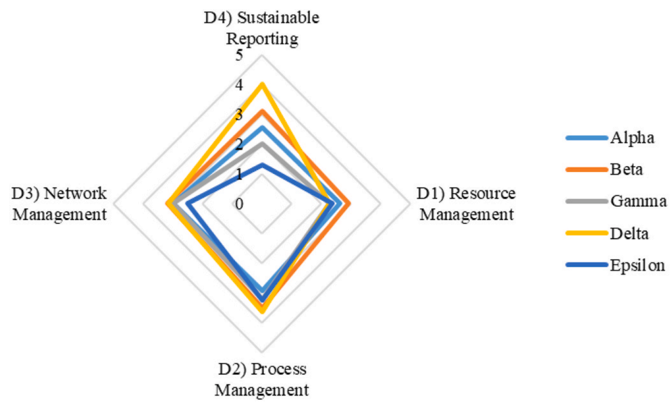


Fig. B2. Scoring of GreLoM model dimensions.

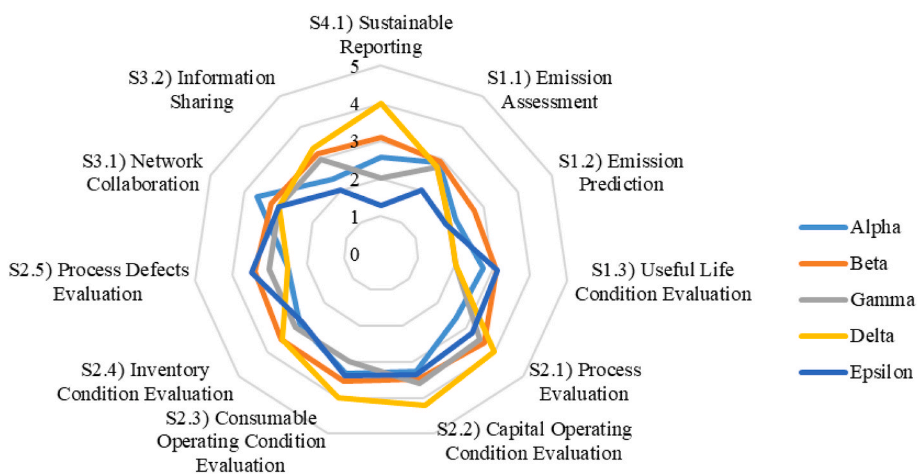


Fig. B3. Scoring of GreLoM model sub-dimensions.

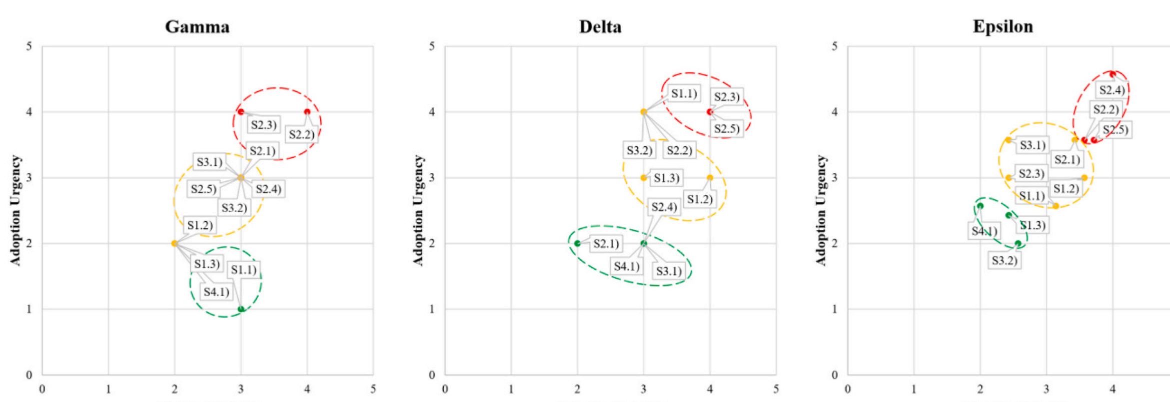


Fig. B4. Priority matrix of the GreLoM model based on respondents' perspective on Company Gamma, Company Delta, and Company Epsilon.

Data availability

The data that has been used is confidential.

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