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An Integrated Modeling Framework for Evaluating Green Product Manufacturing Strategies: Economic and Environmental Insights Using Coloured Petri Nets

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ABSTRACT

In recent years, green product manufacturing has been increasingly adopted by firms to reduce environmental impacts, improve corporate image, and achieve sustainable competitive advantage. The shift toward green production is associated not only with lower pollution and resource use, but also with changes in costs, revenues, and overall economic performance. Although many studies have been conducted in this area, limited attention has been given to models that can examine different scenarios under uncertainty and at the same time evaluate their effects on firms' revenues, costs, and the environment. In this study, Coloured Petri Nets (CPNs) are used to model the production-to-sales process of green and non-green products within a firm. Different scenarios are examined, and their effects on revenues, costs, and environmental conditions over time are evaluated. The proposed model can be used as a decision-support tool for selecting suitable green production strategies. The results show that better environmental and financial performance is achieved when only green products are produced. It is also found that when both green and non-green products are produced, better environmental and revenue outcomes can still be obtained if customer preference for green products is strong enough.

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1) Introduction

In recent years, the escalation of environmental challenges, including increased industrial pollution, global warming, depletion of natural resources, and the growth of waste generation, has driven governments, organizations, and firms toward adopting sustainable development approaches (Fahimnia, Sarkis, & Davarzani, 2015) (Hariyani, Hariyani, Mishra, & Sharma, 2024). In this context, firms bear significant responsibility for mitigating negative environmental consequences because they are one of the most influential contributors to environmental impact. Accordingly, the transition toward green product manufacturing has been widely recognized as a fundamental strategy for reducing adverse effects of production activities (Maditati, Munim, Schramm, & Kummer, 2018). Green production seeks to establish a balance between economic performance and environmental responsibility because it emphasizes the efficient use of resources, reduction of energy consumption, utilization of environmentally friendly raw materials, minimization of waste, and sustainable product life-cycle design.

Despite the potential advantages of green production, implementing this approach at the firm level involves numerous uncertainties and complexities. On the one hand, transitioning to green production may increase short-term costs because it typically requires initial investments, changes in production technologies, modifications in supply chains, and redesign of operational processes. On the other hand, this approach can create opportunities such as access to new markets, enhanced brand reputation, increased customer preference, and reduced costs associated with resource consumption and waste management. Therefore, the simultaneous evaluation of the economic and environmental impacts of decisions related to green production has become a major concern for managers and policymakers. A review of the literature indicates that many studies have examined various aspects of green production; however, a significant portion of this research has focused on static analyses, simplified economic models, or statistical methods that have limited capability in capturing the dynamic behavior of production systems, interactions among system components, temporal dependencies, and the occurrence of uncertain events. In many cases, these models are unable to simultaneously analyze changes in costs, revenues, and environmental indicators in an integrated manner. These limitations have resulted in persistent ambiguity in decision-making regarding the level of investment in green production and the selection of optimal strategies. Consequently, the development of models capable of dynamically simulating production system behavior in a scenario-based framework while incorporating uncertainties is of particular importance.

Petri net formalism and its various extensions have been widely applied in modeling different systems and research domains (Naghash Asadi, Abdollahi Azgomi, & Entezari-Maleki, Analytical evaluation of resource allocation algorithms and process migration methods in virtualized systems, 2020) (Naghash Asadi, Abdollahi Azgomi, & Entezari-Maleki, Model-based evaluation of the power versus performance of network routing algorithms, 2021) (Naghash Asadi, Abdollahi Azgomi, & Entezari-Maleki, Evaluation of the Functionality of Mobile Wireless Sensor Networks using Stochastic Reward Nets, 2022) (Naghash Asadi, Pourjani, & Mirsaeed Ghazi , Modeling of the Wumpus World to Evaluate the Difficulty Level of the Game using Coloured Petri Net, 2025). This formalism provides a powerful modeling environment for evaluating various performance measures. Its advantages include a simple definition, a strong mathematical foundation, and an intuitive graphical representation supported by various tools. These tools can provide analytical or simulation-based results derived from Petri net models. Among these, Coloured Petri Nets (CPN), as a powerful tool for modeling discrete and dynamic systems, offer substantial capability for analyzing complex production systems. They enable the representation of process structures, interactions among activities, resource allocation, flows of materials and information, as well as stochastic events within a formal and graphical framework. Furthermore, by supporting both formal analysis and simulation, CPNs allow for the examination of system behavior under different conditions, analysis of decision scenarios, and evaluation of temporal outcomes. These features have led to their application in various fields such as industrial engineering, manufacturing systems, and process analysis, and they can play an effective role in modeling green production systems (Kaiyandra, Farizal, & Rakoto, 2024). Accordingly, the main objective of this paper is to propose a model based on CPNs for analyzing the production-to-sales process of green and non-green products within a firm, and for evaluating the effects of different decisions on costs, revenues, and environmental indicators over time. The proposed model seeks to incorporate uncertainties, operational events, and various scenarios to enable the comparison of production policies and the assessment of their economic and environmental consequences. The novelty of this research lies in presenting an integrated model for the simultaneous analysis of financial and environmental dimensions of production, and in providing a platform for simulating decision-making scenarios under realistic conditions.

The remainder of this paper is organized as follows: Section 2 reviews related work on modeling and evaluating the impact of green product manufacturing; Section 3 introduces the CPN formalism and presents the proposed model; Section 4 evaluates the results obtained from the model under different scenarios; and finally, the conclusion and future works are provided in the last section.

2) Literature Review

Many studies have been published on modeling green marketing and producing green products. In these researches, models and results are typically produced by collecting data and using machine learning algorithms. However, in these studies the results are usually dependent on the collected data, and it is not possible to compare different scenarios while accounting for uncertainty. For example, a technique has been proposed in (Jerbi, Vincy, Aoun, Abbassi, & Kchaou, 2026) for smart bin monitoring and solid waste management using the machine learning approach for the status predictions of bins incorporated with waste forecasting for the future. In (Pancić, Serdarušić, & Ćućić, 2023), the impact of green marketing strategies on consumers' repurchase intention was investigated using the Smart PLS tool. The effects of green awareness and green satisfaction on these relationships were also examined. For this purpose, a non-probability sampling technique was used to target 371 end consumers on social media platforms. The results of the study showed that green marketing had a positive impact on all green-related outcomes, and that green advertising, brand loyalty, brand equity, and brand innovation positively influenced repurchase intention. In (Yue & Cai, 2025), two scenario simulation experiments and questionnaire surveys have been employed to explore the intrinsic connection between green advertising appeal methods and consumers' purchase intentions by targeting university students as the main consumer group for investigation. Governments formulate different subsidy policies to incentivize manufacturers to produce green products, and these policies may have different subsidy effects. In (Lu, Huang, & Cheng, 2021), it has been found that the rankings of indices to evaluate steady-state subsidy effects under the different subsidy policies are time invariant, and the government can preliminarily evaluate these policies according to different subsidy goals. In (Vindhya Kalyani, Venkata Ramana, & Sunitha, 2025), a major research gap in the role of green human resource management in emerging frugalities has been addressed by establishing the impacts of practices in IT firms using data collected from 214 employees.

Unlike studies based on data collection and the use of machine learning algorithms, there are also researches that attempt to model green marketing using game theory. However, these researches have limitations as well, including the lack of model construction. In these approaches, results are obtained and analyzed merely by considering assumptions. For example, a closed-loop supply chain system consisting of a manufacturer, a retailer, and a service provider was considered in (Ma, 2020), and a game theory approach was employed to compare optimal decisions. The results demonstrated that different cooperation scenarios have a significant impact on the supply chain system, and that cooperation consistently performs better than non-cooperation. A differential game model has been constructed in (Lan, Si, Li, & Tang, 2026) for a closed-loop supply chain operating under environmental, social, and governance constraints within a cap-and-trade setting to capture emission reduction activities, recycling investments, goodwill dynamics, and stochastic shocks, and to compare decentralized and centralized decision-making under two allocation criteria, grandfathering and benchmarking. A closed-loop supply chain, made up of one manufacturer and one retailer, as a stochastic dynamic game has been modeled in (Kanani Kuchesfehani, Parilina, & Zaccour, 2023) to simultaneously capture the strategic interactions between the agents, the intertemporal nature of the return of past-sold products for remanufacturing, and the uncertainty in the parameter values. A green supply chain pricing model has been designed in (sazegari, davoodi, & goli, 2024) using a multi-criteria decision-making approach and game theory (case study: the home appliance industry). In this study, after identifying key indicators for predicting green supply chain pricing, screening of the indicators was carried out in three stages using the fuzzy Delphi method. A green closed-loop supply chain network has been designed in (Fathi, Saffarinia, & Pahlevanzadeh, 2026) for minimizing total cost, energy consumption, and carbon emissions in battery products, balancing economic efficiency, environmental responsibility, and timely customer delivery using a multi-objective mathematical model.

Meanwhile, there are also articles that have addressed various aspects of green marketing using Petri nets. However, the assumptions and factors examined in them differ from what is done in this paper. For example, the CPN approach to model and simulate a green supply chain system has been proposed in (Kaiyandra, Farizal, & Rakoto, 2024). The forward supply chain network starts from the raw material suppliers, to the manufacturers, wholesalers, retailers and to the final customers. The reverse supply chain network is made of collecting points, recycling plants, disassembly plants, and secondary material market. A government environment agency plays the role of regulation of the recycling process. In (Liu, Pu, Liu, & Liu, 2023), a model based on Generalized Stochastic Petri Nets was proposed for a green closed-loop supply chain to examine its operational performance under random events. The results indicated that, compared with recycling waste products, the production and distribution of green products require more time. In (Dolinina, Pechenkin, Gubin, & Kushnikov, 2018), within the context of smart city-related topics, the problem of modeling the solid waste disposal process was addressed. Priority Petri Nets were used as the mathematical modeling tool. The proposed model not only enables the analysis of the waste disposal process but also allows the implementation of optimization methods with different characteristics. In (Outmal, Kamrani, Abouel Nasr, & Alkahtani, 2016), an extension of the use of first-order hybrid Petri nets as a modeling and performance analysis tool from supply chain to closed-loop supply chain has been presented to assess simultaneously operational, financial, and environmental network's performance measures at different managerial decision-making levels. In (Ding, Chen, Sun, Yan, & Fang, 2021), a hybrid modelling technique has been proposed to combine Petri nets' usability and the compositionality of PEPA for creating a novel and enhanced formal modelling technique that is particularly suitable for systems such as green supply chain systems. Table 1 summarizes a comparison between literature review and the research conducted in this paper. The symbols × and ✓ mean "not addressed" and "addressed", respectively.

Table 1) Comparison of the literature review and the research conducted in this paper

Ref	Green Marketing	Customers' Preferences	Environmental Health Status	Firms' Revenues and Costs	Petri Net
(Jerbi, Vincy, Aoun, Abbassi, & Kchaou, 2026)	×	×	✓	×	×
(Pancić, Serdarušić, & Ćućić, 2023)	✓	✓	×	×	×
(Yue & Cai, 2025)	✓	✓	×	×	×
(Lu, Huang, & Cheng, 2021)	✓	×	×	×	×
(Vindhya Kalyani, Venkata Ramana, & Sunitha, 2025)	✓	×	✓	✓	×
(Ma, 2020)	✓	×	×	✓	×
(Lan, Si, Li, & Tang, 2026)	✓	✓	✓	✓	×
(Kanani Kuchesfehani, Parilina, & Zaccour, 2023)	✓	×	×	✓	×
(sazegari, davoodi, & goli, 2024)	✓	×	✓	✓	×
(Fathi, Saffarinia, & Pahlevanzadeh, 2026)	✓	×	✓	×	×
(Kaiyandra, Farizal, & Rakoto, 2024)	✓	×	×	×	✓
(Liu, Pu, Liu, & Liu, 2023)	✓	×	✓	×	✓
(Dolinina, Pechenkin, Gubin, & Kushnikov, 2018)	✓	×	✓	×	✓
(Outmal, Kamrani, Abouel Nasr, & Alkahtani, 2016)	✓	×	✓	✓	✓
(Ding, Chen, Sun, Yan, & Fang, 2021)	✓	×	×	×	✓
This Paper	✓	✓	✓	✓	✓

Based on the process shown in Figure 1, this paper uses a CPN formalism to model a firm's production-to-sales process for green and non-green products, and evaluates how firms' decisions and customers' purchasing preferences affect costs, revenues, and environmental impacts over time.

Assumptions
- Green and Non-Green Products
- Environmental Health
- Sale or Expiration of Products
- Customers' Preferences
- Firms' Revenues and Costs

Formalism
- CPN

Tool
- CPN Tools

Advantages of the Proposed Model
- Ability to Create Various Scenarios without Modifying the Model, Simply by Changing Parameter Values
- Considering Uncertainty in Processes
- The Graphical Representation of the Model
- Simultaneously Evaluating Impacts on Firms' Revenues, Costs, and the Environment

Evalution Measures
- Environmental Health Status
- Firm's Revenue
- Number of Products Produced
- Number of Expired Products

Fig. 1) The research process in this paper

3) Methodology

3-1) Coloured Petri Net Formalism

In the basic definition of Petri net formalism and its various extensions, two main components are defined: places and transitions (Dennis, 2011). Places are responsible for holding tokens, while transitions are responsible for transferring tokens between places. Places and transitions are connected through a set of directed arcs, where each arc connects a place to a transition (or vice versa). Any model developed using Petri nets or their extensions may consist of multiple places and transitions. The foundation of Petri nets lies in defining different system states and the mechanisms by which these states change. Each place, along with the number of tokens it contains, can represent the state of a particular part of the system under study. Coloured Petri Nets (CPN) are one of the most important extensions of Petri nets (Jensen, 1996), supported by the CPN Tools software (Ratzer, et al., 2003). This formalism is similar to the basic Petri net structure and shares the same fundamental definitions, with the key distinction that tokens can carry different data structures. In other words, in classical Petri nets, each place is associated only with an integer value representing the number of tokens, whereas in CPNs, each place can be associated with a specific data type. Figure 2 illustrates the graphical representation of the components in CPNs.

As illustrated in Figure 2, each place can have a name, a data type, and an initial marking. The data type of a place may consist of primitive types (e.g., *int*, *float*, *string*, etc.) or complex types (e.g., *product string*int*, which represents a set of pairs in the form *(string, int)*). For instance, if the data type of a place is defined as *product string*int*, it can hold a token such as ("ABC", 5). To specify the initial tokens (initial marking) of a place, the notation *N`Value* is used, where *N* denotes the number of tokens and *Value* represents the token value. For example, 2`("ABC", 5) indicates that there are two tokens with the value ("ABC", 5) in a given place. According to Figure 2, each transition can have a name, a guard (precondition), and a delay. The guard of a transition is a conditional expression; if it evaluates to true, the transition becomes enabled and can transfer tokens. If the places connected to a transition have time-stamped data types, the transition may include a delay, in which case the specified delay is added to the activation time of the tokens after the transition fires.

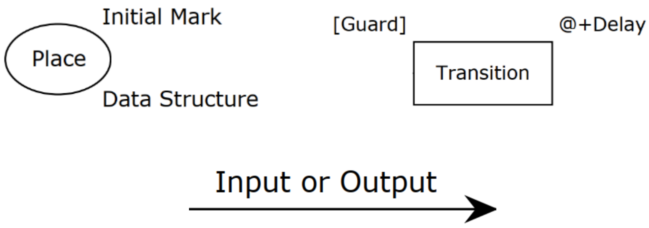


Fig. 2) Components of the CPN formalism

3-2) The proposed model

Figure 3 presents the proposed model for evaluating the impact of green product manufacturing on firms' revenues, costs, and the environment. For this purpose, the CPN formalism and the CPN Tools software have been utilized. The model consists of 9 places and 7 transitions, which are described in Table 2. Among the 9 places within the model as shown in Figure 3, three places (namely *Env*, *Product*, and *GProduct*) are defined with the data type *Data*, while the remaining places are of type *INT*. Places with the *INT* data type indicate that the tokens they contain represent integer values. In contrast, places with the *Data* type can hold tokens that consist of a pair of values (*REAL*, *INT*). In other words, each token in these places contains both real and integer values.

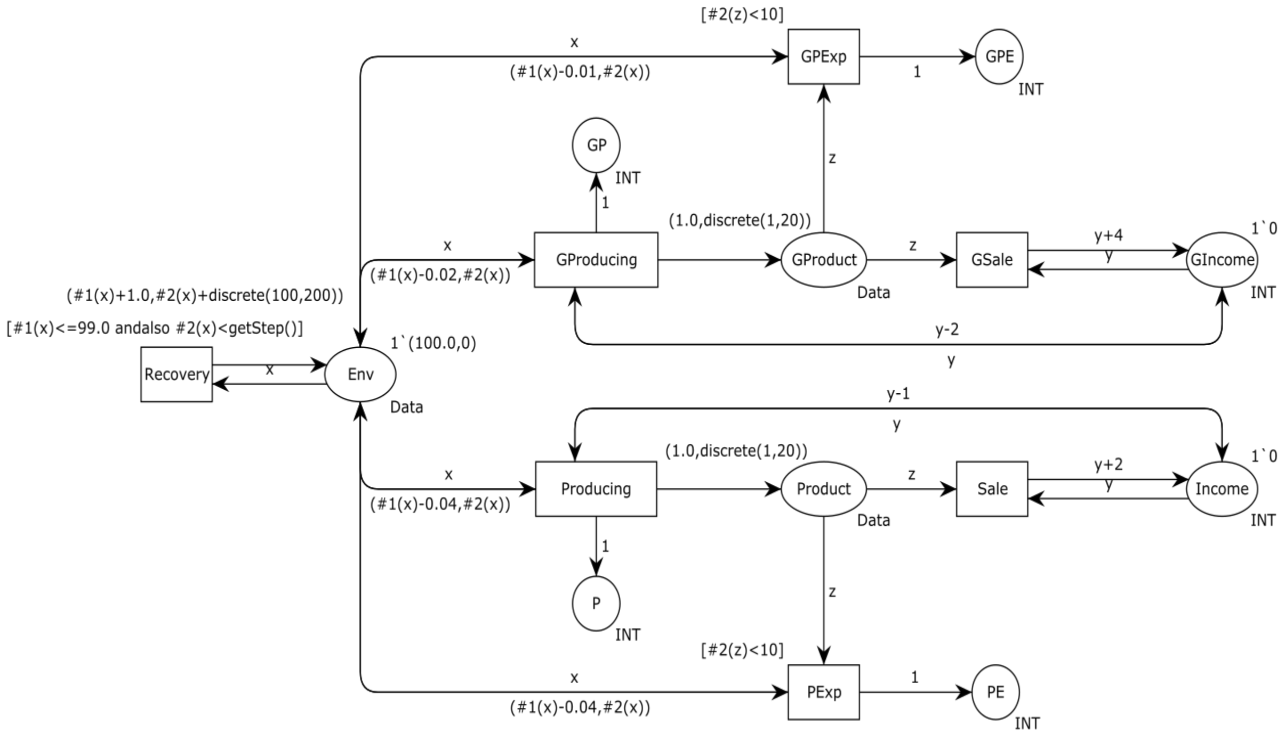


Fig. 3) The proposed model for evaluating the impact of green product manufacturing on firms' revenues, costs, and the environment using CPNs

Table 2) Introducing the places and transitions of the proposed model

Type	Title	Description
Place	Env	The place *Env* always contains a single token of type *Data*, where the real component ranges between 0 and 100 and represents the level of environmental health. The integer component is a random value that determines the next step of environmental improvement.
Place	Product GProduct	The places *Product* and *GProduct* contain a number of tokens of type *Data*, where the number of tokens represents the quantity of non-green (*Product*) and green (*GProduct*) products ready for sale. If these products are not sold, they may expire. The real component of these tokens is always equal to 1.0, while the integer component is a random value indicating the probability of product expiration.
Place	Income GIncome	The places *Income* and *GIncome* always contain a single token with an integer value representing the total income from production and sales (i.e., profit minus costs) of non-green and green products, respectively.
Place	P GP	The places *P* and *GP* contain a number of tokens with a value of one, where the number of tokens represents the total number of produced products (including available, sold, and expired) for non-green and green products, respectively.
Place	PE GPE	The places *PE* and *GPE* contain a number of tokens with a value of one, where the number of tokens represents the number of expired non-green and green products, respectively.
Transition	Recovery	The transition *Revocery* represents the improvement of environmental health over time. When this transition fires, the real component of the token in the *Env* place increases.
Transition	Producing GProducing	The transitions *Producing* and *GProducing* represent the production of non-green and green products, respectively. When these transitions occur, one token is added to *Product* and *P*, or to *GProduct* and *GP*. In addition, production leads to a decrease in environmental health and an increase in costs. Therefore, firing these transitions decreases the real component of the token in *Env* and also reduces the value of the token in *Income* or *GIncome*.
Transition	Sale GSale	The transitions *Sale* and *GSale* represent the sale of non-green and green products, respectively. When these transitions fire, one token is removed from *Product* or *GProduct*. Upon selling a product, the production cost along with profit is recovered; therefore, firing these transitions increases the value of the token in *Income* or *GIncome*.
Transition	Exp GExp	The transitions *Exp* and *GExp* represent the expiration of non-green and green products due to lack of sales. When these transitions occur, one token is removed from *Product* or *GProduct* and one token is added to *PE* or *GPE*. Since expired products do not recover production costs and contribute to waste generation, they lead to a decrease in environmental health. Consequently, firing these transitions reduces the real component of the token in *Env*.

In the model shown in Figure 3, the place *Env* represents the level of environmental health. For this purpose, it always contains a single token of type *Data*, with an initial value of (100.0, 0). The real component of this token can take a value between 0 and 100 and may increase or decrease depending on different events. The integer component stores a random value that determines at which future simulation step the environmental condition may recovery. As illustrated in Figure 3, the real component of this token is initially set to 100. Since the passage of time generally leads to improvements in environmental conditions, the transition *Recovery* is introduced in the model for this purpose. This transition receives the token from the *Env* place through the variable *x* which has the *Data* type. According to its guard condition (#1(x) ≤ 99.0 andalso #2(x) < getStep()), the transition is enabled if the real component of the token in *Env* (#1(x)) is less than 99.0 and its integer component (#2(x)) is less than the current simulation step. When this transition fires, the token x is removed from *Env* and replaced by a new token with value (#1(x)+1.0, #2(x)+discrete(100,200)). In other words, the real component increases by 1.0, while the integer component is incremented by a random value between 100 and 200.

In the model of Figure 3, the number of tokens in the places *Product* and *GProduct* represents the number of non-green and green products ready for sale, respectively. The production of these products is carried out by the transitions *Producing* and *GProducing*. These transitions are always enabled. When either transition fires, the token from *Env* (denoted by *x*) is removed. If a non-green product is produced (*Producing* fires), a token with value (#1(x)-0.04, #2(x)) is added to *Env*; otherwise, when *GProducing* fires, a token with value (#1(x)-0.02, #2(x)) is added. Thus, only the real component of the *Env* token is affected, indicating that non-green production causes twice as much environmental damage as green production. When the *Producing* transition fires, a token with value (1.0, discrete(1,20)) is added to *Product*, and a token with value 1 is added to the *P* place, indicating the production of one non-green product. In addition, the token in the *Income* place with value y is removed and replaced with a token of value y-1, reflecting a production cost of one monetary unit. Similarly, when *GProducing* fires, a token with value (1.0, discrete(1,20)) is added to *GProduct*, and a token with value 1 is added to the *GP* place, representing the production of one green product. The token in *GIncome* is updated from y to y-2, indicating that producing a green product incurs a cost of two monetary units, twice that of a non-green product. This assumption reflects the higher cost typically associated with green production.

In the model, the sale of non-green and green products is represented by the transitions *Sale* and *GSale*, respectively. These transitions are enabled whenever there are products available for sale. When *Sale* fires, one token is removed from *Product*, indicating the sale of a non-green product. The token in the *Income* place is updated from y to y+2, meaning that two monetary units are recovered (covering cost and profit). Similarly, when *GSale* fires, one token is removed from *GProduct*, and the token in *GIncome* is updated from y to y+4, indicating a return of four monetary units. It is assumed that producing a non-green product costs one unit and yields two units upon sale, while producing a green product costs two units and yields four units upon sale.

In this model, unsold products may expire, resulting not only in unrecovered costs but also in negative environmental impacts. The expiration of non-green and green products is modeled by the transitions *Exp* and *GExp*, respectively. These transitions receive tokens from *Product* and *GProduct* via the variable *z* of type *Data*. According to their guard condition (#2(z)<10), the transitions are enabled when products exist and the integer component of their tokens is less than 10. As explained earlier, when products are generated, tokens with value (1.0, discrete(1,20)) are added. The integer component is thus a random value between 1 and 20. If this value is greater than or equal to 10, the product will certainly be sold, since only *Sale* and *GSale* (which have no guards) are enabled, while *Exp* and *GExp* remain disabled. However, if the value is less than 10, both sale and expiration transitions are enabled, and one of them fires randomly. In other words, such products may either be sold or expire. Therefore, approximately 75% of produced products are sold, while 25% expire. When the *Exp* transition fires, one token is removed from *Product*, and a token with value 1 is added to the *PE* place, indicating the expiration of a non-green product. Additionally, the token in *Env* is updated from x to (#1(x)-0.04, #2(x)), reducing only the real component. Similarly, when *GExp* fires, one token is removed from *GProduct*, a token is added to the *GPE* place, and the *Env* token is updated to (#1(x)-0.01, #2(x)). This indicates that the expiration of a non-green product causes four times more environmental damage than that of a green product. It is assumed that producing a non-green product reduces environmental health by 0.04, and its expiration causes an additional reduction of the same amount. In contrast, producing a green product reduces environmental health by 0.02, while its expiration reduces it by only 0.01.

One of the advantages of the proposed model is its flexibility: by adjusting parameter values without modifying the model structure, different scenarios can be implemented. Through simulation over various time horizons, the impacts of these changes on firms' costs, revenues, and environmental conditions can be evaluated. In the next section, several scenarios are introduced, and the corresponding simulation results are analyzed.

4) Evalution and Discussion

4-1) Evaluating results in various scenarios

In this section, the results obtained from the proposed model are evaluated under various scenarios. The designed scenarios aim to assess the impact of customers' preferences for purchasing green or non-green products, as well as the willingness of firms to produce green or non-green products, on their revenues and the environment. The scenarios are defined as follows:

- **Scenario 1 (Baseline):** This corresponds to the model presented in Figure 3. Customer preferences for both product types (green and non-green products) are assumed to be equal.
- **Scenario 2 (Green-only production):** In the model of Figure 3, the production of non-green products (*Producing* transition) is disabled, so the firm produces only green products, and customers can purchase only green products.
- **Scenario 3 (Non-green-only production):** In the model of Figure 3, the production of green products (*GProducing* transition) is disabled, so the firm produces only non-green products, and customers can purchase only non-green products.
- **Scenario 4 (Preference for green products):** In the model of Figure 3, the random function of the output arc of the *GProducing* transition is changed from discrete(1,20) to discrete(1,40), reducing the number of expired green products due to higher customer preference for green products. This scenario evaluates the impact of customer preference for purchasing green products.
- **Scenario 5 (Preference for non-green products):** In the model of Figure 3, the random function of the output arc of the *Producing* transition is changed from discrete(1,20) to discrete(1,40), reducing the number of expired non-green products due to higher customer preference for non-green products. This scenario evaluates the impact of customer preference for purchasing non-green products.

Figure 4 illustrates the effect of these scenarios on environmental health. The horizontal axis represents the simulation steps, reflecting the passage of time, while the vertical axis shows the percentage of environmental health. As observed, the Scenario 2 in which the firm produces only green products and customers purchase only green products results in the smallest decline in environmental health. This is followed by the Scenario 5 where customers prefer non-green products, which has a smaller negative impact compared to other cases. The reason is that the expiration of non-green products significantly harms the environment, and when customers prefer to buy non-green products, fewer non-green products expire, mitigating the negative effect. Next, the Scenario 4 with a preference for green products has a slightly larger negative impact because, although customers prefer green products, non-green products are still being produced, leading to some expiration and environmental damage. The baseline scenario (equal preference and production of green and non-green products) follows, showing a moderate negative effect on the environment. The worst-case scenario, Scenario 3, with the greatest negative environmental impact, occurs when the firm produces only non-green products and customers purchase only non-green products. From these results, it can be concluded that producing green products, even when a firm continues to produce non-green products and customers still prefer non-green products (for reasons such as lower price), still provides a significant positive impact on environmental health compared to a situation in which no green products are produced or sold.

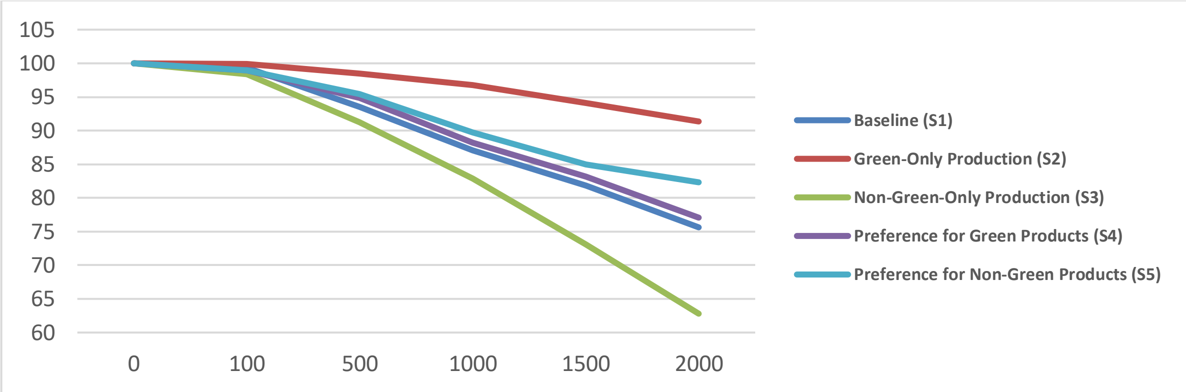


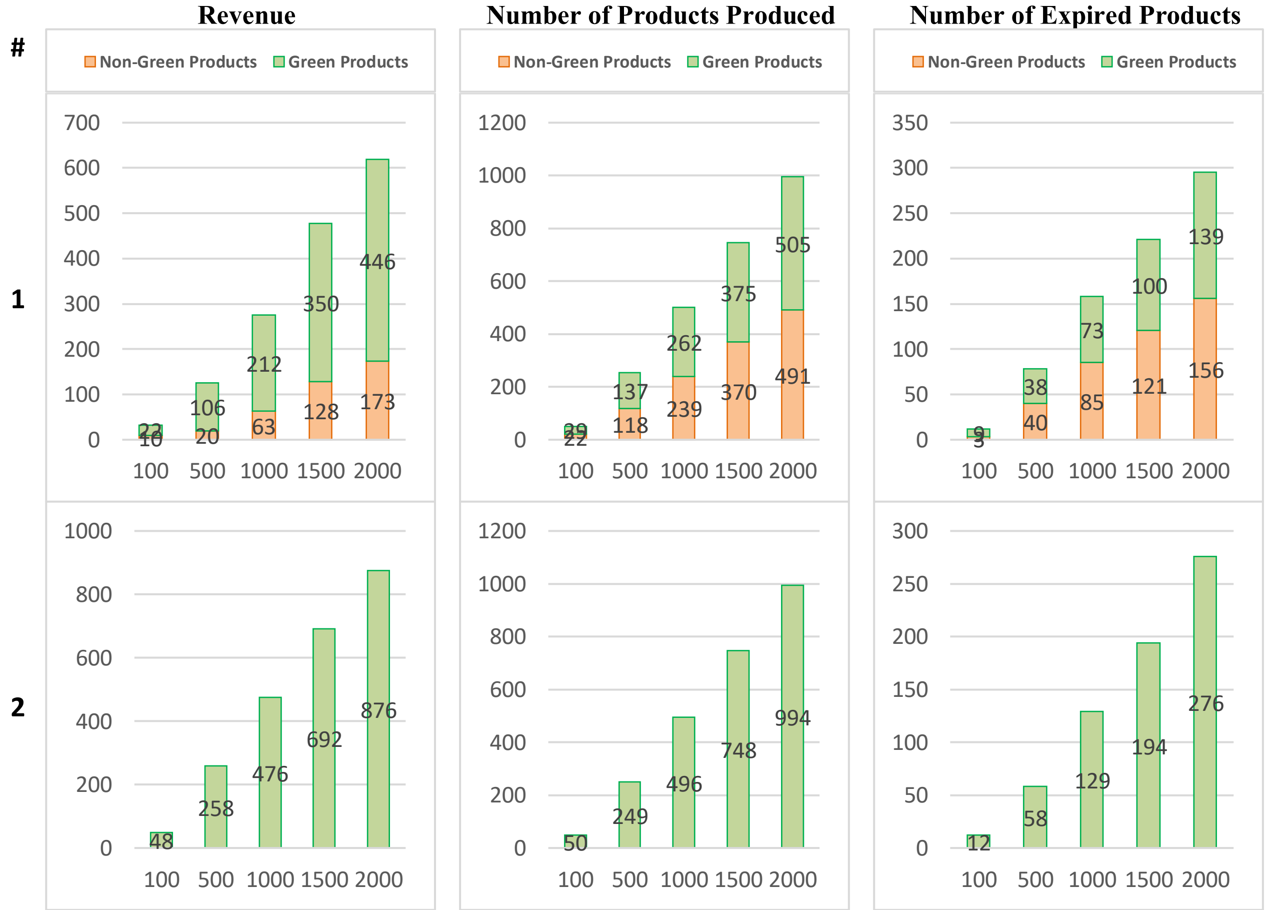
Fig. 4) The Impact of Different Scenarios on Environmental Health Status

Figure 5 illustrates the impact of different scenarios on firm revenue, as well as the number of produced and expired products. In charts of Figure 5, the horizontal axis represents the simulation steps, reflecting the passage of time. Each chart differentiates between green and non-green products. The vertical axis in the revenue charts is measured in financial units and represents profit, calculated as revenue minus production costs. Positive values indicate profit, while negative values indicate losses. In the production and expiration charts, the vertical axis indicates the number of produced or expired products, respectively.

As observed in Figure 5, in Scenario 1 (baseline), where production and customer preferences for green and non-green products are equal, after 2,000 simulation steps, the number of produced green and non-green products is approximately equal (505 and 491, respectively), and the number of expired products in each category is also roughly comparable (139 and 156). Interestingly, fewer green products expire despite their higher production. The main difference is in revenue: after 2,000 steps, the firm earns 446 financial units from selling green products, significantly higher than the 173 financial units earned from non-green products. This reflects the assumed cost and revenue structure, where producing a green product costs 2 financial units and yields 4 units upon sale, while producing a non-green product costs 1 unit and yields 2 units upon sale. Hence, even with equal production, revenue from green products is substantially higher.

In Scenarios 2 and 3, where only green or only non-green products are produced and sold, the total production after 2,000 steps is nearly equal (994 for green, 993 for non-green), and the number of expired products is also similar (276 for green, 287 for non-green). The key difference remains revenue: in Scenario 2 (green-only), the firm earns 876 financial units from sales, whereas in Scenario 3 (non-green-only), revenue is only 419 financial units. In Scenario 4, production of green and non-green products is equal, but customers show a higher preference for green products. After 2,000 steps, total production remains similar (494 green, 505 non-green), but the number of expired products differs markedly: 81 green and 151 non-green products expire. This indicates that stronger customer preference for green products reduces the expiration of green products while more non-green products remain unsold. Revenue reflects this shift: 620 financial units are earned from green products versus only 201 from non-green products. In Scenario 5, production is again equal, but customer preference favors non-green products. After 2,000 steps, total production is similar (495 green, 501 non-green), with 138 green and 84 non-green products expiring. Despite this, revenue from green products remains higher: 434 financial units for green products versus 321 for non-green products.

Overall, the results suggest that producing only green products is optimal, both in terms of environmental impact and revenue. If a firm produces both green and non-green products, having higher customer preference for green products still improves environmental outcomes and revenue. The worst scenario occurs when the firm produces only non-green products, leading to the greatest environmental damage and the lowest revenue.



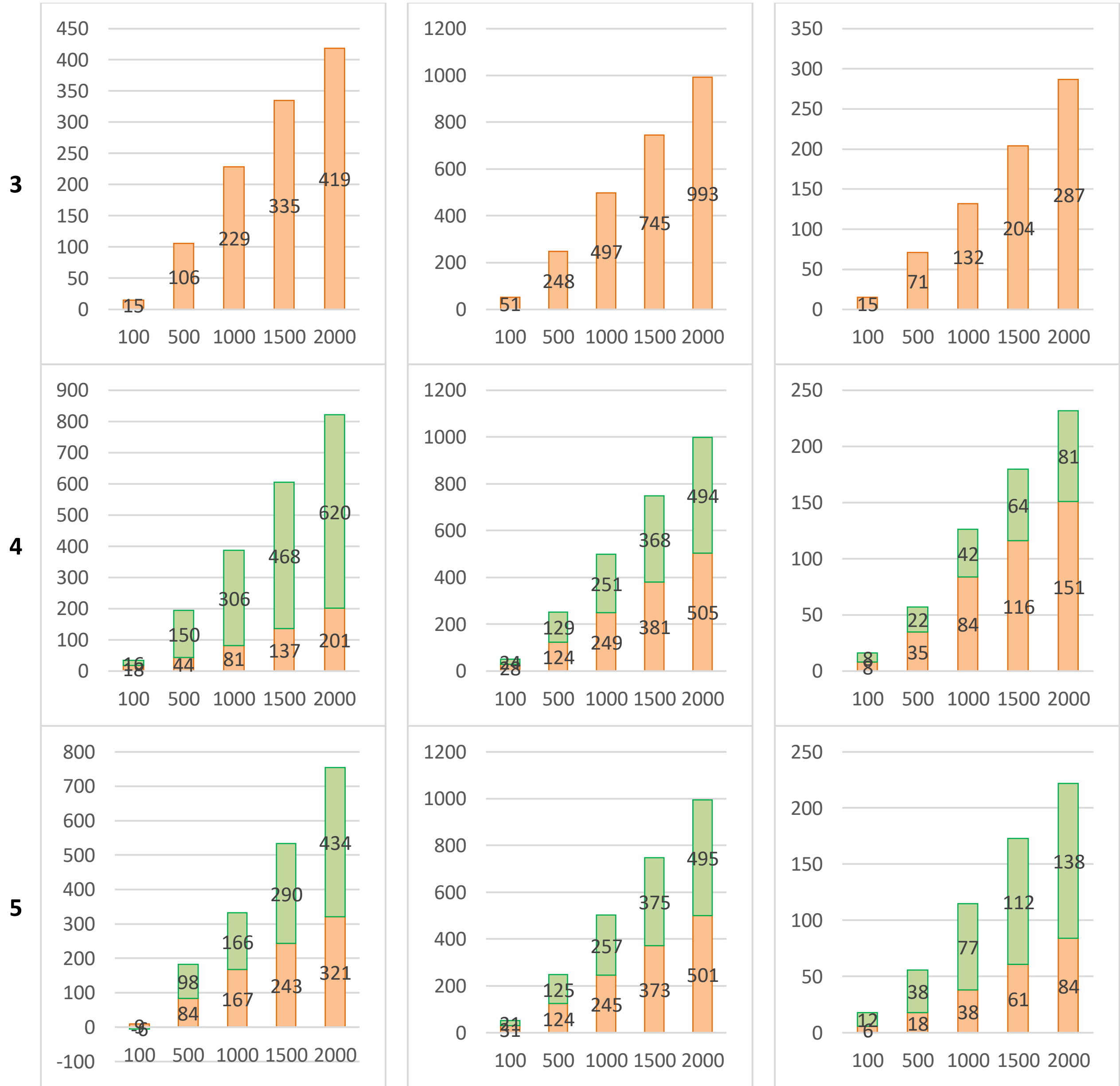


Fig. 5) Evaluation of Firm Revenue, Product Production, and Expiration under Different Scenarios

If we want to examine scenarios 4 and 5 specifically, According to Figure 4, Scenario 5 results in slightly lower environmental damage. In this scenario, fewer non-green products expire, and the higher expiration rate of green products has a negligible environmental impact. In contrast, Scenario 4 causes slightly greater environmental damage because customer preference for green products leads to a higher expiration rate of non-green products, whose disposal has a more harmful effect on the environment. As shown in Figure 5, revenue generated from green products exceeds that from non-green products in both Scenarios 4 and 5. This result follows from the model assumption that green products generate twice the sales revenue of non-green products, although their production cost is also assumed to be twice as high. A comparison of the total revenue generated from both product types shows that the firm achieves higher overall revenue in Scenario 4. Therefore, the simultaneous production of green and non-green products can represent a viable strategy. When customer preference is stronger for green products (Scenario 4), the firm attains higher revenue, although environmental damage is slightly greater due to the expiration of more non-green products. In contrast, when customer preference is stronger for non-green products (Scenario 5), environmental damage is reduced, but the firm's overall revenue is lower. These results highlight the trade-off between environmental performance and revenue when both product types are produced.

4-2) Sensitivity analysis

In this section, in order to analyze the sensitivity of the parameter values in the CPN model, we compare the baseline scenario (Scenario 1) of the previous section with a random scenario (Scenario 6). In Scenario 6, similar to Scenario 1 shown in Figure 3, customer preferences for both product types (green and non-green products) are assumed to be equal. However, there are the following differences for these two scenarios:

- In Scenario 1, when the transition *Recovery* fires, the level of environmental health, represented by the place *Env*, increases by 1.0 (#1(x)+1.0, #2(x)+discrete(100,200)), while in Scenario 6, this amount increases according to a random uniform value between 0.5 and 1.5 (#1(x)+uniform(0.5,1.5),#2(x)+discrete(100,200)).
- In Scenario 1, firing the *Producing* transition removes the token in the *Income* place with value y and replaces it with a token of value y-1, thereby accounting for a production cost of one monetary unit. Likewise, firing *GProducing* updates the token in *GIncome* from y to y-2. In contrast, in Scenario 6, firing the *Producing* transition updates the token in *Income* from y to y-discrete(0,2), whereas firing *GProducing* updates the token in *GIncome* from y to y-discrete(1,3).
- In Scenario 1, when the transition *Sale* fires, the token in the *Income* place is updated from y to y+2, meaning that two monetary units are recovered (covering cost and profit). Similarly, when *GSale* fires, the token in *GIncome* is updated from y to y+4, indicating a return of four monetary units. In contrast, in Scenario 6, firing the *Sale* transition updates the token in *Income* from y to y+discrete(1,3), whereas firing *GSale* updates the token in *GIncome* from y to y+discrete(3,5).

Table 3) Comparison of the baseline scenario with the random scenario after 2,000 steps

#	Environmental Health Status	Revenue	Number of Products Produced	Number of Expired Products
Scenario 1 (Baseline)	75.63	**Non-Green:** 173 **Green:** 446	**Non-Green:** 505 **Green:** 491	**Non-Green:** 139 **Green:** 156
Scenario 6 (Random)	78.50	**Non-Green:** 266 **Green:** 393	**Non-Green:** 505 **Green:** 492	**Non-Green:** 142 **Green:** 146

As can be seen from Table 3, which compares the results of the baseline and random scenarios after 2000 steps, even though many of the fixed values have changed to random values, the final results are still similar, because customer preferences are similar in both scenarios.

4-3) Discussing the implications of the proposed model

As shown, the proposed model with a simple graphical representation was able to evaluate different types of scenarios based on different measures. In this model, more scenarios can be evaluated by changing the parameter values without changing the model. However, the current model does not explicitly consider factors such as the use of recycled raw materials, customer satisfaction, and their potential effects on production costs, product prices, and production rates. Therefore, the proposed model can serve as an effective decision-support tool for managers in selecting optimal green production strategies. For example, using the proposed model, we created scenarios in which the impact of green and non-green product production and customers' purchasing preferences on environmental health and firms' revenue could be assessed. One of the most important results is that producing green products, even when customers prefer to buy non-green products, is still optimal in terms of environmental performance and firms' revenue. This is because the expiration of non-green products will not have a significant negative environmental impact and their sale will also be profitable. Therefore, regardless of customer preferences, it is better for firms to dedicate at least part of their production to green products rather than not producing green products at all.

5) Conclusion

In this paper, the CPN formalism and the CPN Tools software were used to model the production-to-sale process of green and non-green products within a firm. One of the key advantages of the proposed model is its flexibility: by modifying the values of model variables, different scenarios can be implemented without altering the underlying structure of the model. Through simulation over various time periods and considering process uncertainties, the impact of each scenario on firm revenues, costs, and environmental outcomes can be assessed. The model allows evaluation of the effects of managerial decisions on the production of green and non-green products, as well as the influence of customer preferences for each product type. Therefore, this model can serve as an effective decision-support tool for managers in selecting optimal green production strategies.

For future work, additional details could be incorporated into the model to enable the simulation of more scenarios and the assessment of their impacts on firm revenue and environmental health. Such enhancements could include determining production costs and final product prices, which may be significantly affected by sourcing raw materials from recycled resources. This factor could influence both production costs and final prices, as well as environmental outcomes. Other potential enhancements include incorporating customer satisfaction with green and non-green products and its influence on production rates within firms. In the current model, for scenarios in which a firm simultaneously produces both green and non-green products, production rates are assumed to be fixed and equal. However, in practice, production rates may vary over time based on multiple factors, such as firm policies, customer satisfaction, and market conditions.

References

Dennis, J. B. (2011). Petri Nets. In D. Padua (Ed.), *Encyclopedia of Parallel Computing* (pp. 1525-1530). Boston, MA: Springer US. doi:10.1007/978-0-387-09766-4_134

Ding, J., Chen, X., Sun, H., Yan, W., & Fang, H. (2021). Hierarchical structure of a green supply chain. *Computers & Industrial Engineering, 157*, 107303. doi:10.1016/j.cie.2021.107303

Dolinina, O., Pechenkin, V., Gubin, N., & Kushnikov, V. (2018). A Petri Net Model for the Waste Disposal Process System in the "Smart Clean City" Project. *the 3rd International Conference on Smart City Applications* (pp. 1-6). New York, NY, USA: Association for Computing Machinery. doi:10.1145/3286606.3286786

Fahimnia, B., Sarkis, J., & Davarzani, H. (2015). Green supply chain management: A review and bibliometric analysis. *International Journal of Production Economics, 162*, 101-114. doi:10.1016/j.ijpe.2015.01.003

Fathi, M., Saffarinia, A., & Pahlevanzadeh, M. (2026). Multi-objective Green Supply Chain Network Design Considering Carbon Emissions and Electricity Consumption. *Journal of Engineering Management and Soft Computing, 12*(1), 14-35. doi:10.22091/jemsc.2026.14628.1326

Hariyani, D., Hariyani, P., Mishra, S., & Sharma, M. (2024). A literature review on green supply chain management for sustainable sourcing and distribution. *Waste Management Bulletin, 2*(4), 231-248. doi:10.1016/j.wmb.2024.11.009

Jensen, K. (1996). *Coloured Petri Nets; Basic Concepts, Analysis Methods and Practical Use* (Vol. 1). Springer, Berlin, Heidelberg. doi:10.1007/978-3-662-03241-1

Jerbi, H., Vincy, V. G., Aoun, S. B., Abbassi, R., & Kchaou, M. (2026). Optimizing waste management in smart cities: An IoT-Based approach using dynamic bald eagle search optimization algorithm (DBESO) and machine learning. *Journal of Urban Management, 15*(1), 114-130. doi:10.1016/j.jum.2025.05.015

Kaiyandra, D. R., Farizal, F., & Rakoto, N. (2024). Colored Petri Nets for Modeling and Simulation of a Green Supply Chain System. *IFAC-PapersOnLine, 58*(1), 306-311. doi:10.1016/j.ifacol.2024.07.052

Kanani Kuchesfehani, E., Parilina, E. M., & Zaccour, G. (2023). Revenue and cost sharing contract in a dynamic closed-loop supply chain with uncertain parameters. *Annals of Operations Research, 322*, 851-877. doi:10.1007/s10479-022-05055-x

Lan, H., Si, X., Li, X., & Tang, J. (2026). Dynamic decision-making and differential game analysis of ESG-constrained closed-loop supply chains under cap-and-trade regulation. *Scientific Reports, 16*(766), 1-16. doi:10.1038/s41598-025-30391-w

Liu, L., Pu, Y., Liu, Z., & Liu, J. (2023). Analysis of Green Closed-Loop Supply Chain Efficiency under Generalized Stochastic Petri Nets. *Sustainability, 15*(17), 13181. doi:10.3390/su151713181

Lu, C., Huang, W., & Cheng, H. (2021). Comparative Analysis of Government Subsidy Policies in a Dynamic Green Supply Chain Considering Consumers Preference. *Sustainability, 13*(21), 11601. doi:10.3390/su132111601

Ma, C. (2020). Comparison of Cooperation Modes in a Two-Period Closed-Loop Supply Chain System considering Green Manufacturing. *Mathematical Problems in Engineering, 2020*, 1-19. doi:10.1155/2020/9202370

Maditati, D. R., Munim, Z. H., Schramm, H.-J., & Kummer, S. (2018). A review of green supply chain management: From bibliometric analysis to a conceptual framework and future research directions. *Resources, Conservation and Recycling, 139*, 150-162. doi:10.1016/j.resconrec.2018.08.004

Naghash Asadi, A., Abdollahi Azgomi, M., & Entezari-Maleki, R. (2020). Analytical evaluation of resource allocation algorithms and process migration methods in virtualized systems. *Sustainable Computing: Informatics and Systems, 25*, 1-16. doi:10.1016/j.suscom.2019.100370

Naghash Asadi, A., Abdollahi Azgomi, M., & Entezari-Maleki, R. (2021). Model-based evaluation of the power versus performance of network routing algorithms. *Computing, 103*, 1723-1746. doi:10.1007/s00607-020-00882-x

Naghash Asadi, A., Abdollahi Azgomi, M., & Entezari-Maleki, R. (2022). Evaluation of the Functionality of Mobile Wireless Sensor Networks using Stochastic Reward Nets. *Scientia Iranica, 30*(1), 91-103. doi:10.24200/sci.2022.58441.5732

Naghash Asadi, A., Pourjani, M., & Mirsaeed Ghazi , A. (2025). Modeling of the Wumpus World to Evaluate the Difficulty Level of the Game using Coloured Petri Net. *Journal of Algorithms and Computation, 57*(2), 66-79. doi:10.22059/jac.2025.403785.1241

Outmal, I., Kamrani, A., Abouel Nasr, E. S., & Alkahtani, M. (2016). Modeling and performance analysis of a closed-loop supply chain using first-order hybrid Petri nets. *Advances in Mechanical Engineering, 8*(5). doi:10.1177/1687814016649584

Pancić, M., Serdarušić, H., & Ćućić, D. (2023). Green Marketing and Repurchase Intention: Stewardship of Green Advertisement, Brand Awareness, Brand Equity, Green Innovativeness, and Brand Innovativeness. *Sustainability, 15*(16), 12534. doi:10.3390/su151612534

Ratzer, A. V., Wells, L., Lassen, H. M., Laursen, M., Qvortrup, J. F., Stissing, M. S., . . . Jensen , K. (2003). CPN tools for editing, simulating, and analysing coloured Petri nets. *Proceedings of the 24th international conference on Applications and theory of Petri nets*, (pp. 450-462). doi:10.1007/3-540-44919-1_28

sazegari, s., davoodi, s., & goli, a. (2024). Designing a green supply chain pricing model with a multi-criteria decision-making approach and game theory (case study: home appliance industry). *Journal of Engineering Management and Soft Computing, 10*(1), 92-122. doi:10.22091/jemsc.2024.11144.1191

Vindhya Kalyani, M., Venkata Ramana, J., & Sunitha, G. (2025). Examining the Influence of Green HRM Practices on Employee Satisfaction: A Comprehensive Study. *International Journal of Innovation and Technology Management, 22*(07n08), 2540004. doi:10.22059/ijms.2025.392620.677509

Yue, Z., & Cai, Z. (2025). Machine Learning-Based Analysis of Green Advertising Appeals, Brand Awareness, and Self-Construal on Purchase Intention. *the 2nd Guangdong-Hong Kong-Macao Greater Bay Area International Conference on Digital Economy and Artificial Intelligence*, (pp. 910-915). New York, NY, USA. doi:10.1145/3745238.3745381