



Forest 4.0: Technologies and digitalization to create the residual biomass supply chain of the future

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ABSTRACT

Currently, there is an increasing pressure to decarbonize and meet energy demands. In this regard, the usage of renewable energy sources is becoming more prominent. Biomass energy can significantly contribute to this effort. However, due to logistical costs, its exploitation is often considered less 'desirable.' Sometimes, particularly in the context of residual biomass, open burning on site is desirable. This study aims to optimize the residual biomass supply chain by leveraging digitalization's advantages, thereby creating a new model for this purpose. Methodologically, this research initially adopted an empirical approach, analyzing documents from a project that recreated the current scenario. In its second phase, the study involved a literature review to gather insights needed for developing the final model. Consequently, this study offers three major contributions: a detailed mapping of the current scenario, a comprehensive synthesis of the potentials of emerging technologies in the supply chain, and a model illustrating the integration of these technologies in the context of residual biomass. Thus, this research presents an opportunity to transform a common 'leftover' into a value-added material. To better assess the model's value, two analyses, PEST and SWOT, were conducted to align the conceptual proposal with real-world contexts.

1. Introduction

The rise in population, coupled with the expansion of energy-intensive economic activities, has escalated energy demand. Despite the adverse effects linked to fossil fuels, they continue to be the primary energy source. Nonetheless, progress and growing social consciousness have facilitated a partial or complete transition towards renewable energy sources (Olabi and Abdelkareem, 2022), (Benti et al., 2021). An example of this includes the costs associated with technology and policy incentives, which have rendered systems like solar photovoltaic modules and wind turbines more appealing (Ghorbani et al., 2020). In addition to solar and wind power, biomass energy plays a significant

role in the energy transition, accounting for 10% of global energy consumption (Tun et al., 2019). When biomass is converted into electricity, heat, or transportation fuels, it generates biomass energy (bioenergy). Various biomass feedstocks can be used in bioenergy production (Toklu, 2017), (Abdulyekeen et al., 2021).

Biomass has inherent characteristics, such as inconsistencies in the product's characteristics (Zailan et al., 2021) or fluctuations in quantities. Besides this, the logistic costs of this exploitation are very high (Casau et al., 2022a), which leads to a decrease in its exploitation interest. In many countries, such as Malaysia or Thailand, a part of biomass is burnt, wasting the energy potential (Andiappan et al., 2021). Also, burning practices can originate rural fires (Casau et al., 2022b).

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This occurrence is not only in mentioned countries, being also visible in those in the Mediterranean basin, where the fire is used to eliminate residues and it is responsible by almost two thirds of rural fires. Particularly, in Portugal, fire is frequently used to remove agricultural or forestry operations residues (Casau et al., 2022b), and as consequence, Portugal suffers with a growing recurrence the effects of rural fires, causing damages (victims and patrimonial), with different origins. One example has occurred in 2017, in the region of Pedrógão Grande, Castanheira de Pera, and Figueiró dos Vinhos (Magalhães et al., 2021). In 2017, Portugal registered 2000 fires, 539,920 ha of burnt land and 117 deaths (Leone et al., 2023). This occurrence requires attention and mechanisms which aim the fuel management reduction.

In a world tagged by the concept of digitalization, forests cannot be exempted, and the definition of Forest 4.0, which can be comparable to the Smart Cities concept, arises as a combination of three main technologies, Robotics, Artificial Intelligence, and the Internet of Things (Oliveira et al., 2021). According to Singh et al. (2022a), five points are crucial to achieving this digitalization, Sensing Technology, Human to forest interaction, Big data and Cloud Computing, Advanced Analytics, and Artificial Intelligence. At the biomass supply chain (BSC) level, Artificial Intelligence allow prediction at several stages as, production processes of biofuels, quality of final product and allow improvements in gasification processes (Shi et al., 2023), other authors, Liao and Yao (2021) mention this technology as a predictor of biomass characteristics, such as the high heating value with proximity analysis, and harvest predictor with image detection (Shi et al., 2023). Although the digital age is present in the BSC, this context still needs research. In this sense, this work aims to propose a Residual Biomass Supply Chain (RBSC) optimization based on emerging technologies potentialities. The paper will therefore begin by summarizing the literature on the RBSC mechanism based on other works and additional materials such as theses, presenting an exhaustive model of it, followed by an exhaustive review of how 4.0 technologies can help in the supply chain and ending with the main contribution, the 4.0 model for RBSC. Then there are the detailed specific objectives:

- Clarify the design of the residual biomass supply chain (RO1);
- Analyze “digital” trends in the biomass supply chain, complemented by analysis of emerging technologies in other contexts (RO2);
- Present the final proposed model for residual biomass supply chain (RO3).

To complement the objectives, two analyses were conducted: PEST (Political, Economic, Social, and Technological) and SWOT (Strengths, Weaknesses, Opportunities, and Threats). These analyses serve to incorporate the actual context (specifically, the prevailing Portuguese context regarding outdoor burning) and to assess the proposed model accordingly. Additionally, they offer clarification, identify new research avenues, and lay groundwork for future discourse. As such, Section 2 elaborates on the comprehensive methodology, while Section 3 presents the specific results for Research Objectives 1, 2, and 3. Sections 4 and 5 provide discussions and conclusions, respectively.

2. Materials and methods

As stated earlier, this study sets out to achieve three specific objectives: RO1, RO2, and RO3. For RO1, this study adopts an empirical methodology, which encompasses the analysis and integration of data from existing documents, such as scholarly articles and master’s theses, from prior stages of a project. The aim is to elucidate the RBSC in detail. Regarding RO2, a systematic literature review (SLR) was executed employing the PRISMA framework. The article query construction was iterative, as illustrated in Table 1. The initial strategy involved correlating terms associated with Industry 4.0 with Supply Chain and Biomass, which resulted in a scant number of findings. In response, the second phase saw “Industry 4.0” substituted with “digitalization”,

Table 1

Keyword used in each stage and number of publications obtained.

Keywords	Number of publications
Supply + Chain + Industry 4.0	2536
Supply + Chain + Industry 4.0 + Biomass	9
Supply + Chain + Digitalization	26
Supply + Chain + (“Industry 4.0” OR “Digital trans*” OR Digitalization OR “Digital paradigm”)	4144
Supply + Chain + (“Industry 4.0” OR “Digital trans*” OR Digitalization OR “Digital paradigm”) + Biomass	16

though this adjustment similarly led to limited outcomes. The final strategy integrated both terms alongside synonyms identified in existing literature, applying the “OR” operator for queries. Furthermore, the “*” character was used to capture minor variations in spelling, ensuring the inclusion of pertinent studies.

Upon finalizing the query, the PRISMA methodology was implemented (Mengist et al., 2020). This methodology facilitates the identification, evaluation, and synthesis of a comprehensive list of scholarly works. The process begins by delineating the research scope, followed by the selection of pertinent keywords and databases for the literature search. Upon compiling a collection of works, duplicates are removed, and eligibility criteria, such as document type, are established, excluding works that do not match the predefined criteria. The assessment of work relevance is conducted in three sequential phases: analysis of titles, abstracts, and full content. In each phase, works deemed less relevant are systematically excluded. After completing these phases, the sample to be included in the study is finalized. However, it should be noted that the final search in the SCOPUS database yielded 16 results, of which 5 articles were inaccessible. Consequently, the abstract filtering stage was bypassed, and all 11 accessible works were subjected to content analysis.

To accomplish the goal of developing a more digitally integrated residual biomass chain management model, the anticipation was that the findings from the second objective would suffice. However, it becomes evident that the biomass sector still has significant progress to make in adopting digital technologies, especially when contrasted with other sectors (as indicated by the substantial drop in relevant results from 4144 to 16 upon including the keyword “biomass”). To enhance the appeal of the model, an exploratory review was conducted to ascertain the application of other technologies, which are minimally represented in the biomass context, across different domains. This decision was based on the premise that its potential impact on the supply chain could significantly surpass the achievements documented in the SLR. Fig. 1 illustrates the methodological framework employed in this study in a schematic representation.

3. Results and discussion

3.1. Residual biomass supply chain (RBSC)

3.1.1. The concept of biomass in this study

Biomass is considered a renewable energy source because it can be

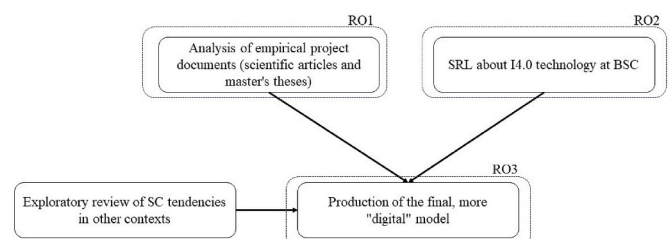


Fig. 1. Methodological approach used in this study.

cultivated, harvested, and regenerated from seeds within a brief period (Benti et al., 2021). Biomass energy represents a significant resource as it functions as a reserve of solar energy and emerges as a viable alternative to fossil fuels (Casau et al., 2021). Considering that biomass carbon is renewable, it may serve as a valuable resource in combating climate change. Biomass feedstocks include forest, agricultural, and animal wastes, short-rotation forest plantations, energy crops, the organic component of municipal solid waste, and additional organic waste streams (Toklu, 2017). Due to its abundant and flexible storage and supply capabilities, worldwide availability, and high conversion efficiency, biomass constitutes a competitive energy source (Sun and Fan, 2020). Nonetheless, several challenges accompany the utilization of this resource, including spatial dispersion, elevated moisture content, low bulk density, and seasonal variability in availability. Furthermore, issues concerning market dynamics, policy frameworks, and weather fluctuations remain unresolved. Certain scholars contend that the viability of producing bioenergy from waste biomass is closely tied to the supply chain costs and frequently correlates with machinery efficiency (Maktoubian et al., 2021).

Agroforestry, encompassing agricultural and forestry activities, represents a source of biomass (Casau et al., 2022a). Practices such as forest management, which includes vegetation removal, or pruning, result in the production of residual biomass in the form of branches or leaves (Nunes et al., 2021), (Chidozie et al., 2023). Following harvesting, trees are transported to the lumber company, while the residual components, including branches, leaves, bark, and crowns, find application in diverse fields, notably in paper manufacturing and biomass energy production (Maktoubian et al., 2021). This study defines “residual biomass” as referring to these materials.

3.1.2. The model of RBSC

The supply chain for residual biomass comprises three principal phases: harvesting, transportation and storage, and customer unloading at the final destination. The harvesting phase entails cutting, collecting, classifying, and temporarily storing the biomass. The transportation and storage phase may recur multiple times, encompassing a cycle of unloading, storage, and reloading. Direct collection and delivery to the customer eliminate the storage component, thereby bypassing this cycle. Occasionally, to enhance the value of the biomass, a pre-treatment stage is introduced, wherein the biomass undergoes drying or pelletization (Nunes et al., 2023).

Brás (2022) analyzed two case studies, later presented in two publications, Rijal et al. (2023a) and Rijal et al. (2023b). In the initial scenario, the BSC typically involves three to four principal actors: the property owner with the biomass, the logger, and the end consumers. In certain instances, additional services such as transportation, storage, or equipment leasing may be provided by external parties, thereby extending the chain to include a fourth actor. Within this framework, forest owners engage loggers to purchase their timber and clear their land. The loggers then evaluate the value of the residual woody biomass and determine its price. The harvesting process involves felling trees and segregating logs from branches. Subsequently, for transportation purposes, logs and branches are collected, with any remaining biomass being either chipped or baled. The second case study examines a larger logging operation that distinguishes itself using a GPS-based application. This technology enables the logger to identify both potential and already exploited resources. Additionally, this scenario introduces a regulatory figure that monitors for uncollected biomass piles. Should these piles exist beyond a specified deadline, the authority alerts the logger via the application to facilitate their collection. Unlike the first scenario, where communication primarily occurs through telephone and direct conversation, this logger employs the application and email for communication and information dissemination. This supply chain is characterized by specific challenges, including the availability and variability of biomass, which hinder efficient harvesting and transportation. Furthermore, storage processes must ensure the maintenance

of biomass quality (Chidozie et al., 2023). Fig. 2 graphically systematizes the aforementioned process in a flowchart.

In the existing RBSC framework (AS-IS model), this supply chain is deemed inefficient owing to its logistical expenses. Generally, the chain is defined by the involvement of numerous distinct participants and a significant deficiency in information and coordination among these entities. Additionally, a notable characteristic of this context is the supply chain’s substantial reliance on human labor (Rijal et al., 2023a). Moreover, certain inherent characteristics of biomass detract from the system’s overall efficiency. These characteristics are low bulk density (Guo et al., 2022) or seasonality and high geographical dispersion (Moretti et al., 2021). In addition to these characteristics, high heterogeneity and a high quantity of inert materials are also considered (Nunes et al., 2015).

Several authors contend that this chain faces numerous challenges necessitating immediate attention. These include the need for enhanced planning across all tasks, improved efficiency in harvesting processes, and optimized route planning. Regarding storage, concerns regarding the potential deterioration of biomass and the risk of infestations should also be addressed (Chidozie et al., 2023). In this chapter, it is noted that several authors concur on the premise that temporary storage can enhance value by diminishing the water content inherently present in biomass (Nunes et al., 2015). Other authors contend that these stores may serve as an asset in mitigating seasonality (Basile et al., 2022). Despite existing positive signals, owners within this supply chain primarily communicate with loggers via telephone or negotiate wood pricing directly with them (Rijal et al., 2023a). Therefore, the three principal challenges facing this RBSC include minimizing human labor while enhancing working conditions, facilitating connections among stakeholders while fostering a transparent information environment, and developing intelligent systems to bolster decision-making support.

3.2. Digitalization of the supply chain in the context of the biomass industry and future developments

3.2.1. Internet of Things in BSC

Internet of Things (IoT), offer numerous advantages, including connectivity and the real-time exchange of information (Dionisio et al., 2022). IoT technology frequently integrates with other technologies to influence the BSC framework. Scholars have noted the synergistic use of IoT and sensors for facilitating real-time data acquisition (Andiappan et al., 2021). This involves collecting data via sensors, storing it in the cloud, and employing IoT for data transmission. Additionally, the incorporation of Blockchain (BC) technology enhances data analysis capabilities due to its provision of traceability and reliability across the entire data chain (Loy et al., 2023). This technology possesses the potential to connect stakeholders within the supply chain, thereby enhancing information accessibility for consumers (Aragónés et al., 2020). This information encompasses various categories, including data on pests and weather conditions. As will be discussed, artificial intelligence (AI) holds significant potential. However, its predictive capabilities depend on the availability of data. Therefore, the integration of the IoT with AI presents considerable promise, as evidenced by scholarly research, including the study referenced in (Zailan et al., 2021).

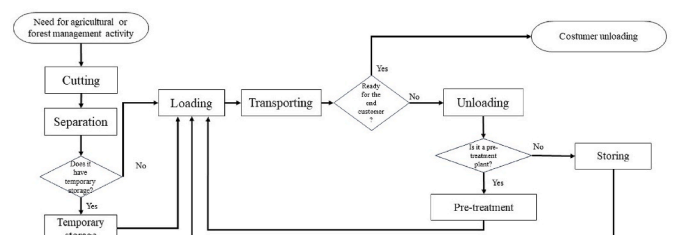


Fig. 2. Systematization of the actual model of RBSC.

3.2.2. Artificial intelligence in BSC

AI comprises machines performing tasks that traditionally require human intelligence (Mhlanga, 2021). In the process of converting specific biomasses into energy, stakeholders frequently employ experimental design. However, AI and machine learning (ML) algorithms now enable the prediction of solubility and the identification of optimal solvents, thereby reducing time and costs (Loy et al., 2023). In the agricultural sector, data on locations acquired through remote sensing can be input into machine learning algorithms. These algorithms can predict agricultural yields and enhancing planning strategies (Martinho et al., 2022). Also, in processes of biomass energy recovery, AI could facilitate the pretreatment method choice (Wang et al., 2023). In conjunction with the previously discussed forecasts, reference (Martinho et al., 2022), suggests that ML possesses the capability to facilitate the mapping of corn farms in the winter season, delineate agricultural lands, and estimate soil carbon content. Within the realm of robotics and machinery pertinent to the BSC, ML holds a pivotal role in predictive maintenance. This application is projected to reduce machinery malfunctions, thereby enhancing the occupational safety of loggers. Notably, loggers are approximately 26% more susceptible to injuries compared to standard factory floor personnel (Maktoubian et al., 2021). This predictive maintenance strategy may reduce the overall costs associated with machinery failure. Additional research, including that by Flak (2020), outlines solutions that integrate machine learning (ML) with Geographical Information Systems (GIS), thereby broadening the scope of forecasting solutions. Furthermore, this study introduces ERPagro, an Enterprise Resource Planning (ERP) system designed to support agricultural forecasting by offering functionalities for production planning, fertilization scheduling, and sales management.

3.2.3. Blockchain in BSC

BC is characterized by offering advantages including security, transparency, and decentralization (Fiore and Mongiello, 2023). This technology has been extensively utilized in the literature due to its applicability across various domains (Bastos and Teixeira, 2024). At the BSC level, the role of BC can be understood through the work of Pakseresht et al. (2023). According to the authors, BC contributes significantly to the agri-food sector by ensuring information traceability and authenticity, positively impacting e-commerce, and safeguarding data integrity and security. Furthermore, BC aids in the reduction and recovery of food waste through enhanced data reliability. Additionally, BC's integration with technologies such as RFID, AI, or sensors enhances information traceability within this domain. In terms of economic transactions, the technology's decentralization of payments is attracting considerable interest. Within the BC sphere, the presence of numerous intermediaries, which are often viewed with skepticism, poses a challenge. However, this issue can be addressed by employing platforms that facilitate engagement among various stakeholders. This notion is supported by Loy et al. (2023), who assert that smart contracts based on BC technology can expedite monetary transactions and enhance their appeal. Consequently, it can be inferred that BC ensures the integrity of information (Andiappan et al., 2021). At the biorefinery level, BC-based digital twins facilitate the integration of data collected from reactors, utilizing 5G technology to ensure connectivity. This integration occurs within a virtual system, known as a digital twin, enabling experimentation within a virtual clone (Loy et al., 2023).

3.2.4. Other technologies in SC

3.2.4.1. Big data and Advanced Analytics. As outlined in the methodology section, the literature pertaining to the application of technology within the BSC framework is relatively limited. Therefore, the objective of section 3.2.4 is to augment the existing analysis by identifying potential technologies capable of facilitating digitalization (Industry 4.0) in diverse SC contexts, beyond the confines of the biomass industry. This

endeavor seeks to uncover unexplored potentials within the realm of BSC and propose a more comprehensive and refined solution.

Big Data (BD) encompasses vast volumes of data generated in real-time by sensors, surpassing the capabilities of conventional software for management. According with Huynh et al. (2023) and Chatterjee et al. (2023), the primary utility of BD lies in its capacity to extract valuable insights, placing it within the domain of Big Data Analytics (BDA). Data Analytics (DA) encompasses the utilization of analytical tools, such as data mining or descriptive analysis, to scrutinize data and derive conclusions (Raut et al., 2021). Another concept encompassed within this framework is Advanced Analytics, a fusion of DA with ML or optimization techniques. Its aim is to expand beyond basic analysis, transitioning from understanding current phenomena to anticipating future trends (Stahl et al., 2023).

BD serve diverse applications and purposes, such as discerning consumer roles in specific online retail environments (Porouhan and Premchaiswadi, 2021), or analyzing trends in consumer behavior (Maddikunta et al., 2022). It offers opportunities in predictive modeling and mitigating failures in the agricultural sector, consequently enhancing system efficiency. Another significant advantage lies in the capability to acquire real-time data and make instantaneous decisions (Wolfert et al., 2017). The main anticipated benefits encompass forecasting accuracy and reduced costs (Hopkins, 2021). Another domain that has benefited from BDA is route optimization, particularly evident in the aviation industry, where factors such as fuel consumption are carefully analyzed (Ghobakhloo and Fathi, 2021). The quantities of generated data are frequently underutilized, yet they present opportunities for exploration (Rowan, 2023). Certain challenges exist in analyzing private and sensitive data, posing risks to security and privacy (Raut et al., 2021).

3.2.4.2. Robotic process automation (RPA). RPA is a very attractive technology that could reduce operating costs. It can be defined as a robot/software capable of performing routine tasks (E-Fatima et al., 2023), such as transferring data, achieving high performance rates and avoid allocate uninteresting work to humans (van Hoek et al., 2022). As RPA advantages, it is possible to note, the decrease in the probability of errors or the possibility of making operations less dependent on humans (E-Fatima et al., 2023). RPA can be used with little training, and once applied can be easily adapted, extended or eradicated (Hartley and Sawaya, 2019). One example of RPA was in Maersk's case, where the robot replaced human tasks, resulting in a decrease in the average handling time from 13.1 to 3.6 days. This could be explained by the fact that the robot can receive an order at any time and follow up on it, without having any problems with weekends (van Hoek et al., 2022). RPA can generate and transmit requests for quotations, assess supplier tender replies to preset criteria, do other tasks related to procurement-to-payment operations, make purchase orders, reconcile them with receipt papers, invoices, and purchase orders, and handle payments (Hartley and Sawaya, 2019). Before implementing RPA, it is important to make sure that the processes have very specific rules, without many exceptions. It is also important to know the costs of the worker carrying out the task (Viale and Zouari, 2020). It is important in RPA to understand which processes can be transferred to bots and which cannot. Sometimes it can be difficult to map out the whole process because the person who carried out the task does not have a complete view (Oshri and Plugge, 2022). Because of this, RPA implementation can be advantageous because it allows the processes to be clarified and documented.

3.2.4.3. 5G technology. 5G is defined as a combination of technologies and mechanisms that are expected to meet the necessary capacity and performance requirements (Jangirala et al., 2020). 5G technologies will enable ubiquitous communication, allowing latency to be reduced by 100 times compared to 4G. 5G works as an IoT enabler because it

requires less energy, reduces latency, and at the same time allows high data transactions (Mistry et al., 2020). The amount of data that the current context requires to be transferred is difficult to achieve given the bandwidth that current infrastructures have (Jangirala et al., 2020). A great enabler of digital SC is 5G. The importance of receiving data at the SC level is very high, because the sooner they receive the data, the less they will spend on recovery costs. This technology makes it possible to adopt new concepts such as cloud manufacturing or digital twins. Real-time data sharing, product production, logistics, and warehouse management can be pointed as the areas with the most to gain from this technology (Dolgui and Ivanov, 2022). Technical implementation issues and management use issues comprise the two main categories of this technology's challenges. Issues with security and privacy, logistical standards, inadequate management of 5G-based supply chain procedures, and, in management support, the 5G are, sometimes, linked to AI, which could represent the possible replacement of human labor (Dolgui and Ivanov, 2022). Another concern inherent to this technology is the possibility of external threats because 5G is, sometimes, associated with networking between various companies (Javaid et al., 2022).

3.2.4.4. Edge computing (EC). The rapid growth of concepts such as IoT and the cloud has brought about a new concept, EC, which is defined as data processing at the edge of the network (Maddikunta et al., 2022). This emerges as an addition to cloud computing, being an application-aware network that can recognize and instantly adjust to changing requirements (Rowan, 2023). This technology has advantages such as reducing latency costs and response times, and increasing data protection and security because it can process data without passing it to public clouds. Another advantage is that EC filters data "a priori", allowing only relevant data to reach the processors (servers) (Maddikunta et al., 2022). The architecture based on 3 technologies, IoT, BC and EC, is proposed in some works. The purpose of IoT is to collect data, incorporating technologies such as sensors, cameras, or GPS. The objective of EC is to put all the data in the same format since the data is collected by different hardware and in different formats and the BC is used in the cloud computing phase (Hu et al., 2021). With an identical structure, there is the Wang & Wang (Wang and Wang, 2022) model, used in the financial sector, where the EC was used to link the user interface with the BC. The security could be a challenge in this technology, since there are many data interfaces, together with the fact that cutting-edge devices sometimes have low performance levels, which makes it difficult to implement security algorithms (Qiu et al., 2020).

3.2.4.5. Virtual reality (VR) and augmented reality (AR). In VR, users wear glasses on their faces where virtual simulation worlds are created that allow them to understand real phenomena without interacting with reality (de la Peña Zarzuelo et al., 2020). AR allows 3D objects to be integrated into real environments (Rejeb et al., 2021), and could be used for some fields, such as training. In terms of logistics, this technology makes possible to reduce the time spent by the operator (Sharifpour et al., 2022), (Aravindaraj and Rajan Chinna, 2022). VR has a positive impact in prototyping processes, acting in smart design (Singh et al., 2023), it also allows the analysis of new products in different contexts, or simulation, as in the case of driving lessons (Hamad and Jia, 2022). The negative points of VR include problems with software, which takes up a lot of space and is demanding in computational terms, the hardware is relatively heavy, which can cause physical injuries. In addition, users can get cyber sickness (like motion sickness). The last point is the cost of buying both headsets and computers (Hamad and Jia, 2022). Concerning AR, in the marine context, the possibility of enhancing the perception and quality of the information received on a ship's bridge by integrating actual and virtual objects and evaluating information in real-time makes docking and undocking operations easier for pilots and commanders (de la Peña Zarzuelo et al., 2020). In terms of order picking, this task is often associated with waiting times, which can be

reduced by using AR. In production terms, AR makes it possible to reduce assembly errors, reduce the consumption of raw materials and is also a very useful tool in terms of maintenance processes (Rejeb et al., 2021). The AR still lacks some maturity to be able to assess its profitability, as is the case in the fashion sector, where there is some distrust about investing in this technology (Parekh et al., 2020).

3.2.4.6. Cyber-physical systems (CPS). CPS are intelligent systems that combine communication and computing capabilities with physical systems. They are seen as the main drivers of Industry 4.0 (I4.0) as they allow the physical and virtual worlds to converge (Ghadge et al., 2022). It can improve decisions by providing real data on the state of systems. CPS with technologies such as RFID or sensors can increase the visibility and tracking of products throughout the SC. CPS can also facilitate preventive maintenance (Fatorachian and Kazemi, 2021). Still in the benefits chapter, CPS could have a positive impact on MRP (Material Requirement Planning) (Yadav et al., 2022), also in energy systems, agriculture (Smetana et al., 2021), autonomous systems, automotive systems, aeronautical systems, robotic systems, industrial systems, or IoT applications (Alfuhaid et al., 2023). With the emergence of real-time sensing, enhanced control, AI, and service-oriented manufacturing, CPS has become crucial to many emerging technologies (Kamble et al., 2022). CPSs can collect data from various products, allowing them to focus on the "whole" rather than the individual (Smetana et al., 2021). As CPS involves data exchange, they are an ICT, and they are exposed to cyber-attacks (Jimada-Ojuolape and Teh, 2020). The main challenges facing CPS are bandwidth structures, production interruptions due to data failures, the lack of prioritization on the part of the administration, and data security (Sahin et al., 2022). This last one is discussed in Feng et al. (2020), which talks about the data security CPSSs (CPSs that include a social component).

3.2.4.7. Digital twins (DT). DT allow the creation of a clone supply chain that can allow the perception of current status and allow the determination of corrective actions using a virtual world (Andiappan et al., 2021), (Kamble et al., 2022). DT has advantages such as the possibility of process integration, the possibility of process optimization, the reduction of errors, the aid in predictive maintenance (Kamble et al., 2022) and the flow visualization, predicting for example the energy consumption (Ghobakhloo and Fathi, 2021). DT can optimize aspects such as packaging performance, fleet management, and route efficiency. In the agricultural sector, it can help reduce energy costs, and predict crops according to soil conditions, invasive plants, or animals. It also makes possible to increase transparency and communication between the various stakeholders (Attaran and Celik, 2023). DT can make a strong contribution to the circular economy, for example by helping to process customized orders more quickly and automating processes (Preut et al., 2021). The design of a DT, although very advantageous, faces several challenges such as the price of the design, and in the context of SC, DT is a relatively scarce technology (Marmolejo-Saucedo, 2022).

3.2.4.8. Quantum computing (QC). QC is a technique that has gained a lot of popularity in the scientific community because it offers greater computing speed, which can be very useful in solving complex problems (Dixit et al., 2023). This computing has been widely used to solve problems such as Manufacturing Cell Formation or Vehicle Routing (Ajagekar et al., 2020). This computing could be very useful in SC problems (Dixit et al., 2023). Quantum algorithms can offer huge performance improvements over known classical algorithms for solving important problems such as integer factorization and the simulation of quantum mechanics (Weinberg et al., 2023). In terms of transportation problems, QC proves to be very useful for solving large-scale problems, with better results obtained more quickly (Dixit and Niu, 2023). There are also studies that apply this technique to problems such as stochastic

time-dependent shortest path routing (Dixit et al., 2023). Often, to obtain a better result, it is necessary to use many “shots”, reducing the advantage that can be gained from subroutines (Egger et al., 2020). Noise and value decoherence can affect the results of QC (Bhattacharya and Chatterjee, 2022).

3.3. New model of RBSC with the technology inputs

3.3.1. Brief exploratory analysis of other technologies at the SC level

The previous section aimed to summarize the primary contributions of I4.0 technologies in enhancing digitalization within the BSC framework, extending to other SC domains. Following the exploratory analysis described in methodology, it is evident that AI holds potential beyond biomass-related contexts, with documented experiences indicating additional contributions. Drone image-capturing capabilities have proven beneficial for integration into AI technologies, facilitating knowledge enhancement through inherent algorithms. This combination has been used in several areas such as detecting water leaks (Islam et al., 2023), detecting pests in the agricultural sector, where individual analysis of each product would be unfeasible by humans (Chin et al., 2023). Still in the chapter on detecting products using ML algorithms, some work as Zaman (2022) which shows a mechanism for identifying types of waste using ML, and the work of Islam et al. (Amani and Sarkodie, 2022) which proposes a deep learning algorithm to analyze the state of meat at its SC level. Still at the level of drones in a forest context, this technology can be associated with LiDAR technology to better understand the forest (Jucker et al., 2023). Robotization, a component of I4.0, has also been talked about in the context of the forest, as in the case of the work of Oliveira et al. (2021). In this work, four categories are approached for robots, such as preserving and monitoring the environment, battling wildfires, maintaining inventories, and planting, and harvesting forests. Table 2 summarizes the main contributions of each technology.

The analysis of Table 2 indicates that the primary contributions of these technologies lie in data exchange and subsequent information sharing. This is particularly evident in technologies facilitating real-time information exchange or bolstering data transaction security. Additionally, certain technologies are closely tied to process automation, notably within administrative tasks, resulting in expedited document turnover and enhanced information flow. These functionalities collectively fall under the purview of Information Management. Another significant aspect of digitalization, frequently deliberated, is the support these technologies offer in predictive maintenance, particularly in preemptive failure mitigation. Within the logistics domain, technologies such as VR and AR are gaining prominence, especially given the significant transportation challenges inherent in SC management. Notably, technologies make substantial contributions in this domain as well. The integration of automation and predictive mechanisms significantly benefits harvesting processes. Although harvesting is not the sole stage affected by these technologies, the insights they offer can be extrapolated to other stages of the RBSC. Given potential overlaps across RBSC activities, the subsequent chapter will present the digital model within

the framework of the four designated areas (Information Management, Maintenance, Logistic Operations, and Stages Process) delineated in the primary contributions, correlating them with specific RBSC activities.

3.3.2. Proposal for a new model for RBSC

3.3.2.1. Stages process.

In this sector, technology, particularly AI, significantly contributes due to its advanced algorithms, particularly in predictive capabilities. For instance, in agriculture, machine learning enables the anticipation of production quantities (Martinho et al., 2022). In this context, the harvest forecast can be extrapolated to predict residual biomass resulting from these productions. Complementing this technology, data collection is essential, wherein sensors and IoT connections play a pivotal role (Andiappan et al., 2021). In this context, 5G technology significantly facilitates data exchange due to its capacity for real-time transmission of large volumes of data (Mistry et al., 2020). In the realm of ML technology, the integration of this technology with drones has emerged. Drones facilitate the transmission of images, enabling efficient data delivery to algorithms. This capability, for instance, facilitates the identification of pests in agricultural crops (Chin et al., 2023), and then it is possible to obtain information about what biomass can be collected (Liao and Yao, 2021). Another ML work shows the possibility of recognizing different types of trash through images (Zaman, 2022), which could be an opportunity if extrapolated to the recognition of forest species by combining drone images with ML algorithms. Another technology that also revealed the potential for increasing efficiency and detecting failures in the agricultural sector is BD (Maddikunta et al., 2022), (Wolfert et al., 2017). GIS can also provide important spatial information that can complement AI analysis, for example, helping to calculate the costs of using biomass in remote areas. Thus, in terms of the cutting process, the work of Oliveira et al. (2021) has demonstrated the significant impact of robotization within these sectors, enhancing operators’ living conditions and positively affecting system efficiency. Despite potential economic concerns, these are counterbalanced by social benefits. Moreover, robotization not only benefits the cutting process but also extends to the pre-treatment phase, influencing treatment selection based on biomass nature and characteristics (Wang et al., 2023). Drone and machine learning mechanisms play a pivotal role in aiding this decision-making process. Valuable information guiding collection decisions can also inform decisions in the pre-treatment phase. Additionally, big data analysis, previously utilized in understanding online consumer behavior, offers another significant contribution in this context (Porouhan and Premchaiswadi, 2021). Herein lies potential for extrapolation, enabling enhancements in end consumer demand forecasting, thereby fostering improved alignment between supply and demand.

3.3.2.2. Maintenance.

In the maintenance chapter, applicable to all machinery and transportation means in this context, new technologies can significantly contribute to two primary areas. The first area is preventive maintenance, where existing research demonstrates the efficacy of BD technology coupled with ML in enhancing maintenance processes

Table 2
Summary of the main contributions by technology.

Tech	Main contributions	Tech	Main contributions	Tech	Main contributions
IoT	Player’s connection Information sharing	RPA	Process robotization	CPS	Predictive maintenance
AI	Process understanding Planning and forecasting Predictive maintenance	5G	Real-time information share	DT	Real environment simulation
BC	Data security Transaction security	EC	Data protection	QC	Transportation problems
BD	Demand forecasts Failure prediction Route optimization	VR/AR	Training (driving) Docking/undocking operations Order picking	Robotization	Harvesting activities

(Maktoubian et al., 2021). Another contributing technology is the DT. Its capacity to replicate real-world environments in a virtual space enables the anticipation of potential failures (Kamble et al., 2022). In this scenario, integrating sensors with IoT connectivity becomes crucial for simulating real-time data within the DT. Additionally, significant advancements can be observed at the maintenance level through the utilization of AR technology (Rejeb et al., 2021). By integrating 3D tools into the physical environment, employees gain the capability to efficiently address machinery issues.

3.3.2.3. Logistics operations. At the logistics operations level, the aforementioned technologies can enhance two primary components: transportation and warehouse management. A significant challenge in transportation is the Vehicle Routing Problem, which involves determining the optimal routes to efficiently serve all customers. In this regard, one technology that has made a substantial contribution is QC (Ajagekar et al., 2020). In the realm of transportation, VR technology facilitates employee immersion in a virtual environment, serving as a valuable tool for driver training (Hamad and Jia, 2022). Given the substantial scale of biomass transports, their contribution to the transportation sector is deemed critical. Biomass logistics are also integral in addressing efficiency concerns, particularly evident in the aviation industry where route optimization is paramount (Ghobakhloo and Fathi, 2021). In warehouse management, AR can assist in docking and unloading operations (de la Peña Zarzuelo et al., 2020), and streamline logistical processes like material collection. This applicability can readily extend to biomass logistics initiatives, aiding personnel in their duties. Within warehouses, sensor integration with AI can identify pest infestations (Chin et al., 2023), or be adapted akin to the methodology outlined in (Amani and Sarkodie, 2022), albeit geared towards identifying spoiled biomass using drone imagery processed by ML algorithms. Effective utilization of IoT and 5G resources is essential for linking drone-generated data to ML algorithms.

3.3.2.4. Information Management. One of the problems in this chain is the lack of communication channels, sometimes resorting to word of mouth or email. In this sense, technologies such as IoT and BC (Loy et al., 2023), due to their characteristics of increasing transparency, traceability, and tracking, can enhance the creation of trustworthy communication channels (Aragonés et al., 2020). Combined with these two technologies, EC can appear, allowing increased data protection and security as stated by Hu et al. (2021) and Wang & Wang (Wang and Wang, 2022). This could increase the confidence of the various actors in the chain in the model, transforming information from the entire chain

into a reality easily accessed by everyone. BC technology also has another strong contribution which lies in the fact that it is associated with the security of financial transactions, so this technology can stimulate the emergence of new business models and the emergence of new payment models that replace the usual cash transactions (Loy et al., 2023). Still in terms of creating integrated tools, if they exist, RPA can make a huge contribution, allowing, for example, the entry of orders at any time (van Hoek et al., 2022) or the management of information related to payments in a simple way (Hartley and Sawaya, 2019). BD has proven in other contexts to be viable for analyzing trends (Maddikunta et al., 2022), something that can also be disruptive and innovative by allowing forest owners, for example, to know which main residual biomasses are being consumed. The convergence of real and virtual worlds necessitates the integration of 5G and CPS technologies to unlock their full potential. Fig. 3 presents a schematic representation of the revised RBSC model. Notably, transportation and storage are distinctly addressed through specialized technologies for each function.

3.3.3. TO-BE model (analysis of the AS-IS model in the light of emerging technologies)

In the AS-IS model (Section 3.1.2), communication and integration issues among chain stakeholders are identified as significant. This model proposes leveraging emerging technologies like BC and IoT to facilitate extensive data exchange, ensuring security and transparency. Additionally, technologies such as 5G and EC can enhance communication speed and synchronize data from various devices, fostering trust among stakeholders. Addressing labor-intensive processes, robotization in harvesting can enhance efficiency and worker safety. AR improves warehouse operations and maintenance, indirectly benefiting worker conditions. BD and ML aid in preventive maintenance, minimizing machinery failures and reducing reliance on manual labor. Decision support tools play a crucial role, utilizing drones, IoT, and AI to detect pest infestations and assess species diversity. Algorithms optimize biomass collection and warehouse management. DT simulate system scenarios for informed decision-making. QC offers potential solutions for routing challenges, a critical issue in the supply chain.

One of the biggest problems associated with digitalization technologies lies in data security (Raut et al., 2021). Their privacy is also seen as a negative aspect of this digitalization (Raut et al., 2021). Regarding more specific objectives, a lot of detail is required when describing processes to, for example, enable the implementation of RPA (Viale and Zouari, 2020). Another problem is the possible replacement of human work by machinery/algorithms (Dolgui and Ivanov, 2022). Negative points include acquisition or implementation costs, as well as the

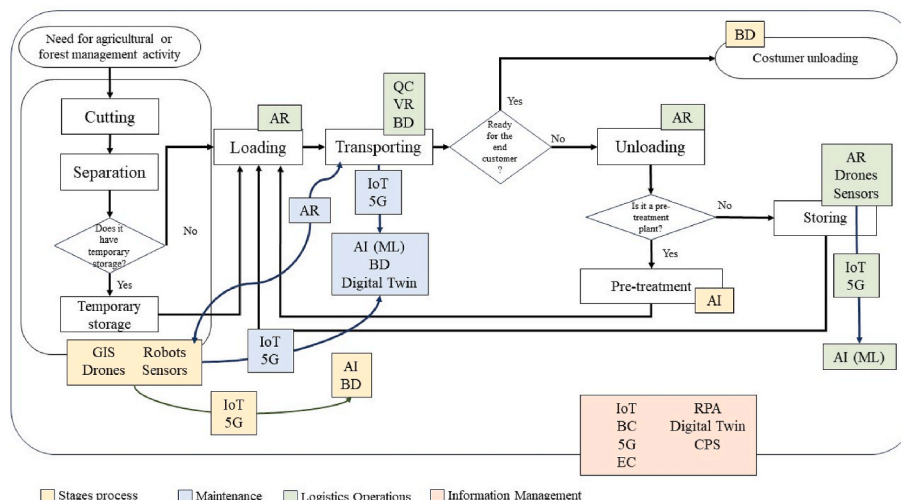


Fig. 3. New model of RBSC.

possibility of physical injuries, as in the case of VR equipment (Hamad and Jia, 2022). However, as a great enabler of optimization of the entire chain, DT appears, whose main benefits are the possibility of creating a real environment, allowing the optimization (Kamble et al., 2022) or the reduction of energy consumption (Attaran and Celik, 2023). This tool can become very viable in supporting the entire digitalization process and consequent optimization of the chain. Its use may allow the perception of other challenges, but at the same time facilitate decision-making.

4. Reflection of the results based on PEST and SWOT analysis

To initiate a discussion on the proposed model, two PEST and SWOT analyses were employed. These analyses leverage the collective experience and expertise of the research team and were constructed being in mind the Portuguese context. The PEST analysis is a methodological tool utilized to delineate external macro-environmental factors crucial for strategic assessment (Akinsolu, 2023). The analysis aims to evaluate the newly proposed model across four primary categories: political, economic, social, and technological. Employing the SWOT analysis framework, the study intends to assess both internal factors (strengths and weaknesses) and external factors (opportunities and threats) that may impact a defined set of objectives (Abraham and Franken, 2023).

4.1. PEST analysis

4.1.1. Political factors

Regarding external political factors, a notable concern is the General Data Protection Regulation (GDPR). The primary objective of this regulation is to safeguard personal data, potentially posing challenges to the model efficacy and potential optimization gains. Additionally, within the Portuguese context, there exists a property registration platform known as BUPI (“Balcão Único do Prédio,” translated as “One-stop Shop for Buildings”). This platform aims to aggregate information on buildings, thereby contributing to the preservation and understanding of Portuguese heritage. Such aggregation of data could serve as a significant resource for understanding the Portuguese forest landscape. Another significant political aspect pertains to the burning period, which permits individuals to burn waste during specific seasons of the year, which may signify a maintenance of traditional methods rather than embracing digitalization. The digitization of forestry processes has the potential to reduce production costs associated with renewable energy. This cost reduction could amplify interest in renewable energy sources, consequently diminishing reliance on fossil fuels and aligning with decarbonization policies.

4.1.2. Economic factors

In economic terms, inflation may hinder the adoption of this technology due to its potentially high costs. Additionally, a decrease in economic growth can dampen enthusiasm for investment. However, during times of crisis, such technology may be scrutinized more closely, potentially making it a valuable asset. Another avenue for funding lies in research and development (R&D) projects aimed at creating innovative solutions, which could prove beneficial for addressing future needs. Numerous initiatives have emerged to support the transition to renewable energy, with potential funding opportunities arising from integrating digital solutions to enhance energy efficiency. Also, increased investment in machinery for deforestation could lead to a reduction in workplace injuries, thereby attracting new labor and mitigating unemployment. The prevalence of elderly landowners with limited pensions who incur high expenses for land maintenance may further drive interest in these solutions within this demographic.

4.1.3. Social factors

In contemporary social discourse, there is a notable escalation in the appreciation of concepts such as green energy and decarbonization. This

proposed model, aimed at optimizing RBSC, presents potential value by enabling the imposition of a marginal additional levy (dedicated to financing the entire technological system), thereby ensuring a future less reliant on fossil fuels. Given the widespread integration of technology within society – exemplified by the ubiquitous ownership of smartphones among a significant portion of the populace – there exists a potential facilitative pathway for the digital transition inherent in this model. Another pertinent consideration lies in the increasing consciousness surrounding the utilization of AI tools such as GPT chat, alongside ongoing discussions pertaining to emerging professions that can leverage these tools. Within this evolving landscape, the viability and contemporaneity of this model appear increasingly evident.

4.1.4. Technological factors

In technological contexts, particularly within digital transition models, a notable challenge arises from the perpetual evolution of technology. This evolution can pose significant compatibility issues, necessitating infrastructure adjustments. However, within an increasingly technocentric landscape, there is a prevailing trend towards expanded supply offerings at more accessible price points, potentially mitigating the aforementioned challenges. Infrastructure alterations may introduce complications such as equipment disposal, often associated with waste. Nonetheless, scholarly inquiry has addressed this concern, suggesting the emergence of novel strategies for managing obsolete technology. Table 3 provides a summary of factors outlined in the PEST Analysis.

PEST analysis in the field of biomass has already been addressed in other works. Thus, in political terms, there is a strong potential for this model to help the energy transition and, consequently, decarbonization. This potential has also been mentioned by other authors, who talk about the construction of biomass co-firing at coal power plants as an enabler of compliance with the Paris agreement (Sugiyono et al., 2022), or Nunes et al. (2015), which refers to the potential of biomass as an enabler of compliance with decarbonization targets. Also, in shipping sector, the policies for using biogas in this context are mentioned (Mallouppas et al., 2023). Another aspect approached in this work is the burning period, which in addition to reducing interest in these models, can also lead to fires. The use of biomass, besides the energy potential, has the power to reduce fires, and this issue may be of political interest (Nunes et al., 2023). This paper also discusses the GDPR and BUPI, which are not covered in any of the works cited. The first one because they do not involve such a data-based model, while the second is justified by the fact that is a relatively recent development in the Portuguese context.

In economic terms, the major constraint of this model lies in the investment inherent in the technology. This problem is also reported in the work (Nunes et al., 2015), which points the crisis as an inhibitor of this investment, which is in line with this work. Another work (Nunes et al., 2023), indicates the operating costs as something that inhibits the

Table 3
Summary of the factors listed in PEST Analysis.

Political	Economic	Social	Technological
Problems with privacy related with GDPR; Obligation to register with BUPI; Burning legislation; Decarbonization policies.	Inflation and economic decline; R&D project funds; Energy transition project funds; Reduced injury costs; Low reforms and high forest management costs.	Valorization of concepts such as green energy or decarbonization; Familiarity of the population with new technologies; Familiarity of relationship with AI technology.	Constant evolution of technology; Decrease in technology prices.

use of residual biomass, which in this context can even be mitigated by all the advantages already explored. Looking at the investment problem, this work talks about the possibility of using funds, something that is pointed out as an enabler in the context of biofuels in shipping (Mallouppas et al., 2023), showing that this will be the “main” path for this type of funding. The work of (Sugiyono et al., 2022) talks about the possibility of making a return on the carbon market, something that could be explored in this model where implemented. In terms of workers, (Nunes et al., 2015) talks about the development of job opportunities, this study, as result of all the technological advantages, discusses the possibility of increasing the quality of life of these employees.

In social terms, the major point discussed almost unanimously in the various analyses is in line with the results of this one, the positive impact that the use of renewable energies can have on society (Nunes et al., 2015), (Mallouppas et al., 2023). Another relevant aspect in this model is the familiarity of people with new technologies, which can be an enabler of this model, possibly providing new job opportunities, which is in line with Nunes et al. (2023) and Sugiyono et al. (2022), where besides the difference in purpose also points the exploitation of biomass as an enabler of job creation. In technological terms, conversion technologies govern most of the works, but this one looks at technological aspects from an 14.0 perspective, which makes it innovative, showing the relevance of analyzing these aspects in the biomass context, and constitutes a interesting future work.

4.2. SWOT analysis

4.2.1. Strengths

The presented model exhibits several strengths. Firstly, it offers enhanced knowledge of forest ecosystems, filling a current gap in understanding. This increased knowledge base could lead to more informed decision-making processes, thereby enhancing certainty. Secondly, the model reduces the likelihood of human errors due to its extensive utilization of technology. By leveraging predictive mechanisms, decisions can be bolstered, reducing reliance on human intuition as the primary decision support tool. Thirdly, it contributes to a general reduction in logistical activities within the forestry supply chain, minimizing unnecessary unloading and temporary storage. Additionally, the model improves social conditions by facilitating robotization and mitigating machinery failures through advanced preventive maintenance technologies. These improvements can enhance working conditions for all stakeholders involved in the supply chain. The model addresses the issue of information asymmetry within the current forestry landscape, often resulting in reliance on unreliable sources such as word of mouth, culminating in a reduction misinformation and enabling more informed decision-making processes.

4.2.2. Weaknesses

In terms of weaknesses, the foremost issue is the cost associated with the required technologies. Implementing this model necessitates not only the adaptation or modification of existing infrastructure but also significant investment in new technologies. Additionally, a considerable portion of the forests targeted for conservation is in underdeveloped regions lacking adequate technological and social infrastructure. From a technological standpoint, there remain numerous areas devoid of essential network coverage, which may persist due to sparse population densities and prolonged payback periods. On the social front, remote areas often suffer from a deficiency in digital literacy, particularly among older demographics comprising most of the population. Resistance to embracing this model may arise, as some individuals may perceive a loss of control over traditional business or market structures, potentially sparking opposition movements against the transition.

4.2.3. Opportunities

In terms of opportunities, several key points emerge. Firstly, there is

potential for an increased adoption of renewable energy sources, which could yield cost advantages. Secondly, leveraging domestic biomass resources reduces reliance on imported fossil fuels, a significant consideration for Portugal given its lack of domestic fossil fuel sources. Additionally, valorizing residual biomass can mitigate rural fire risks by preventing open burning and reducing forest fuel loads. Implementing algorithms coupled with sensory systems offers a means to safeguard stored materials, thereby averting potential losses due to neglect, decay, or pest infestations. Furthermore, the emergence of technologies like BC holds promise for enhancing trust among stakeholders and streamlining monetary transactions within the biomass value chain, potentially fostering novel business models. The valorization of biomass resources can also lead to socioeconomic benefits, such as providing supplemental income for pensioners and fostering forest maintenance activities. Moreover, the imperative to engage with digital technologies may prompt widespread upskilling, thereby enhancing the digital literacy of the populace. There is an opportunity for infrastructure development in remote areas, potentially catalyzing economic growth and attracting new investments and talent. This, in turn, could give rise to new professions centered around managing complex biomass systems, while increased automation may reduce workplace injuries and facilitate immersive training experiences, such as virtual reality-based driving simulations.

4.2.4. Threats

In terms of threats, the primary concern lies in the potential lack of perceived value by investors, whether external or state-funded, leading to a reluctance to invest in these solutions. Additionally, the requirement for individual investments in equipment such as smartphones or computers to access information presents a significant challenge. It is impractical for local authorities or other entities to provide such equipment for the entire population. Moreover, there may be inherent distrust among individuals, particularly in less developed areas, toward these new models, impeding their acceptance. Presently, a substantial portion of information exchanges, as outlined in section 3.1.2, still rely on word-of-mouth or email. In this context, the adoption of RPA and other technologies may lead to the obsolescence of certain professions.

Table 4 succinctly outlines the factors identified in the SWOT Analysis.

In terms of the strengths of the model, the use of residual biomass energy allows for greater energy independence (Nunes et al., 2023). In terms of digitalization, (Loy et al., 2023) point to the increased

Table 4
Summary of the factors listed in SWOT Analysis.

Strengths	Weaknesses
Greater knowledge of the forest; Reduction of human errors; Reduction in logistics activities in this chain; Improvement of social conditions; Reduce aspects such as misinformation among forest owners.	Price of technologies; Lack a lot of technological development in rural areas; Lack a lot of social development in rural areas; Fear of losing control of current business models.
Opportunities	Threats
Increase in the share of renewable energy; Reduces dependence on fossil fuels; Reduction of rural fires; Prevent the deterioration of stored biomass materials; Creation of new business models; Create new forms of income; Increase in the population’s “digital” literacy; Development of rural areas; Creation of new professions; Attract people to these jobs.	Investors do not perceive the real value of the solution; Individual investments in equipment; Distrust of people; Disappearance of certain jobs.

traceability of information, which is in line with what has been discussed in this paper, in terms of reducing disinformation in the chain. The possibility of reducing human error could also have a lot of potential as a strength of this model, which could lead to lower costs and improved working conditions for employees. In terms of weaknesses, one that is very relevant and corroborated in the literature (Loy et al., 2023) is the possible lack of network coverage in less developed areas. High investment is also clearly a weakness, also mentioned in other works (Singh et al., 2022b). The lack of coordination between the various players in the chain, mentioned by the same authors, can be highly correlated with the weakness of “fear of losing control of current business models” because if there were more coordination, there would be more information and there would be no fear of losing certain models that happen due to a lack of knowledge on the part of certain players.

In the chapter on renewable energies, the work of (Nunes et al., 2023) points to the growth of the share of renewable energies as a strength, here it is considered an opportunity, this difference can be justified by the major focus of the work, in one case it is the use of residual biomass, and in this work, it is the optimization of the global model of RBSC, based on technology. The work of (Singh et al., 2022b) also sees this issue as an opportunity. So, whether it is a strength or an opportunity, it is a positive aspect. The works of (Nunes et al., 2023), (Singh et al., 2022b) also talk about the possibility of increasing the potential for creating job opportunities, something that is in line with the conclusions of this work. Reducing the fuel load and consequently mitigating the risk of fires is another opportunity (Nunes et al., 2023) that is in line with this work. Another very relevant opportunity considered in this work is the development of rural areas, which in addition to enhancing the model, has enormous potential to develop typically less developed areas.

In terms of threats, (Loy et al., 2023) points to the possible alienation of people. In this study's view, there is the possibility of professions disappearing, which could indirectly alienate people. A lack of communication could be pointed out as a threat to valorization (Nunes et al., 2023), however, this work has a huge proposal for this threat identified in the literature. Finally, the possibility of investors not seeing the value in the solution may not allow it to be maximized.

4.3. PEST and SWOT analysis and discussion

The primary objective of this section is to enhance the depth of analysis by establishing connections between various points previously discussed. In the political context, Portugal is experiencing a rise in land data due to the mandatory requirement for individuals to fill out BUI forms. This initiative has the potential to increase knowledge about forests, bolstering the model's effectiveness and reinforcing its strengths. Additionally, reducing misinformation is crucial, as it ensures compliance with regulations and cultivates a well-informed society, addressing a key aspect highlighted in the SWOT analysis.

The phenomenon of the burning season in Portugal poses a challenge, potentially leading individuals to maintain traditional practices and thereby showing disinterest in investing in alternative solutions, a threat outlined in the SWOT analysis. Furthermore, political pressure to decarbonize, driven by climate change concerns, underscores the need to transition from fossil fuels to renewable energy sources. The digitalization of RBSC, as highlighted in the SWOT analysis, presents an opportunity to increase the share of biomass energy, aligning with political objectives and potentially catalyzing economic investments in energy transition projects.

Economically, the analysis from the PEST perspective complements the opportunities identified in the SWOT analysis. Funding allocations, particularly towards energy transition and research and development (R&D), hold significant promise. Direct contributions to reducing fossil fuel consumption and long-term energy independence align with Portugal's context, where reliance on imported fossil fuels is a concern. Additionally, investing in renewable energy projects could stimulate

rural development, create employment opportunities, and enhance digital literacy among the population.

From a social standpoint, the incentivization of green initiatives, such as the valorization of green points, can foster social acceptance of proposed models, potentially mitigating the risk of underinvestment in individual needs. Moreover, increased familiarity with technology may alleviate infrastructure deficiencies in rural areas, as demand for infrastructure prompts improvements from network providers. This familiarity also fosters trust among investors, who may be more inclined to support initiatives with proven success.

Regarding technology, ongoing advancements are anticipated to drive down costs, making high-tech solutions more accessible across various sectors. This evolving landscape suggests a departure from the current constraint of high technology costs, with continuous innovation and economies of scale making technology increasingly accessible. This shift not only reflects technological progress but also signals a changing market dynamic, where advanced technology becomes more widely available, transcending its previous status as a privilege for select users and industries.

5. Conclusions

The pressure to use renewable energy led to a look at biomass, however, its characteristics associated with logistic costs have led to not taking advantage of certain biomass types as residual biomasses, preferring its burning and threat populations. To combat that logistic costs, this study proposes a technological model that could optimize the RBSC. To accomplish this overarching purpose, two specific objectives were identified. Firstly, to comprehensively map the current state of the RBSC to gain insights into its existing status, based on empirical documents, that contribute to future works in this chain. Subsequently, the second aim was to investigate the implementation of I4.0 technologies in the biomass industry. Given the limited literature in this domain, an exploratory analysis was employed to fulfill this aim. As contributions, it is possible to state that a model to future developments based on practical insights and a comprehensive revision about impact of emerging technologies in supply chain. Lastly, the proposed model contributes both practically and theoretically: practically, by presenting a replicable and testable model in the actual RBSC context, and theoretically, by introducing a pioneering digital model to the literature, thus catalyzing the digitization of the RBSC. PEST and SWOT analyses were conducted to transcend theoretical solutions and offer a conceptual framework analyzed in the context of real-world challenges, thus providing practical value as a basis for discussions among decision-makers and theoretical value by introducing novel perspectives and avenues for future exploration. With regards to limitations, while the first aim benefited from practical work, analyzing a different case study could enhance its analysis. As for the second aim, the exploratory review conducted does not guarantee comprehensive coverage of all relevant literature. For future research, presenting this study to domain experts could refine the analyses and validate the proposed model. Additionally, future avenues could involve the development of the discussed algorithms as potential future implementations.

CRedit authorship contribution statement

Tiago Bastos: Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Data curation. **Leonor C. Teixeira:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Leonel J.R. Nunes:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

None of the authors have any financial or personal relationships with other people or organizations that could inappropriately influence or bias the work presented in this manuscript. This includes employment, consultancies, stock ownership, honoraria, paid expert testimony, patent applications/registrations, and grants or other funding. The authors confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome. We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We understand that this statement will be available to the Editor and the reviewers and will form part of the public record if the manuscript is accepted for publication.

Data availability

Data will be made available on request to corresponding author.

References

- Abdulyekeen, K.A., Umar, A.A., Patah, M.F.A., Daud, W.M.A.W., 2021. Torrefaction of biomass: production of enhanced solid biofuel from municipal solid waste and other types of biomass. *Renew. Sustain. Energy Rev.* 150, 111436 <https://doi.org/10.1016/j.rser.2021.111436>.
- Abraham, K., Franken, M., 2023. A SWOT analysis of the complex interdependencies of the Maltese reimbursement processes. *Health Policy Open* 4, 100095. <https://doi.org/10.1016/j.hpopen.2023.100095>.
- Ajagekar, A., Humble, T., You, F., 2020. Quantum computing based hybrid solution strategies for large-scale discrete-continuous optimization problems. *Comput. Chem. Eng.* 132, 106630 <https://doi.org/10.1016/j.compchemeng.2019.106630>.
- Akinsolu, M.O., 2023. Applied artificial intelligence in manufacturing and industrial production systems: PEST considerations for engineering managers. *IEEE Eng. Manag. Rev.* 51 (1), 52–62. <https://doi.org/10.1109/EMR.2022.3209891>.
- Alfuhaid, S., Amyot, D., Anda, A.A., Mylopoulos, J., 2023. A mapping review on cyber-physical smart contracts: architectures, platforms, and challenges. *IEEE Access* 11, 65872–65890. <https://doi.org/10.1109/ACCESS.2023.3290899>.
- Amani, M.A., Sarkodie, S.A., 2022. Mitigating spread of contamination in meat supply chain management using deep learning. *Sci. Rep.* 12 (1), 1–10. <https://doi.org/10.1038/s41598-022-08993-5>.
- Andiappan, V., How, B.S., Ngan, S.L., 2021. A perspective on post-pandemic biomass supply chains: opportunities and challenges for the new norm. *Process Integrat. Optimiz. Sustain.* 5 (4), 1003–1010. <https://doi.org/10.1007/s41660-021-00176-5>.
- Aragónes, M.M., et al., 2020. Digital innovation hubs as a tool for boosting biomass valorisation in regional bioeconomies: andalusian and South-East Irish case studies. *J. Open Innov.: Tech. Market Complex.* 6 (4), 1–26. <https://doi.org/10.3390/joitmc6040115>.
- Aravindaraj, K., Rajan Chinna, P., 2022. A systematic literature review of integration of industry 4.0 and warehouse management to achieve Sustainable Development Goals (SDGs). *Clean. Logist. Suppl. Chain* 5, 100072. <https://doi.org/10.1016/j.clscn.2022.100072>.
- Attaran, M., Celik, B.G., 2023. Digital Twin: benefits, use cases, challenges, and opportunities. *Decision Anal. J.* 6, 100165 <https://doi.org/10.1016/j.dajour.2023.100165>.
- Basile, F., Pilotti, L., Ugolini, M., Lozza, G., Manzolini, G., 2022. Supply chain optimization and GHG emissions in biofuel production from forestry residues in Sweden. *Renew. Energy* 196, 405–421. <https://doi.org/10.1016/j.renene.2022.06.095>.
- Bastos, T., Teixeira, L., 2024. Digital transition and sustainable development goals: a theoretical reflection on the impact of I4.0 technologies. In: *International Conference on Flexible Automation and Intelligent Manufacturing*. Springer, pp. 713–720. https://doi.org/10.1007/978-3-031-38165-2_83.
- Benti, N.E., et al., 2021. The current status, challenges and prospects of using biomass energy in Ethiopia. *Biotechnol. Biofuels* 14 (1), 1–24. <https://doi.org/10.1186/s13068-021-02060-3>.
- Bhattacharya, S., Chatterjee, A., 2022. Digital project driven supply chains: a new paradigm. *Supply Chain Manag.* 27 (2), 283–294. <https://doi.org/10.1108/SCM-12-2020-0641>.
- Brás, P., 2022. *Residual Agroforestry Biomass Supply Chain Characterization: A Mapping Approach*. NOVA University, Lisbon.
- Casau, M., Cancela, D.C.M., Matias, J.C.O., Dias, M.F., Nunes, L.J.R., 2021. Coal to biomass conversion as a path to sustainability: a hypothetical scenario at pego power plant (Abrantes, Portugal). *Resources* 10 (8), 84. <https://doi.org/10.3390/resources10080084>.
- Casau, M., Dias, M.F., Matias, J.C.O., Nunes, L.J.R., 2022a. Residual biomass: a comprehensive review on the importance, uses and potential in a circular bioeconomy approach. *Resources* 11 (4), 35. <https://doi.org/10.3390/resources11040035>.
- Casau, M., Ferreira Dias, M., Teixeira, L., Matias, J.C.O., Nunes, L.J.R., 2022b. Reducing rural fire risk through the development of a sustainable supply chain model for residual agroforestry biomass supported in a web platform: a case study in Portugal central region with the project BioAgroFloRes. *Fire* 5 (3), 61. <https://doi.org/10.3390/fire5030061>.
- Chatterjee, S., Chaudhuri, R., Gupta, S., Sivarajah, U., Bag, S., 2023. Assessing the impact of big data analytics on decision-making processes, forecasting, and performance of a firm. *Technol. Forecast. Soc. Change* 196, 122824. <https://doi.org/10.1016/j.techfore.2023.122824>.
- Chidozie, B.C., Ramos, A.L., Ferreira, J.V., Ferreira, L.P., 2023. Residual agroforestry biomass supply chain simulation insights and directions: a systematic literature review. *Sustainability* 15 (13), 9992. <https://doi.org/10.3390/su15139992>.
- Chin, R., Catal, C., Kassahun, A., 2023. Plant disease detection using drones in precision agriculture. *Precis. Agric.* 24 (5), 1663–1682. <https://doi.org/10.1007/s11119-023-10014-y>.
- de la Peña Zarzuelo, I., Freire Soeane, M.J., López Bermúdez, B., 2020. Industry 4.0 in the port and maritime industry: a literature review. *J. Ind. Inf. Integr.* 20, 100173. <https://doi.org/10.1016/j.jii.2020.100173>.
- Dionisio, M., de Souza Junior, S.J., Paula, F., Pellanda, P.C., 2022. The role of digital social innovations to address SDGs: a systematic review. In: *XLVI Encontro da ANPAD - EnANPAD 2022*.
- Dixit, V.V., Niu, C., 2023. Quantum computing for transport network design problems. *Sci. Rep.* 13 (1), 12267. <https://doi.org/10.1038/s41598-023-38787-2>.
- Dixit, V.V., Niu, C., Rey, D., Waller, S.T., Levin, M.W., 2023. Quantum computing to solve scenario-based stochastic time-dependent shortest path routing. *Transport. Lett.* 1–11. <https://doi.org/10.1080/19427867.2023.2238461>.
- Dolgui, A., Ivanov, D., 2022. 5G in digital supply chain and operations management: fostering flexibility, end-to-end connectivity and real-time visibility through internet-of-everything. *Int. J. Prod. Res.* 60 (2), 442–451. <https://doi.org/10.1080/00207543.2021.2002969>.
- E-Fatima, K., Khandan, R., Hosseinian-Far, A., Sarwar, D., 2023. The adoption of robotic process automation considering financial aspects in beef supply chains: an approach towards sustainability. *Sustainability* 15 (9), 7236. <https://doi.org/10.3390/su15097236>.
- Egger, D.J., et al., 2020. Quantum computing for finance: state-of-the-art and future prospects. *IEEE Transact. Quant. Eng.* 1, 1–24.
- Fatorachian, H., Kazemi, H., 2021. Impact of Industry 4.0 on supply chain performance. *Prod. Plann. Control* 32 (1), 63–81. <https://doi.org/10.1080/09537287.2020.1712487>.
- Feng, J., Yang, L.T., Gati, N.J., Xie, X., Gavuna, B.S., 2020. Privacy-preserving computation in cyber-physical-social systems: a survey of the state-of-the-art and perspectives. *Inf. Sci.* 527, 341–355. <https://doi.org/10.1016/j.ins.2019.07.036>.
- Fiore, M., Mongiello, M., 2023. Blockchain technology to support Agri-food Supply Chains: A comprehensive review. *IEEE Access* 11, 75311–75324. <https://doi.org/10.1109/ACCESS.2023.3296849>.
- Flak, J., 2020. Technologies for sustainable biomass supply-overview of market offering. *Agronomy* 10 (6), 798. <https://doi.org/10.3390/agronomy10060798>.
- Ghadge, A., Mogale, D.G., Bourlakis, M., Maiyar, L.M., Moradlou, H., 2022. Link between Industry 4.0 and green supply chain management: evidence from the automotive industry. *Comput. Ind. Eng.* 169, 108303. <https://doi.org/10.1016/j.cie.2022.108303>.
- Ghobakhloo, M., Fathi, M., 2021. Industry 4.0 and opportunities for energy sustainability. *J. Clean. Prod.* 295, 126427. <https://doi.org/10.1016/j.jclepro.2021.126427>.
- Ghorbani, N., Aghahosseini, A., Breyer, C., 2020. Assessment of a cost-optimal power system fully based on renewable energy for Iran by 2050 – achieving zero greenhouse gas emissions and overcoming the water crisis. *Renew. Energy* 146, 125–148. <https://doi.org/10.1016/j.renene.2019.06.079>.
- Guo, T., et al., 2022. Energy pellets from whole-wheat straw processed with a deep eutectic solvent: a comprehensive thermal, molecular and environmental evaluation. *Renew. Energy* 194, 902–911. <https://doi.org/10.1016/j.renene.2022.05.143>.
- Hamad, A., Jia, B., 2022. How virtual reality technology has changed our lives: an overview of the current and potential applications and limitations. *Int. J. Environ. Res. Publ. Health* 19 (18), 11278. <https://doi.org/10.3390/ijerph191811278>.
- Hartley, J.L., Sawaya, W.J., 2019. Tortoise, not the hare: digital transformation of supply chain business processes. *Bus. Horiz.* 62 (6), 707–715. <https://doi.org/10.1016/j.bushor.2019.07.006>.
- Hopkins, J.L., 2021. An investigation into emerging industry 4.0 technologies as drivers of supply chain innovation in Australia. *Comput. Ind.* 125, 103323. <https://doi.org/10.1016/j.compind.2020.103323>.
- Hu, S., Huang, S., Huang, J., Su, J., 2021. Blockchain and edge computing technology enabling organic agricultural supply chain: a framework solution to trust crisis. *Comput. Ind. Eng.* 153, 107079. <https://doi.org/10.1016/j.cie.2020.107079>.
- Huynh, M.T., Nippa, M., Aichner, T., 2023. Big data analytics capabilities: patchwork or progress? A systematic review of the status quo and implications for future research. *Technol. Forecast. Soc. Change* 197, 122884. <https://doi.org/10.1016/j.techfore.2023.122884>.
- Islam, M.A., Rashid, S.I., Hossain, N.U.I., Fleming, R., Sokolov, A., 2023. An integrated convolutional neural network and sorting algorithm for image classification for efficient flood disaster management. *Decision Anal. J.* 7, 100225.
- Jangirala, S., Das, A.K., Vasilakos, A.V., 2020. Designing secure lightweight blockchain-enabled RFID-based authentication protocol for supply chains in 5G mobile edge computing environment. *IEEE Trans. Ind. Inf.* 16 (11), 7081–7093. <https://doi.org/10.1109/TII.2019.2942389>.

- Javaid, M., Haleem, A., Singh, R.P., Suman, R., 2022. Enhancing smart farming through the applications of Agriculture 4.0 technologies. *Int. J. Intellig. Networks* 3, 150–164. <https://doi.org/10.1016/j.ijin.2022.09.004>.
- Jimada-Ojuolape, B., Teh, J., 2020. Impact of the integration of information and communication technology on power system reliability: a review. *IEEE Access* 8, 24600–24615. <https://doi.org/10.1109/ACCESS.2020.2970598>.
- Jucker, T., et al., 2023. Using multi-platform LiDAR to guide the conservation of the world's largest temperate woodland. *Remote Sens. Environ.* 296, 113745 <https://doi.org/10.1016/j.rse.2023.113745>.
- Kamble, S.S., Gunasekaran, A., Parekh, H., Mani, V., Belhadi, A., Sharma, R., 2022. Digital twin for sustainable manufacturing supply chains: current trends, future perspectives, and an implementation framework. *Technol. Forecast. Soc. Change* 176, 121448. <https://doi.org/10.1016/j.techfore.2021.121448>.
- Leone, V., Elia, M., Lovreglio, R., Correia, F., Tedim, F., 2023. The 2017 extreme wildfires events in Portugal through the perceptions of volunteer and professional firefighters. *Fire* 6 (4), 133. <https://doi.org/10.3390/fire6040133>.
- Liao, M., Yao, Y., 2021. Applications of artificial intelligence-based modeling for bioenergy systems: a review. *GCB Bioenergy* 13 (5), 774–802. <https://doi.org/10.1111/gcbb.12816>.
- Loy, A.C.M., Kong, K.G.H., Lim, J.Y., How, B.S., 2023. Frontier of digitalization in Biomass-to-X supply chain: opportunity or threats? *Journal of Bioresources and Bioproducts* 8 (2), 101–107. <https://doi.org/10.1016/j.jobab.2023.03.001>.
- Maddikunta, P.K.R., et al., 2022. Industry 5.0: a survey on enabling technologies and potential applications. *J. Ind. Inf. Integr.* 26, 100257 <https://doi.org/10.1016/j.jii.2021.100257>.
- Magalhães, M.R., Cunha, N.S., Pena, S.B., Müller, A., 2021. FIRELAN—an ecologically based planning model towards a fire resilient and sustainable landscape. A case study in center region of Portugal. *Sustainability* 13 (13), 7055. <https://doi.org/10.3390/su13137055>.
- Maktoubian, J., Tashkiri, M.S., Turner, P., 2021. Intelligent predictive maintenance (Ipdm) in forestry: a review of challenges and opportunities. *Forests* 12 (11), 1495. <https://doi.org/10.3390/f12111495>.
- Mallouppas, G., Yfantis, E.A., Ioannou, C., Paradesiotis, A., Ktoris, A., 2023. Application of biogas and biomethane as maritime fuels: a review of research, technology development, innovation potentials, and market potentials. *Energies* 16 (4), 2066. <https://doi.org/10.3390/en16042066>.
- Marmolejo-Saucedo, J.A., 2022. Digital twin framework for large-scale optimization problems in supply chains: a case of packing problem. *Mobile Network. Appl.* 27 (5), 2198–2214. <https://doi.org/10.1007/s11036-021-01856-9>.
- Martinho, V.J.P.D., et al., 2022. Machine learning and food security: insights for agricultural spatial planning in the context of agriculture 4.0. *Appl. Sci.* 12 (22), 11828 <https://doi.org/10.3390/app122211828>.
- Mengist, W., Soromessa, T., Legese, G., 2020. Method for conducting systematic literature review and meta-analysis for environmental science research. *MethodsX* 7, 100777. <https://doi.org/10.1016/j.mex.2019.100777>.
- Mhlanga, D., 2021. Artificial intelligence in the industry 4.0, and its impact on poverty, innovation, infrastructure development, and the sustainable development goals: lessons from emerging economies? *Sustainability* 13 (11), 5788. <https://doi.org/10.3390/su13115788>.
- Mistry, I., Tanwar, S., Tyagi, S., Kumar, N., 2020. Blockchain for 5G-enabled IoT for industrial automation: a systematic review, solutions, and challenges. *Mech. Syst. Signal Process.* 135, 106382 <https://doi.org/10.1016/j.ymssp.2019.106382>.
- Moretti, L., Milani, M., Lozza, G.G., Manzolini, G., 2021. A detailed MILP formulation for the optimal design of advanced biofuel supply chains. *Renew. Energy* 171, 159–175. <https://doi.org/10.1016/j.renene.2021.02.043>.
- Nunes, L.J.R., Matias, J.C.O., Catalão, J.P.S., 2015. Analysis of the use of biomass as an energy alternative for the Portuguese textile dyeing industry. *Energy* 84, 503–508. <https://doi.org/10.1016/j.energy.2015.03.052>.
- Nunes, L.J.R., Casau, M., Ferreira Dias, M., 2021. Portuguese wood pellets market: organization, production and consumption analysis. *Resources* 10 (12), 130.
- Nunes, L.J.R., Casau, M., Dias, M.F., Matias, J.C.O., Teixeira, L.C., 2023. Agroforest woody residual biomass-to-energy supply chain analysis: feasible and sustainable renewable resource exploitation for an alternative to fossil fuels. *Result. Eng.* 17, 101010 <https://doi.org/10.1016/j.rineng.2023.101010>.
- Olabi, A.G., Abdelkareem, M.A., 2022. Renewable energy and climate change. *Renew. Sustain. Energy Rev.* 158, 112111 <https://doi.org/10.1016/j.rser.2022.112111>.
- Oliveira, L.F.P., Moreira, A.P., Silva, M.F., 2021. Advances in forest robotics: a state-of-the-art survey. *Robotics* 10 (2), 53. <https://doi.org/10.3390/robotics10020053>.
- Oshri, I., Plugge, A., 2022. Introducing RPA and automation in the financial sector: lessons from KAS Bank. *J. Inf. Technol. Teach. Cases* 12 (1), 88–95. <https://doi.org/10.1177/2043886921994828>.
- Pakseresh, A., Yavari, A., Kaliji, S.A., Hakelius, K., 2023. The intersection of blockchain technology and circular economy in the agri-food sector. *Sustain. Prod. Consum.* 35, 260–274. <https://doi.org/10.1016/j.spc.2022.11.002>.
- Parekh, P., Patel, S., Patel, N., Shah, M., 2020. Systematic review and meta-analysis of augmented reality in medicine, retail, and games. *Vis. Comput. Ind. Biomed. Art* 3 (1), 1–20. <https://doi.org/10.1186/s42492-020-00057-7>.
- Porouhan, P., Premchaiswadi, W., 2021. Big data analytics of supply chains with process mining. In: *International Conference on ICT and Knowledge Engineering*. IEEE, pp. 1–5. <https://doi.org/10.1109/ICTKE52386.2021.9665705>.
- Preut, A., Kopka, J.P., Clausen, U., 2021. Digital twins for the circular economy. *Sustainability* 13 (18), 10467. <https://doi.org/10.3390/su131810467>.
- Qiu, T., Chi, J., Zhou, X., Ning, Z., Atiquzzaman, M., Wu, D.O., 2020. Edge computing in industrial internet of Things: architecture, advances and challenges. *IEEE Commun. Surv. Tutor.* 22 (4), 2462–2488. <https://doi.org/10.1109/COMST.2020.3009103>.
- Raut, R.D., Yadav, V.S., Cheikhrouhou, N., Narwane, V.S., Narkhede, B.E., 2021. Big data analytics: implementation challenges in Indian manufacturing supply chains. *Comput. Ind.* 125, 103368 <https://doi.org/10.1016/j.compind.2020.103368>.
- Rejeb, A., Keogh, J.G., Wamba, S.F., Treiblmaier, H., 2021. The potentials of augmented reality in supply chain management: a state-of-the-art review. *Manag. Rev. Quart.* 71 (4), 819–856. <https://doi.org/10.1007/s11301-020-00201-w>.
- Rijal, P., Carvalho, H., Matias, J., Garrido, S., Pimentel, C., Carvalho, H., 2023a. Residual forestry biomass supply chain: a mapping approach. *Int. J. Indust. Eng. Manag.* 14 (3), 244–256. <https://doi.org/10.24867/ijiem-2023-3-336>.
- Rijal, P., Carvalho, H., Matias, J., Garrido, S., Pimentel, C., 2023b. Drivers and barriers for sustainable and efficient biomass valorization processes [Online]. Available: <https://ieomsociety.org/proceedings/2023lisbon/265.pdf>.
- Rowan, N.J., 2023. The role of digital technologies in supporting and improving fishery and aquaculture across the supply chain – quo Vadis? *Aquac. Fish* 8 (4), 365–374. <https://doi.org/10.1016/j.aaf.2022.06.003>.
- Sahin, M.E., Tawalbeh, L., Muheidat, F., 2022. The security concerns on cyber-physical systems and potential risks analysis using machine learning. *Procedia Comput. Sci.* 201 (C), 527–534. <https://doi.org/10.1016/j.procs.2022.03.068>.
- Sharifpour, H., Ghaseminezhad, Y., Hashemi-Tabatabaei, M., Amiri, M., 2022. Investigating cause-and-effect relationships between supply chain 4.0 technologies. *Eng. Manag. Product. Serv.* 14 (4), 22–46. <https://doi.org/10.2478/emj-2022-0029>.
- Shi, Z., Ferrari, G., Ai, P., Marinello, F., Pezzuolo, A., 2023. Artificial intelligence for biomass detection, production and energy usage in rural areas: a review of technologies and applications. *Sustain. Energy Technol. Assessments* 60, 103548. <https://doi.org/10.1016/j.seta.2023.103548>.
- Singh, R., Gehlot, A., Vaseem Akram, S., Kumar Thakur, A., Buddhi, D., Kumar Das, P., 2022a. Forest 4.0: digitalization of forest using the internet of Things (IoT). *J. King Saud Univ. - Comput. Inform. Sci.* 34 (8), 5587–5601. <https://doi.org/10.1016/j.jksuci.2021.02.009>.
- Singh, N., Singhania, R.R., Nigam, P.S., Di Dong, C., Patel, A.K., Puri, M., 2022b. Global status of lignocellulosic biorefinery: challenges and perspectives. *Bioresour. Technol.* 344, 126415 <https://doi.org/10.1016/j.biortech.2021.126415>.
- Singh, A., Madaan, G., Hr, S., Kumar, A., 2023. Smart manufacturing systems: a futuristic roadmap towards application of industry 4.0 technologies. *Int. J. Comput. Integrated Manuf.* 36 (3), 411–428. <https://doi.org/10.1080/0951192X.2022.2090607>.
- Smetana, S., Aganovic, K., Heinz, V., 2021. Food supply chains as cyber-physical systems: a path for more sustainable personalized nutrition. *Food Eng. Rev.* 13 (1), 92–103. <https://doi.org/10.1007/s12393-020-09243-y>.
- Stahl, C., Stein, N., Flath, C.M., 2023. Analytics applications in fashion supply chain management – a review of literature and practice. *IEEE Trans. Eng. Manag.* 70 (4), 1258–1282. <https://doi.org/10.1109/TEM.2021.3075936>.
- Sugiyono, A., Febijanto, I., Hilmawan, E., Adiarso, 2022. Potential of biomass and coal co-firing power plants in Indonesia: a PESTEL analysis. In: *IOP Conference Series: Earth and Environmental Science*. IOP Publishing, 12007. <https://doi.org/10.1088/1755-1315/963/1/012007>.
- Sun, O., Fan, N., 2020. A review on optimization methods for biomass supply chain: models and algorithms, sustainable issues, and challenges and opportunities. *Process Integrat. Optimiz. Sustain.* 4 (3), 203–226. <https://doi.org/10.1007/s41660-020-00108-9>.
- Toklu, E., 2017. Biomass energy potential and utilization in Turkey. *Renew. Energy* 107, 235–244. <https://doi.org/10.1016/j.renene.2017.02.008>.
- Tun, M.M., Juchelkova, D., Win, M.M., Thu, A.M., Puchor, T., 2019. Biomass energy: an overview of biomass sources, energy potential, and management in Southeast Asian countries. *Resources* 8 (2), 81. <https://doi.org/10.3390/resources8020081>.
- van Hoek, R., Gorm Larsen, J., Lacity, M., 2022. Robotic process automation in Maersk procurement—applicability of action principles and research opportunities. *Int. J. Phys. Distrib. Logist. Manag.* 52 (3), 285–298. <https://doi.org/10.1108/IJPDLM-09-2021-0399>.
- Viale, L., Zouari, D., 2020. Impact of digitalization on procurement: the case of robotic process automation. In: *Supply Chain Forum*. Taylor & Francis, pp. 185–195. <https://doi.org/10.1080/16258312.2020.1776089>.
- Wang, J., Ma, D., Lou, Y., Ma, J., Xing, D., 2023. Optimization of biogas production from starw wastes by different pretreatments: Progress, Challenges and prospects. *Science of Total Environment* 905. <https://doi.org/10.1016/j.scitotenv.2023.166992>.
- Wang, L., Wang, Y., 2022. Supply chain financial service management system based on block chain IoT data sharing and edge computing. *Alex. Eng. J.* 61 (1), 147–158. <https://doi.org/10.1016/j.aej.2021.04.079>.
- Weinberg, S.J., Sanches, F., Ide, T., Kamiya, K., Correll, R., 2023. Supply chain logistics with quantum and classical annealing algorithms. *Sci. Rep.* 13 (1), 4770. <https://doi.org/10.1038/s41598-023-31765-8>.
- Wolfert, S., Ge, L., Verdouw, C., Bogaardt, M.J., 2017. Big data in smart farming—a review. *Agric. Syst.* 153, 69–80.
- Yadav, V.S., Singh, A.R., Raut, R.D., Mangla, S.K., Luthra, S., Kumar, A., 2022. Exploring the application of Industry 4.0 technologies in the agricultural food supply chain: a systematic literature review. *Comput. Ind. Eng.* 169, 108304 <https://doi.org/10.1016/j.cie.2022.108304>.
- Zailan, R., Lim, J.S., Manan, Z.A., Alwi, S.R.W., Mohammadi-ivatloo, B., Jamaluddin, K., 2021. Malaysia scenario of biomass supply chain-cogeneration system and optimization modeling development: a review. *Renew. Sustain. Energy Rev.* 148, 111289 <https://doi.org/10.1016/j.rser.2021.111289>.
- Zaman, A., 2022. Waste management 4.0: an application of a machine learning model to identify and measure household waste contamination—a case study in Australia. *Sustainability* 14 (5), 3061. <https://doi.org/10.3390/su14053061>.