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MORE THAN REPORTING: ENTERPRISE RESOURCE PLANNING AS ENABLER OF BUSINESS MODEL TRANSFORMATION FOR CLIMATE CHANGE MITIGATION

Sînziana-Maria RÎNDAȘU[1]✉, Adalberto RANGONE[2], Liliana IONESCU-FELEAGĂ[3], Yuriy BILAN[4, 5]

[1]Department of Management Information Systems, Faculty of Accounting and Management Information Systems, Bucharest University of Economic Studies, Bucharest, Romania
[2]Department of Law, University of Perugia, Perugia, Italy
[3]Department of Accounting and Audit, Faculty of Accounting and Management Information Systems, Bucharest University of Economic Studies, Bucharest, Romania
[4]Kautz Gyula Faculty of Business and Economics, Széchenyi István University, Gyor, Hungary
[5]UNEC Empirical Research Center, Azerbaijan State University of Economics (UNEC), Baku, Azerbaijan

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Abstract. Enterprise resource planning (ERP) systems are evolving to support organisations in addressing their climate impact. Yet, there is a paucity of empirical and cross-sectoral data on how these solutions can mitigate organisations' negative climate impact through changes in business models. By focusing on a dataset of ERP-related patents published between 2020 and 2024, within a climate change classification, this study aims to shed light on how ERP-based solutions can enable business model transformation to improve environmental performance and to investigate Industry 4.0 technologies that facilitate such mitigations. Through a pragmatic inductive approach employing mixed methods, the study uncovers three main areas of business model transformation for climate change mitigation: production optimisation, sustainability management and monitoring, and supply chain performance improvement. While most of the examined patents prioritise production optimisation, the findings reveal the emergence of novel applications designed to enhance organisational sustainability management and monitoring. Furthermore, the research emphasises unexploited opportunities to enhance ERPs through the integration of Industry 4.0 technologies. This study provides a substantial contribution to the existing literature by focusing on a significant yet underexplored area: ERP-based solutions designed to enable business model transformation to mitigate climate change, with implications for researchers, organisational adopters, and system developers.

Keywords: enterprise resource planning (ERP), climate change mitigation, business model transformation, patent data analysis, sustainable development goals (SDGs), Industry 4.0 technologies.

JEL Classification: M15, Q01, Q53, Q54.

✉Corresponding author. E-mail: *sinziana.rindasu@cig.ase.ro*

1. Introduction

Mitigating climate change requires an overview of the entire value chain (Chofreh et al., 2020; Streimikiene & Stankuniene, 2024). This involves integrated, auditable data to ensure transparency, compliance, and traceability (Turner et al., 2022; Zhang et al., 2025), disseminating knowledge (Voda et al., 2025), and investing in green technologies (Hao & Dragomir, 2024).

Supporting this, enterprise resource planning (ERP) systems are rapidly becoming the digital backbone of climate monitoring (Yurtay, 2025), as they fundamentally provide companies with a unified view of their operations (Robert Jacobs & 'Ted' Weston, 2007).

Beyond managing core transactional data (Bhattacharya et al., 2023), researchers explored ERPs' potential in addressing sustainability issues and enabling circular business practices (Chofreh et al., 2014). This introduced the concept of sustainable ERPs, "an enterprise system that incorporates the key elements of the corporate sustainable value chain into a centralised system" (Chofreh et al., 2020, p. 1). Yet, the current literature lacks cross-sectoral evidence on how ERPs can be redesigned to mitigate climate change by transforming business models (Anjaria, 2024), rather than only reporting the environmental impact (Setiawan et al., 2023; Yurtay, 2025).

ERPs were long used as operational rather than strategic tools (Gupta & Kohli, 2006; Rodriguez et al., 2019; Scapens & Jazayeri, 2003), the literature also noting sometimes their under-utilisation in the post-implementation phase (Chou et al., 2014; Dambrin & Grall, 2021; Maas et al., 2014). Designed for inventory management and control in the 1960s, the ERPs' scope expanded over time to overcome adoption and operational constraints (Katuu, 2020). The 1970s and 1980s saw the emergence and evolution of material requirements planning (MRP) systems (Rashid et al., 2002), while the 1990s coined the generic term "enterprise resource planning" (Nazemi et al., 2012), a new system for integrating business processes to provide "accessibility, visibility, and consistency across the enterprise" (Rashid et al., 2002, p. 4). Y2K marked ERPs' maturity (Robert Jacobs & 'Ted' Weston, 2007), with the dotcom bubble supporting another generational shift driven by cloud computing (Katuu, 2020). The postmodern versions of ERPs (2010s) integrated additional emerging technologies to provide more flexibility and agility (Gartner, 2020), leading to the emergence of digital operational platforms (Dumitru et al., 2023). By the 2020s, ERPs became part of Industry 5.0 (Franke & Riedel, 2023), supporting business sustainability strategies (Perau et al., 2023).

Recent studies show that ERPs can support organisations in achieving the Sustainable Development Goals (SDGs) (Alzahmi et al., 2025; Praharaj & Chhatoi, 2025; Yurtay, 2025), primarily through integration with Industry 4.0 technologies such as artificial intelligence, robotic process automation, machine learning (Dumitru et al., 2023), blockchain (Sislian & Jaegler, 2022), the Internet of Things (Jaradat et al., 2025), big data, and cloud computing (Qureshi, 2022). However, existing research often examines a narrow set of solutions, typically from leading ERP vendors, relies on self-reported data, or focuses on single industries. This reveals gaps in understanding how ERPs integration enhances sustainability capabilities and environmental performance monitoring (Anjaria, 2024), as well as how ERPs support the SDGs across industries (Anaya et al., 2025; Jaradat et al., 2025). Moreover, research on ERP evolution for climate change mitigation remains limited, most studies concentrating on reporting functions (Yurtay, 2025).

To address this shortage, this study investigates how recent developments in ERP systems can support business models transformation to mitigate climate change, drawing on patents from the European Patent Office database, published after 2020, and classified under the Y02 schema for climate change applications. Despite the paucity of research in this area, patent data emerges as a potentially valuable source of information, enabling researchers to document innovation initiatives and competitive dynamics (Daim et al., 2024). Unlike previous research, the present study offers a comprehensive cross-sectoral analysis on the ERPs' evolution, focusing on their potential to support organisations in mitigating, and not merely reporting, climate change.

Throughout this paper, "business model transformation" refers to changes in how companies operate and generate value, as defined by Saebi et al. (2017). Additionally, we employ the findings of Selezneva et al. (2025, p. 1379), where business model transformation entails: (1) "a set of dynamic capabilities in the context of digitalisation", (2) "a firm ecosystem change aimed at sustainability", and (3) "an instrument for building corporate identity through organisational learning".

The remainder of the paper is structured as follows. The first section presents the relevant literature on sustainable ERPs and the technologies employed to augment these solutions. Next, the research methodology and details of the data collection and analysis processes are described. The following section outlines the study's findings, while the fourth section introduces the discussion. Finally, the conclusions, limitations, and future research directions are presented.

2. Literature review

From a theoretical perspective, ERPs' effectiveness in driving business model changes meant to mitigate climate change is strongly linked to the dynamic capabilities theory, which emphasises a company's ability "to integrate, build, and reconfigure internal and external competences to address rapidly changing environments" (Teece et al., 1997, p. 516). As posited by Latif et al. (2025) and Groenewald and Okanga (2019), companies are leveraging ERPs to optimise their activities and navigate disruptions by acquiring and assimilating information, thereby enhancing dynamic capabilities. Such an outcome is fostered by ERPs' role in promoting organisational agility, enabling the improvement, alignment, and adaptation of the core operational capabilities (Zongyuan & Haiyan, 2024).

Dynamic capabilities enable business model transformation (Teece, 2023) and help manage tensions arising from the shift from linear to circular models (Pascucci et al., 2024). Teece's (2023) three high-level dynamic capabilities: sensing, seizing, and transforming, are central to designing new business models. Firms first sense opportunities in new or emerging technologies, then seize them to enhance organisational agility, including the assessment of emerging innovations such as patents (Teece, 2023). During transformations, organisations identify and address capability gaps. As climate change mitigation becomes a core business objective (Leoveanu-Soare & Nimerenco, 2025; Mondal et al., 2025), ERP systems are evolving into digital enablers of dynamic capabilities, supporting business models that prioritise climate mitigation (Anaya et al., 2025).

Widely acknowledged for their importance in business management from Sardinas Jr (1981) to Praharaj and Chhatoi (2025), ERPs integrate key processes within and beyond organisational boundaries (Hitt et al., 2002), with various capacities for climate change mitigation (Sadeghi et al., 2025). Thus, nowadays companies seek ERPs solutions in an effort to strengthen their sustainability strategies (Pugna & Boldeanu, 2025) and are advocating for the integration of sustainability capabilities into the solutions (Backer et al., 2023). Besides contributing to SDGs, these systems promote sustainable business practices by facilitating efficient resource management, providing sustainable infrastructure, and improving accountability and transparency (Anaya et al., 2025).

Sustainable ERPs are also designed to capture data on companies' long-term viability and their environmental and social impacts (Chofreh et al., 2020). Early developments integrated product life cycle assessment, enabling the incorporation of environmental sustainability into business processes (El Haouat et al., 2024). This evolution was strengthened by Industry 4.0

technologies, which addressed traditional ERP limitations and supported sustainability objectives (Anjaria, 2024; Morawiec & Sołtysik-Piorunkiewicz, 2023). Unlike traditional systems, sustainable ERPs can capture, automate, monitor, and integrate sustainability-related data (Abobakr et al., 2026; Štreimikienė et al., 2022). For instance, traditional ERPs cover only 20% of carbon accounting data needs, while integration with other technologies increases availability to 49% (Perau et al., 2023).

Although ERPs' impact on addressing climate change has been investigated for over a decade (Lara-Pérez et al., 2024), recent studies still focus on creating innovative solutions based on these systems and Industry 4.0 technologies to promote climate-related strategies (Tsai, 2023). While traditional ERPs prioritised profit, sustainable ERPs consider the triple bottom line (Abobakr et al., 2026), enabling organisations to shift towards cleaner production by optimising activities, reducing energy consumption, and decreasing carbon emissions (Chofreh et al., 2020).

Sustainable ERPs mitigate climate change through production efficiency and resource management (Alzahmi et al., 2025; Anaya et al., 2025), enabling organisations to reconfigure their value chains, monitor performance (Abobakr et al., 2023), and enhance life cycle assessment when combined with Industry 4.0 technologies (El Haouat et al., 2024). These capabilities reduce waste and resource consumption. Moreover, sustainable ERPs support real-time monitoring of environmental performance, including resource use and greenhouse gas emissions (Yurtay, 2025), ensure compliance with climate regulations (Agarwal, 2024), and improve transparency and traceability (Alzahmi et al., 2025; Azevedo et al., 2023).

Current developments in sustainable ERP systems are driven by Industry 4.0, which is "synonymous with smart manufacturing" (IBM, n.d.), and includes technologies such as IoT, cloud computing, artificial intelligence, and machine learning. In the ERP contexts, this portfolio also encompasses big data analytics, robotic process automation, and blockchain (Bodkhe et al., 2020; Javaid et al., 2021), which enable applications for climate change mitigation. For example, IoT and RFID sensors can optimise supply chains and reduce emissions (Alzahmi et al., 2025), while big data analytics aggregates information from multiple sources, including IoT systems. Cloud-based ERPs further support mitigation by decreasing the need for physical infrastructure and energy requirements, fostering the use of renewable energy sources (Ojadi et al., 2024). Additionally, artificial intelligence combined with smart grids can optimise energy systems and production processes, reducing carbon emissions while enhancing business resilience (Singh & Goyal, 2023).

As presented, ERPs evolution into sustainable solutions is a relevant research topic. Yet, previous studies focused on end-user perceptions (Abobakr et al., 2026; Azevedo et al., 2023), a limited number of solutions (Anaya et al., 2025), a single industry or country (Abobakr et al., 2026; El Haouat et al., 2024), or reviews of previous research without providing empirical implications (Agarwal, 2024; Alzahmi et al., 2025; Anjaria, 2024; Morawiec & Sołtysik-Piorunkiewicz, 2023; Yurtay, 2025). Thus, despite the important insights, the innovative process driving ERPs' consolidation to mitigate climate change has been mainly overlooked. By focusing on market-ready solutions, these studies provide a limited view of the technological trajectories. To address this gap, this research aims to reveal the patterns of innovation underpinning sustainable ERPs' development through patent data analysis, which indicates newly developed technologies and captures the evolutionary process towards a circular economy (Rainville et al., 2025).

Consequently, the following research questions are proposed, drawing upon a recent patent dataset:

- RQ1. How do ERP-related patents enable business model transformation for climate change mitigation?
- RQ2. Which Industry 4.0 technologies drive this transformation toward a climate change mitigation-oriented business model?

3. Methodology

Adopting a pragmatic, inductive approach, we analysed a set of patents through text mining and qualitative content analysis. Such data source is reliable for predicting trends in various fields (Yuan & Cai, 2021), as it reveals innovations with future economic potential across industries (Wustmans et al., 2022). The patent dataset was retrieved from the European Patent Office (EPO), Espacenet database, a major repository using algorithm-based classification (Da Silva et al., 2024; Tey et al., 2024).

The data collection process involved identifying inventions mentioning "enterprise resource planning" in the title, abstract, or claims, restricting the search to the CPC Y02 scheme – technologies or applications for mitigation or adaptation against climate change, through the following search string: "ctxt = "enterprise resource planning system" AND cpc = "y02"". The patents available on EPO receive a final classification from official examiners (European Patent Office, n.d.), improving the dataset's reliability.

The search was performed on February 26 2025, and returned 104 patents published between 2020 and 2024 (Figure 1). This timeframe coincides with the emergence of various regulations regarding climate change mitigation, such as the EU Taxonomy regulation, in force since July 2020, which guides "business activities in a more structured way to be in accordance with environmental targets" (Hao & Dragomir, 2024, p. 114).

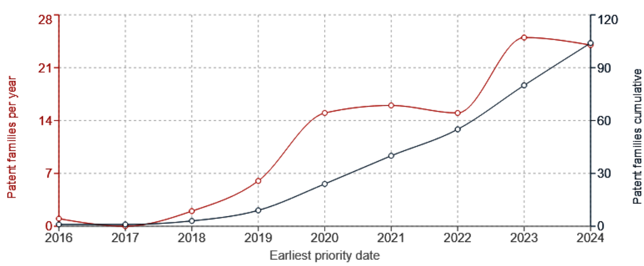


Figure 1. Yearly patent publications (source: retrieved from Espacenet)

The data collection process involved a complete examination of the patents' abstracts, descriptions, and claims, manually retrieved from the repository, to exclude patents that involved a marginal use of an ERP. Most of the removed items (22 inventions) pertained to the use of ERPs as peripheral systems for sending and receiving information without including new functionalities. Several relevant excerpts are the following:

"A status code receiving module, configured to receive the status code returned by the enterprise resource planning system for the procurement data" (CN117575482A (Xie et al., 2024)).

"Step 104, sending the corresponding appearance detection result and the corresponding image data of the circuit board to the server corresponding to the enterprise resource planning system" (CN116051445A (Chen et al., 2023)).

"In a preferred embodiment, an enterprise resource planning system (...) can access the central data management device or the system, as the case may be" (US2023176554A1 (Häusler et al., 2023)).

In the other five patents excluded, the ERP mentions did not clearly specify the technical role or functional contributions or the systems were presented as elements of a third-party infrastructure. Thus, the final dataset consists of 77 applications (Table 1), from two CPC subgroups: Y02D – Climate change mitigation technologies in information and communication technologies and Y02P – Climate change mitigation technologies in the production or processing of goods.

The dataset was explored using quantitative and qualitative methods. For the text mining analysis, we examined only the patents' abstracts through computer-assisted techniques, while the content analysis involved a complete investigation of the documentation. Firstly, a bigram text-mining analysis was conducted in RStudio IDE to identify the main topics. Prior to the analysis, the abstracts were pre-processed in R following Okey et al.'s (2023) methodological approach: tokenising words, removing punctuation, converting words to lowercase, removing stop words, and lemmatising the terms. Additionally, before lemmatisation, domain-specific terms (enterprise, resource, planning, system, erp) and common patent words (datum, method, model, invention) were removed. Such terms, appearing in almost all abstracts, would have dominated the bigram analysis by masking more relevant terms (Dragomir & Dumitru, 2024).

Table 1. Patent classifications based on the Y02 main schema

CPC subgroup	No. of patents	CPC description
Y02D10/00	5	Energy efficient computing
Y02P90/02	7	Total factory control
Y02P90/30	53	Computing systems specially adapted for manufacturing
Y02P90/80	4	Management or planning
Y02P90/82	1	Energy audits or management systems
Y02P90/84	5	Greenhouse gas [GHG] management systems
Y02P90/90	2	Financial instruments for climate change mitigation

The text mining analysis was followed by a qualitative exploratory content analysis (Figure 2), which involved a process of coding, abstraction, and data classification, derived from the methodological approach proposed by Forman and Damschroder (2007), aiming to obtain qualitative data on the sustainability implications of the inventions and identify the technologies used.

We started with data immersion, to "(obtain) a sense of the whole before rearranging it into discrete units for analysis" (Forman & Damschroder, 2007, p. 47), followed by data reduction to uncover thematic segments and themes by coding relevant sections from the abstracts, claims, and descriptions of the examined patents. The data was further aggregated into categories and dimensions.

The coding process, theme validation, and refinement were iterative and involved all authors, with disagreements addressed as the process unfolded. As guidance, during the data reduction process – specifically while identifying relevant paragraphs in the patents – we

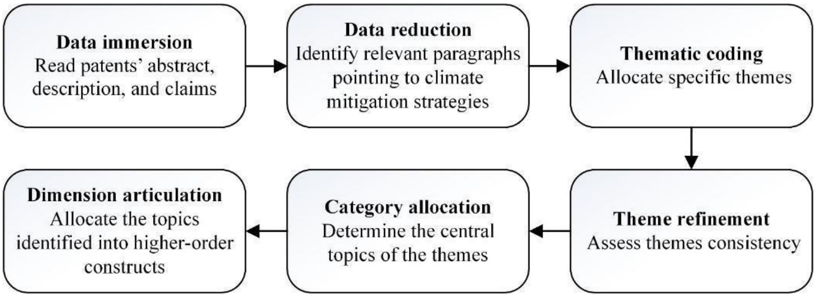


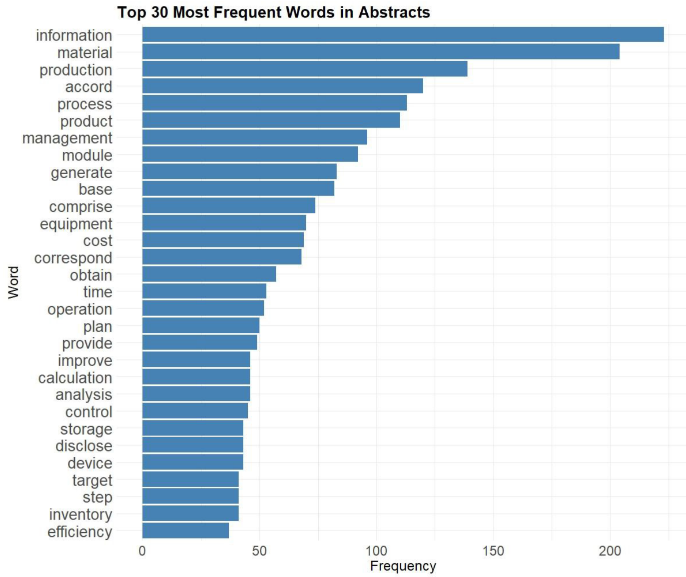
Figure 2. Qualitative content analysis design

based our exploratory coding on the circular economy strategies (slowing, closing, and narrowing), given their significance in climate change mitigation (Leal Filho et al., 2024; Gallego-Schmid et al., 2020). The strategies proposed by Bocken et al. (2016) address the prolonged resource use (slowing the loop), circular resource flows (closing the loop), and resource optimisation through reduced use (narrowing the loop). We also retained patents focused on climate change reporting, as in ERP-enabled transformations reporting functions as a digital mechanism for operationalising, monitoring, and steering targets rather than an end-of-pipe disclosure (Varma et al., 2024). As qualitative content analysis aims to "describe and interpret reality from their view" (Barth & Koch, 2019, p. 661), we did not pursue an initial inter-rater agreement. As noted by O'Connor and Joffe (2020), such agreement is often unrealistic and undesirable, and even reflexive approaches may yield low initial scores (Roberts et al., 2019). Nonetheless, despite differing terminologies, all codings were unanimously approved by the authors.

Employing a combined approach of both types of analysis aims to mitigate the potential for researcher bias, specific to content analysis. In addition, bigram analysis can reveal unexpected themes that emerge only when the co-occurrence patterns are examined and can confirm the dominant concepts.

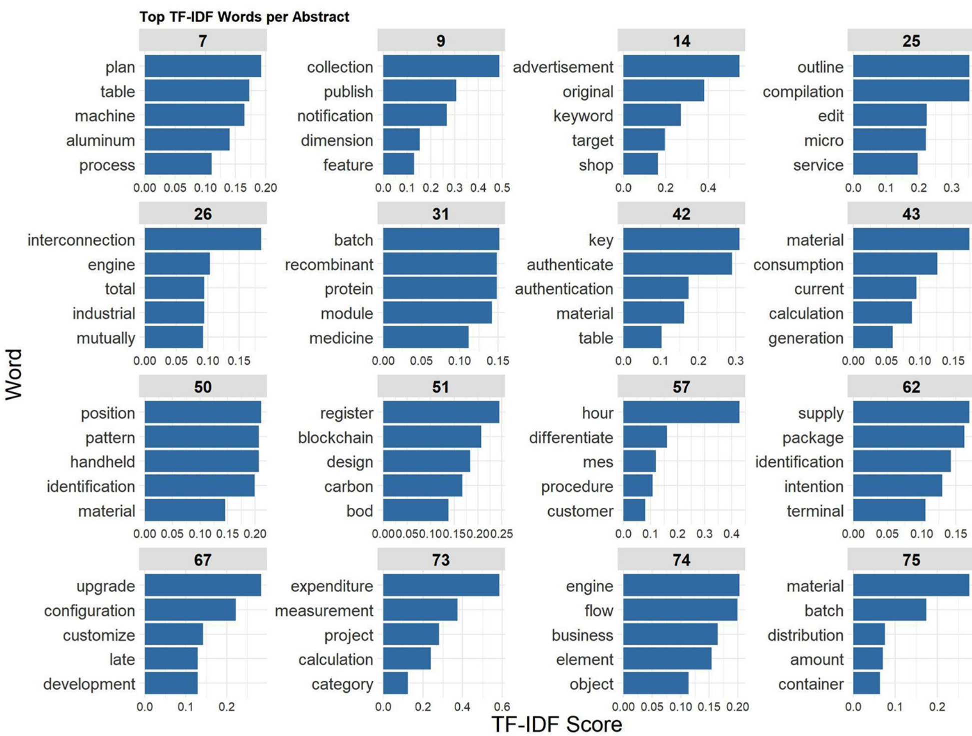
Two descriptive checks validated the dataset and motivated the methodological selection. Figure 3 presents the most frequently used keywords in the patents' abstracts, confirming the ERP-relevance of the language. Additionally, to emphasise the dataset's diversity and provide reasonable assurance that the vocabulary does not obscure heterogeneity, we computed term frequency-inverse document frequency (TF-IDF) scores for each abstract, with 16 randomly sampled patents shown in Figure 4.

The 30 most frequent words from the corpus of patents' abstracts (Figure 3) indicate a manufacturing-oriented dataset (material, production, product, cost, operation, inventory), with software-related elements (module, generate, device), and analytical terms (analysis, calculation, target). However, no terms in this subset were explicitly tied to climate change, as per the patents' validated classification. This outcome suggests that climate-oriented vocabulary constitutes just a minor fraction of the corpus. Yet, frequency counts alone cannot capture climate-related intent, which may be implicit and not explicitly labelled in the abstracts. Overall, Figure 3 emphasises that the selected dataset genuinely reflects the ERP/manufacturing domain, validating its relevance before deeper analysis, and confirming that climate-related terms are not explicitly present, which justifies the need for further methods to uncover latent cues.



Note: The figure validates the ERP/manufacturing focus of the dataset and establishes a baseline vocabulary profile, while motivating the use of more advanced methods to detect latent cues.

Figure 3. Most frequently used keywords in the patents' abstracts



Note: The TF-IDF analysis highlights the most distinctive terms within a subset of individual patents, emphasising the diversity of technical language across the dataset.

Figure 4. Top TF-IDF terms for a random sample of 16 patents (seed = 123)

To highlight individual invention focus, Figure 4 presents a randomly selected subset of patents, with seedings for reproducibility, displaying the five most relevant terms per patent relative to the full corpus, revealing intra-dataset variation. Unlike simple frequency counts, this approach captures heterogeneous, domain-specific vocabulary without dominant manufacturing terms obscuring less frequent concepts. As shown, some patents emphasise manufacturing (7, 75), while others focus on digital activities (51), business methods (43, 73), or modular software (67, 42). Notably, patent 51 includes the term "carbon," indicating that climate-related language is present but rare across the dataset. This demonstrates the value of the TF–IDF approach in surfacing distinctive, invention-level terms, that may be hidden in aggregate analyses. Accordingly, this analysis complements Figure 3 by showing that, despite the prevalence of manufacturing terminology, the patents contain terms aligned with the study's research objective.

4. Results

4.1. Text mining

The bigram analysis (Figure 5), based on patents' abstracts, highlights certain sustainability-related topics and some of the emerging technologies used to augment traditional ERPs by addressing technical and operational challenges. This representation shows how concepts are paired and clustered within the dataset. The patents' strong manufacturing and resource-management focus is reflected in central connections (e.g. "process-production", "warehouse-inventory"), while peripheral connections (e.g. "carbon-emission", "environment-friendly") reflect the existence of sustainability-oriented terminology.

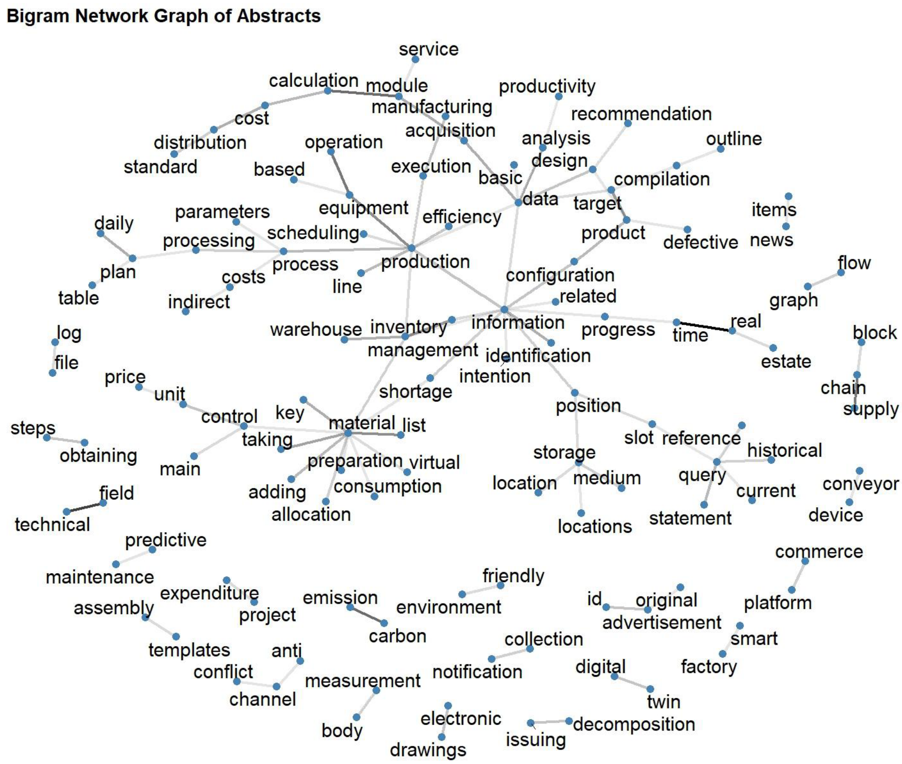
This analysis highlights clusters related to climate change, such as carbon-emission and environment-friendly, though disconnected from the main groups. This result underlines that although the analysed patents are classified in the Y02 category, their impact in addressing climate change issues might not be explicit. This apparent mismatch suggests that ERP-related patents may not have a central environmental functionality but rather enable sustainability-driven initiatives.

The central cluster, linking most of the keywords, points to sustainability-related objectives, focusing on improving production and reducing waste through intelligent monitoring, optimising warehouse management, and enhancing planning and forecasting. The spatial and thematic centrality of the terms in this cluster suggests that ERP systems support process optimisation in response to the demand for sustainability.

In terms of technologies leveraged to improve ERP systems' capabilities, the bigram analysis directly points to blockchain solutions and clusters such as predictive-maintenance and smart-factories suggesting that the inventions include some types of machine learning and predictive algorithms, along with IoT-driven production-based environments.

The marginality of implicit sustainability clusters and the lack of association with technology-related terms may indicate missed opportunities, highlighting the need for stronger technological integration for climate change mitigation.

Table 2 presents a selection of the most important clusters and groups them into three business-model-transformation directions. These directions highlight that ERP-related inventions create mitigation through improved efficiency, forecasting, and data-driven management.



Note: The bigram network shows how keywords co-occur in the abstracts, highlighting a dense manufacturing-oriented core alongside peripheral climate-related terms.

Figure 5. Bigram network of the most frequently paired keywords in the patents' abstracts

Table 2. Relevant clusters resulting from the bigram network

Business-model transformation directions for climate change mitigation	Associations
Production optimisation	Production-efficiency-scheduling-process-inventory
	Inventory-management-warehouse-material
	Material-list-shortage-allocation-consumption-control
	Product-configuration-defective-target
Forecasting	Predictive-maintenance
Business methods	Standard-distribution-cost-calculation-module
	Process(ing)-plan-parameter-costs-indirect
	Equipment-based-operation-execution
	Equipment-manufacturing-module-acquisition
	Data-design-analysis-productivity-recommendation
	Information-identification-progress-real-time

For instance, clusters such as production-efficiency-scheduling-process-inventory and material-list-shortage-allocation-consumption-control point to inventions meant to optimise flow, reduce stocks and rework, and decrease material/energy waste. This outcome aligns mainly with the circular strategy for narrowing resource loops, as defined by Bocken et al. (2016). The predictive-maintenance cluster, on the other hand, suggests some sort of monitoring meant to conserve resources, in line with the slowing strategy. Moreover, the association within the final category implies a shift towards real-time, analytics-driven decision support, crucial for environmental performance management. Significantly, the associations within the final category extend beyond narrowing and slowing strategies to actively closing resource loops. To validate and contextualise these computationally derived patterns, the bigram results were triangulated with a qualitative, exploratory content analysis, uncovering the patents' climate change mitigation related potential.

4.2. Content analysis

The content analysis aimed to add depth and breadth to the research. While text mining provided directions and revealed associations not readily apparent in large datasets, such as patent descriptions and claims, averaging more than 20 pages per invention, the content analysis focused on identifying climate change mitigation solutions that emerge from the dataset.

Table 3. Centralisation of dimensions and categories

Dimension	Categories	Number of patents
Production optimisation	Waste/resources reduction	49
	Improved efficiency	46
	Digitalised operations	13
	Production planning and forecasting	8
Sustainability management and monitoring	Emission management, monitoring, and disclosure	6
	Traceability, transparency, and certification	6
	Improved data accuracy	5
	Energy consumption monitoring	1
Supply chain performance	Warehouse efficiency improvement	7
	Logistics optimisation	5
	Supply chain management, resilience, and transparency	4
	Risk management	1

The results of this investigation (Table 3) uncovered three main dimensions related to climate change mitigation solutions, pertaining to business model transformation (Saebi et al., 2017; Selezneva et al., 2025). These dimensions aggregate distinct categories from themes identified in the patents' documentation, corroborated with the previously presented clusters of terms. In total, 151 codes were allocated to the 77 patents, with inventions often spanning multiple categories.

Given the patents' concentration in subgroup Y02P90/30 and the text-mining clusters, most inventions focus on production optimisation across sectors such as textiles, pharmaceuticals, aeronautics, logistics, and manufacturing, supporting the view that these innovations primarily target resource efficiency through narrowing strategies. However, the remaining two dimensions differ from the corresponding groups in Table 2, highlighting that abstract-based terms do not fully capture the nuances identified through manual analysis. For instance, the supply-chain–block cluster from Figure 5 suggests a focus on supply chain and blockchain, yet content analysis revealed no such invention; this discrepancy arises because both terms share the word "chain," creating a textual but not empirical association.

4.2.1. Production optimisation

The first category of mitigation initiatives includes solutions for decreasing production-generated waste or strategies for reducing the resource cycle (narrowing the loops), driven by the digitalisation of activities to simplify outcomes, such as paperless operations, or other more complex results. For example, by improving the reliability of manufacturing processes while leveraging new technologies, companies can "effectively ensure product reliability to further meet product design reliability goals and user needs" (patent CN113094827A (He et al., 2021)), thereby reducing waste, rework, and scrap. Other patents reflect the importance of reducing manpower and space requirements, as captured by the following excerpt:

"(...) multiple orders can usually only be processed in batches for the same material (...) if a single order is processed one by one, more manpower and space are required, and the cost will increase significantly" (patent CN116011782A (Wang et al., 2023)).

Material wastage resulting from overproduction or misallocation of resources, including computational power, is another area of interest, reflected in the energy consumption, cost allocations, and production losses.

The second category correlates with waste/resources reduction, as decreasing resource use and waste usually streamlines production processes. One representative patent, with an explicit impact on climate change mitigation, points to process optimisation through green energy and reduced emissions:

"The enterprise resource planning system signal is connected to the data storage and transmission module, receives the optimal carbon emission strategy, and performs production scheduling and control (....) the optimal carbon emission strategy can change the production schedule in real time (...) to achieve the effect of timely importing green power and further reducing carbon emissions" (patent TWI776596B (She et al., 2022)).

Improving efficiency and reducing waste and resource use are partly determined by the digitalisation of production processes and by the functionality of traditional ERPs. For example, several patents focus on automating the Bill of Materials (BoM) to optimise production by controlling material consumption:

"Automatically capture data in the BoM table in the enterprise resource planning system (...) by improving the processing accuracy of BoM data, enterprises can more effectively carry out resource planning and inventory management, reduce costs and increase market response speed" (patent CN118446781A (Rao, 2024)).

Digitalisation improves production while reducing resources and waste. In this category, we included patents that point to efficient production management through various technologies, the digital transformation of operational activities, and digital twins. Such applications are expected to contribute to the decarbonisation goals, with a representative excerpt presented below:

"The invention discloses a blockchain big data-based full-link enterprise digital intelligence system and method, and the system comprises an order subsystem which is used for synchronising order production information generated according to order information sent by a demand side to a blockchain" (patent CN117495243A (Wang, 2024)).

Production planning and forecasting, the last category, is supported by digitalised operations, with implications for waste and resource management. The patents relate to various manufacturing industries, with applications that focus on using real-time data via IoT and on predicting the future using machine learning algorithms. The following patent highlights how waste and carbon emissions can be reduced by improving organisations' planning and forecasting capabilities:

"(...) the data interaction application layer is also used to perform data analysis and classification on the carbon emission monitoring data through the random forest algorithm and the support vector machine algorithm (...) the data interaction application layer is also used for forecasting and future dynamic simulation of the key indicators and data that affect the carbon peak" (patent CN116228171A (Huang, 2023)).

4.2.2. Sustainability management and monitoring

The second dimension includes fewer patents but primarily focuses on direct applications for climate change mitigation. The emissions management, monitoring, and disclosure category relates to real-time tracking of carbon emissions, flexible use of materials, greenhouse gas emissions modelling systems, estimating products' carbon footprint, and emissions management through blockchain-based applications. Such inventions focus on reducing the error rates of traditional backward methods, enabling the emergence of intelligent manufacturing and carbon emissions decision systems:

"The enterprise resource planning system signal is connected to the data storage and transmission module, receives the optimal carbon emission strategy, and performs production scheduling and control of at least one production machine according to the optimal carbon emission strategy" (patent TWI776596B (She et al., 2022)).

Traceability, transparency, and certification are intended to improve accountability, ensure sustainable sourcing practices, and build trust between stakeholders. The inventions focus on improving these factors, primarily through blockchain-based solutions and smart grid networks. For example, one of the patents examined (KR20230068574A (Jinhong, 2023)) focuses on a carbon emissions management system in the form of non-fungible tokens. In this way, production-related energy use data is verifiable, decentralised, and tamper-proof, fostering compliance, preventing greenwashing, and enabling transparent practices.

Although data accuracy can be linked to optimised production, we included this category under the second dimension, as the focus is on enabling informed decision-making, supporting accurate assessment of environmental performance, and ensuring compliance. The inventions focus on data synchronisation, addressing the challenges posed by large volumes of complex data that affect production efficiency and quality, while also correcting for anomalous and marginal data.

The last category of this dimension, although related to only one of the patents analysed, is presented separately due to its importance in achieving environmental performance. The patent focuses on energy consumption monitoring and relates to a system for tracking, recording, and monitoring the workflow process in manufacturing and assembly, extending and automating an ERP system by using artificial intelligence to track and archive energy consumption as energy profiles across the BoM, thereby increasing plant efficiency.

These inventions primarily support the slowing and closing strategies. Real-time emissions monitoring, traceability, and certification support slowing resource loops. In contrast, blockchain-based accountability mechanisms and transparent emissions records underpin closing loops by enabling verification, compliance, and reintegration of materials and energy flows into circular systems.

4.2.3. Supply chain performance

Supply chain performance is critical to tackling climate change, as it directly impacts emissions, resource efficiency, and waste reduction through production and distribution. Despite the relatively limited number of inventions, the categories identified contribute to reducing the environmental impact of manufacturing activities.

Warehouse efficiency improvements focus on eco-efficient storage, real-time space analytics, and space optimisation. The patents in this category do not directly address climate change but focus on reducing energy consumption and emissions by decreasing warehouse utilisation, using sensor-based storage methods, and enabling intelligent distribution. A representative excerpt from a method for inventory management through an ERP system is presented below:

"Through the management and analysis of the storage space of the warehouse, the space coefficient is obtained, and the space occupancy of the warehouse is fed back through the space coefficient. Match out objects, reduce the cost of warehouse transfer, and improve the convenience of transfer" (patent CN114926127A (Shen, 2022)).

Logistics optimisation includes innovations that address inefficiencies, such as synchronising systems, cost verification methods in supply chain planning, smart packaging and sorting management, and anti-channelling supervision. As with the previous category, none of the patents have a direct impact on climate change but are intended to reduce resource consumption and thereby decrease emissions in the supply chain.

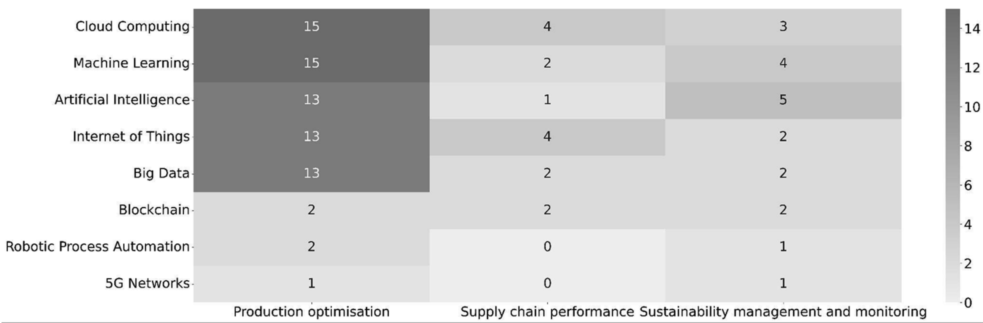
Supply chain management, resilience, and transparency focuses on improving data integration, particularly from the BoM, through "deep learning models, automatic semantic understanding and anomaly detection of data (...) thereby optimising inventory management and reducing errors in the supply chain" (patent CN118446781A (Rao, 2024)), but also by leveraging 5G networks, IoT systems, blockchain, and machine learning. The following excerpt from a patent describes an ERP-based method for managing product supply inventory. By enhancing supply chain agility and resilience, companies can better adapt to market disruptions, enabling improved monitoring and responsiveness:

"(the invention) is used for solving the problem that an existing supply chain inventory management method cannot dynamically adjust data such as commodity production and warehousing according to a sales curve prediction result" (patent CN114926127A (Shen, 2022)).

The last category includes a patent on risk mitigation and business continuity through the use of artificial intelligence. Its relevance lies in enhancing the supply chain's resilience and adaptability, supporting climate change goals, and ensuring the continuity of sustainable activities.

4.2.4. Industry 4.0 technologies used

The content analysis was also wielded to identify the technologies leveraged to enhance or create new add-ins to ERPs in support of achieving climate change mitigation objectives. Not all examined patents explicitly mentioned the supporting technologies, using generic terms (e.g., data analytics, large amounts of data), which were deemed insufficient to attribute to a specific technology. Thus, only explicitly mentioned technologies were included in the results. Figure 6 maps the Industry 4.0 technologies identified across the three dimensions. This mapping illustrates the list of digital technologies being mobilised to extend ERP systems beyond traditional functions, linking them to climate related organisational objectives.



Note: The heatmap highlights the Industry 4.0 technologies referenced in the patents as enablers of the innovations proposed.

Figure 6. Industry 4.0 technologies used in the analysed patents, across dimensions

Cloud computing, machine learning, IoT, artificial intelligence, and big data are the most commonly used technologies, indicating specific ERP functionalities. For example, cloud computing highlights the evolution towards new systems designed to provide advanced functionality with higher flexibility. Machine learning and artificial intelligence, on the other hand, support predictive analytics and smart decision-making, while IoT focuses on providing real-time data. Still, only 39 patents presented such insights; this result suggests that inventors may be disregarding the use of these Industry 4.0 technologies or that the applicants may have emphasised the innovative nature of the patents rather than the potential technologies.

The low frequency of 5G mobile networks and blockchain could be due to their relative novelty in the ERP context, integration limitations, or lower perceived patentability. However, the same cannot be assumed for robotic process automation, which is already widely used in ERP systems (Dumitru et al., 2023). Instead, this result may be driven by the fact that applications involving this technology may be too incremental to be patentable.

5. Discussion

Business transformations for climate change mitigation through optimising production represents the main objective of the inventions examined. As sustainable ERPs aim to enable organisations to integrate diverse data from the value chain (Chofreh et al., 2020), these solutions point, albeit indirectly, to the development of such systems. Most of the categories identified empirically support the objectives of sustainable ERPs (Alzahmi et al., 2025). In addition, our research reveals additional strategies to address climate change through production planning and forecasting, along with traceability, transparency, and certification, while providing additional methods to optimise supply chain performance.

The emphasis on production optimisation appears to stand out in contrast to the anticipated role of sustainable ERPs, which are expected to prioritise assisting organisations in managing and monitoring their environmental impact. Nevertheless, the increase in efficiencies across processes contributes to lowering the environmental impact through reduced use of resources, such as raw materials and energy (Leal Filho et al., 2024; Gallego-Schmid et al., 2020).

Comparing the study's findings, categorised by carbon footprint reduction potential, with the results of Yurtay (2025), shows convergence in the analysed patents. This alignment results from integrating Industry 4.0 applications, particularly smart factories and digital manufacturing, with sustainable production and environmental management practices. The findings point to an interconnected development framework where technological advancements are increasingly aligned with climate change mitigation, highlighting the central role of ERPs in promoting sustainability (Anaya et al., 2025). Although only one invention used 5G networks to enable connectivity, this suggests the emerging role of advanced communication technologies in supporting real-time data sharing for climate mitigation strategies.

From a theoretical perspective, production optimisation is primarily aligned with the narrowing strategy (Bocken et al., 2016). Reducing resource use through new digital and manufacturing processes is considered relatively easy to implement, either through internal research or in collaboration with external partners (Bocken & Geradts, 2022). In addition, this strategy drives cost savings and other resources, including energy. Thus, it is not uncommon for companies transitioning to circular business models to begin this process by increasing efficiency, which will further enable advances in slowing and closing resource loops (Bocken & Geradts, 2022; O'Keeffe et al., 2025).

By reducing resource use and optimising production planning, the patents point to measurable, immediate gains in climate change mitigation. Within the 9Rs framework, business model innovation primarily reflects a narrowing strategy centred on the refuse, rethink, and reduce principles (Bartwal & Kumar, 2025), which correspond to smarter product use and manufacturing (World Economic Forum, 2022). Theoretically, this emphasis on efficiency suggests that firms transitioning to circular business models follow a narrowing-first pathway, where ERP-embedded optimisation capabilities act as microfoundations. Accordingly, these principles appear at the top of the 9Rs hierarchy, indicating that firms institutionalise efficiency logics before developing capabilities to close and slow resource loops.

The second dimension, sustainability management and monitoring, underpins closing and slowing strategies, as related patents emphasise emissions reporting, traceability, and data accuracy. By embedding sustainability metrics into ERPs' architecture, these solutions shift reporting from compliance to an active steering mechanism. Patents addressing traceability, transparency, and certification support reuse and recycling through digital item identification, chain-of-custody enforcement, and material provenance certification, thereby enabling lifecycle emissions quantification and improved supply-chain visibility. Although other categories align less directly with the nine circular economy principles, they still contribute to mitigation. Emissions management and disclosure embed telemetry to identify hotspots and validate avoided emissions, while enhanced data accuracy strengthens lifecycle assessment and energy monitoring supports energy orchestration and process resilience.

Finally, supply chain performance patents illustrate an early but important trend towards ecosystem-wide optimisation, indicating a gradual movement toward a circular supply chain, vital for mitigating climate change through reduced emissions. Supply-chain performance is a direct lever on Scope 3 emissions and a buffer against climate disruption; thus, improving reliability and network efficiency reduces the need for carbon-intensive expedites. Yet the relatively small number of patents suggests that cross-boundary data integration, which is essential for closing and slowing loops, is still in its infancy.

While prior research highlights ERPs' role in enabling sustainable business models, this study extends that view by showing that, in climate change mitigation, ERPs are primarily associated with a narrowing strategy that creates path dependencies reinforcing the slowing and closing of resource loops. Once efficiency rules are embedded as standard operating procedures, they institutionalise processes that extend resource use and direct residuals into recovery streams. These findings imply that future ERP design should move beyond efficiency-focused modules towards architectures that explicitly integrate slowing and closing functionalities, positioning ERPs as key enablers of business model transformation for climate change mitigation.

6. Conclusions

This paper examines the evolution of sustainable ERPs as enablers of business model transformation for climate change mitigation, while tracing the Industry 4.0 technologies supporting this role. Analysing 77 patents, the study empirically maps ERPs development in response to organisations' needs to measure and manage environmental impacts. The findings identify multiple applications for climate change mitigation, confirming prior research while extending it with practical insights into business model transformation and addressing the geographical, industrial, and perception-based limitations of earlier studies.

The text mining analysis reveals the existence of a diverse and interconnected network of technological concepts, focused on optimising processes, business methods, and improving forecasting. These findings were confirmed and extended through a content analysis across three dimensions: production optimisation, sustainability management and monitoring, and supply chain performance improvement. The related categories present practical applications addressing climate change issues and make a substantial contribution to mitigation efforts.

The focus on production optimisation reflects the traditional aim of ERPs, despite the growing regulatory and social pressures, which should be better reflected in the sustainability management and monitoring dimension. Furthermore, the study highlights a diverse set of associated Industry 4.0 technologies and identifies potential missed opportunities, particularly to improve trust, transparency, and traceability.

These findings show that modern ERPs extend beyond their traditional reporting role to enable business model transformation. By revealing how ERP-related patents focus on production optimisation, sustainability monitoring, and supply chain performance, the study contributes to circular economy research by demonstrating ERPs' role as microfoundations of circularity through a narrowing strategy that reduces resource use and creates conditions for subsequent slowing and closing opportunities. From a practical perspective, the findings suggest that managers, system designers, and policymakers should view ERP implementation as a strategic means of embedding sustainability logic into core operations rather than as a source of isolated efficiency gains. Organisations adopting ERPs can use these insights to reconfigure processes to meet environmental performance goals, while developers can identify underexplored strategies and technologies, highlighting the gap between ERP potential and current innovation levels. Finally, the study informs future research by exposing a relatively overlooked innovation domain and illustrating concrete pathways through which ERP-based solutions support business transformation.

Notwithstanding the contributions and implications of this study, there are limitations to the generalisability of the findings. Firstly, patents pertain to supply-side innovation; thus, this study emphasises only the potential of ERPs as enablers of business model transformation for climate change mitigation. Moreover, the dataset was collected from Espacenet, which, although it contains a significant number of patents, may not fully capture all relevant information on climate change-related innovation in ERP systems. Other databases or national patent offices may include additional or region-specific data. Additionally, patents do not always relate to the actual commercial and successful implementation of the applications. Accordingly, future research could validate the commercial character of such innovations and compare the study's findings with current organisational practices.

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Author contributions

Authors contributed equally to this work.

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