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Colored Petri Nets for Modeling and Simulation of a Green Supply Chain System^{*}

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Abstract: Green supply chain is an emerging approach in supply chain management to reduce environmental impact of the process concerning the flow of goods and materials. As a discrete-event system, supply chain can be modeled using Petri Nets. Colored Petri Nets (CPNs) extend the classical Petri net formalism with data, time and hierarchy. These extensions makes it possible to deal with the green aspects of the supply chain.

This paper deals with the Colored Petri Net approach to model and simulate a green supply chain system. 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. A colored Petri net model of the green supply chain is developed and simulated with CPN Tools, a dedicated software for CPN models. The simulation results as well as the state-space analysis results validate the correctness of the model.

Keywords: Green Supply Chain Management; Colored Petri Nets; Modeling; Simulation.

1. INTRODUCTION

Supply chain is a network of facilities and distribution options that performs the functions of procurement of materials, transformation of these materials into intermediate and finished products, and the distribution of these finished products to customers Atasu and Van Wassenhove (2012). Supply chains are constantly upgraded to better meet changing client needs and gain a competitive edge. Rising production and transportation costs required a more efficient supply chain. Efficient supply chains are the ones that can deliver items to clients at a cheap cost while preserving product and service quality.

Nowadays however, there are increasing awareness of the environmental impact of industrial activities, which leads companies aiming to reduce their carbon footprint, minimize waste, and use more sustainable material. Businesses are now also realizing that consumers are becoming more environmentally conscious and some are even willing to pay more for eco-friendly products. Governments around the world are also implementing strict environmental regulations to promote sustainable practices in industries and companies that do not comply may face legal penalties which in turns may have becoming a significant loss of profit and opportunity.

The combination of these factors has led to a development of a new model of supply chain that takes into account the environmental impact of each step, the new model is called green supply chain. Compared to the traditional

supply chain, green supply chain implies approaching factors according to the imperatives of the environment and adopting strategies in the sense of sustainable development. Adding the term “green” to supply chain implies approaching the supply chain from the traditional perspective by corroboration/combination with the natural environment Srivastava (2007).

Green supply chain management has emerged as a widely acknowledged approach for reducing the environmental impact of processes concerning the flow of goods and materials throughout the supply chain. A green supply chain integrates eco-friendly elements into the traditional supply chain thereby contributing to the reduction of production costs, supporting economic growth and benefiting the environment ecologically. The rising incline towards green supply chain in today’s industry is not only due to the growing ecological concerns but also because of the competitive edge and economic advantages it offers when managed appropriately. There are many aspects of green supply chain management, such as green design, green operations, waste management, reverse logistics and network design, and green manufacturing and remanufacturing Srivastava (2007).

The supply chain, as well as the green supply chain, is a dynamic system that involves the constant flow of information, products, and money between different layers that are constantly changing. It also has a dynamic behavior due to changing customer demands and goals for competitive advantage that are desired to be achieved. The ever-changing dynamics of the supply chain make modeling and analysis challenging.

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Many studies Zhang et al. (2011) and Fierro et al. (2020) defined supply chain network and green supply chain Ding et al. (2021) as discrete-event systems. Discrete events in the supply chain include: trucks departing from the supplier, materials arriving at the manufacturer, the manufacturing process beginning, trucks departing from the manufacturer to deliver finished products to the distributor, product delivered to the final customers Zhang et al. (2011).

Petri Net, introduced by C. A. Petri (1962) is a classical tool for modeling, simulation, control and verification of discrete-event systems Cassandras and Lafortune (2021), Murata (1989). See Guia and Silva (2018) for a historical perspective of Petri Nets in Control. Colored Petri Nets (CPN)s have been introduced by K. Jensen (1992) in order to extend classical Petri Nets formalism with data, time and hierarchy. Many other extensions have been proposed e.g. Hybrid Petri Nets (HPN) David and Alla (2001) or First-Order Hybrid Petri Nets (FOHPN) Balduzzi et al. (2000), Dotoli et al. (2009), Balduzzi et al. (2010).

The paper is organized as follows. In Section 2, a colored Petri net model is given, and the methodology given in Section 3. In Section 4, simulation results are provided. Finally a conclusion is given in Section 5.

2. COLORED PETRI NET MODEL

A colored Petri Net is a five-tuple $CPN = (P, T, Pre, Post, C)$ where:

- P is a set of places,
- T is a set of transitions,
- $Pre : P \times T \rightarrow N$ is the pre-incidence function,
- $Post : P \times T \rightarrow N$ is the post-incidence function,
- $C : P \cup T \rightarrow \{c_1, c_2, \dots, c_n\}$ is the color function.

A common model of a green supply chain network has been developed by various authors Srivastava (2007), Ding et al. (2021), Sheu et al. (2005), Pan and Wu (2014). Figure 1 is proposed as an example of the green supply chain model Sheu et al. (2005). On this model there are common supply chain actors such as material suppliers, manufacturers, wholesalers, retailers, and end customers. Also, there are reverse supply chain network consisting of collecting points, recycling plants, disassembly plants, and secondary material market. There is also government environment agency who regulates the recycling process.

On this green supply chain model, manufacturer can procure their supply from their usual raw material supplier or secondary material market which sells recycled materials. After they receive their supply, they can produce the products for the consumers to buy. If the wholesalers buy it, they can sell to retailers too. As for the end-customers, they have options on where to buy it. They can buy it directly from manufacturers, wholesalers, or retailers. Usually, customers can buy only from retailers, and if they want to buy the products in bulk or huge quantity, then they can buy from manufacturer or wholesalers.

After the customers finishes using the products, they can send the products to collecting points, recycling plants, or directly to disassembly plants, depending on the condition of the used products. If they decided to send the used products, the customers will receive money. At the disassembly plants any reusable materials will be sold to secondary material market, where it would be sold again to the manufacturers. But, if the materials are in an unusable condition, they would be sent to the final disposal.

On this model, manufacturers are obliged to pay a sum of recycling fee to the government environment agency where it would be used to subsidize disassembly plants. The reason for this is because in some countries, manufacturers are responsible for the waste of their products, so manufacturers have to have a processing plant for their used products. But, most of the manufacturers did not have the facility for that, so instead forcing the company to build a new processing plant, the government impose a regulation where manufacturers have to pay a recycling fee to the government environment agency or third-party environment organization, where the recycling process or waste processing will be done by a third-party entities such as recycling plant or disassembly plant.

3. METHODOLOGY

A Colored Petri Net of this model has been developed (see Figure 2 and Table 1 for the explanation) to analyze the properties of the system. The modelling is done in a tool for creating, modifying, verifying, and simulating CPN called CPN Tools [33]. In the CPN model, the tokens are finite, it is to represent the properties of resources that are not unlimited. There are five color sets that represents five types of data: color set CASH to represent cash flow between the supply chain actors, color set MATERIAL to represent flow of material for the manufacturers, color set PRODUCTS to represent the finished products produced by the manufacturer, color set USED to represent used products or products that have reach its end-of-life, and lastly, color set WASTE to represent the flow of waste after the disassembly process.

In the CPN model, there are two inhibitor arcs that connect P0' (Manufacturer's pre-production stage) and T1 (Manufacturer order material from raw material supplier) and T2 (Manufacturer buy material from secondary material market), the reason for this is to prevent manufacturer procure new materials when they already have the material. By doing this, we prevent the manufacturer to have large amount of inventory which in real-life will be costly for the manufacturing company. There is also an inhibitor arc to model a simple transaction, to enable an order transition (T1, T2, T3, T4, T5, T6, T7) the input transition of the place must have 'cash' from the actors (or places) who bought the items and 'materials' or 'products' from actors who sells it. The output will be 'cash' flow to the seller, and 'materials' or 'products' to the buyer.

For the latter half of the model, the reverse supply chain that starts from the end-customer, the process and also

Table 1. Petri Net Based Models of Supply Chains

Authors	Scope	Methods
Dotoli et al. (2009)	Forward Supply Chain	FOHPN
van der Aalst (1992)	Forward Supply Chain	CPN
Srinivasa and Viswanadham (1999)	Forward Supply Chain	Basic Petri Nets
Makajic-Nikolic et al. (2004)	Forward Supply Chain	CPN
Khilwani et al. (2010)	Forward Supply Chain	HPN
Bevilacqua et al. (2012)	Forward Supply Chain	Timed CPN
Mazzuto et al. (2012)	Forward Supply Chain	Timed CPN
Santana-Robles et al. (2012)	Forward Supply Chain	CPN
Mukhlash et al. (2018)	Forward Supply Chain	FOHPN
Azougagh et al. (2019)	Forward Supply Chain	CPN
Idel Mahjoub (2021)	Forward Supply Chain	Timed CPN
Hanafi et al. (2008)	Reverse Supply Chain	CPN
Haiyan and Shengqiang (2009)	Reverse Supply Chain	GSPN
Murayama et al. (2003)	Forward and Reverse Supply Chain	CPN
Wang (2013)	Forward and Reverse Supply Chain	Timed CPN
Pan and Wu (2014)	Forward and Reverse Supply Chain	GSPN
Outmal et al. (2016)	Forward and Reverse Supply Chain	FOHPN
Ding et al. (2021)	Forward and Reverse Supply Chain	GSPN

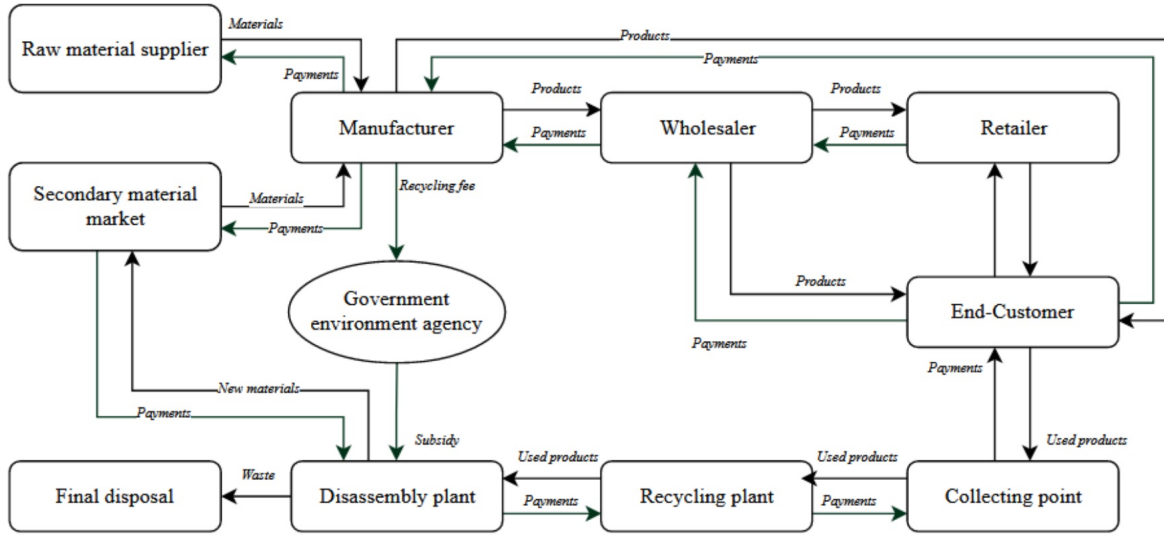


Fig. 1. Green Supply Chain Model (modified from Sheu et al. (2005))

the place/transition modelling is similar but the real-life scenario is a little bit different. On the reverse supply chain, the end- customer can decide on where to send the products (on the CPN model, P3” have options to fire to T9, T10, or T11). In the green supply chain model, manufacturer have to pay a sum of fee to government environment agency who will subsidize the third-party disassembly processing plants. To model this, in every production process (or T0), manufacturer will send ‘cash’ to the government environment agency.

4. SIMULATION RESULTS

The green supply chain has been simulated with the CPN Tools software. 50.000 random firings have been performed. The results of the simulation are presented

in Table 2. From Table 2, the number of firing of each transition is given. Transition T0 (production process by the manufacturer) is the transition that has been fired the most (4703 times). 1000 times come from raw material supplier, while 3703 times come from secondary material market. Then come the 3 transitions T8, T18 and T19 which fires 4702 times each. These high numbers of firings is explained by the fact that transition T18 and T19 receive tokens from place P10, which receives tokens every time the production process is active. Transition T8 has a high number of firings because its input place (P3’) receives tokens from both T4 and T7. Transition T1 only fired 1000 times because place P1’ has a maximum capacity of 1000 tokens. Customers mostly buy the products directly from the manufacturer (T4, 2344 times) more than from the wholesaler (T6, 1176 times) or from the retailer (T7, 1183 times).

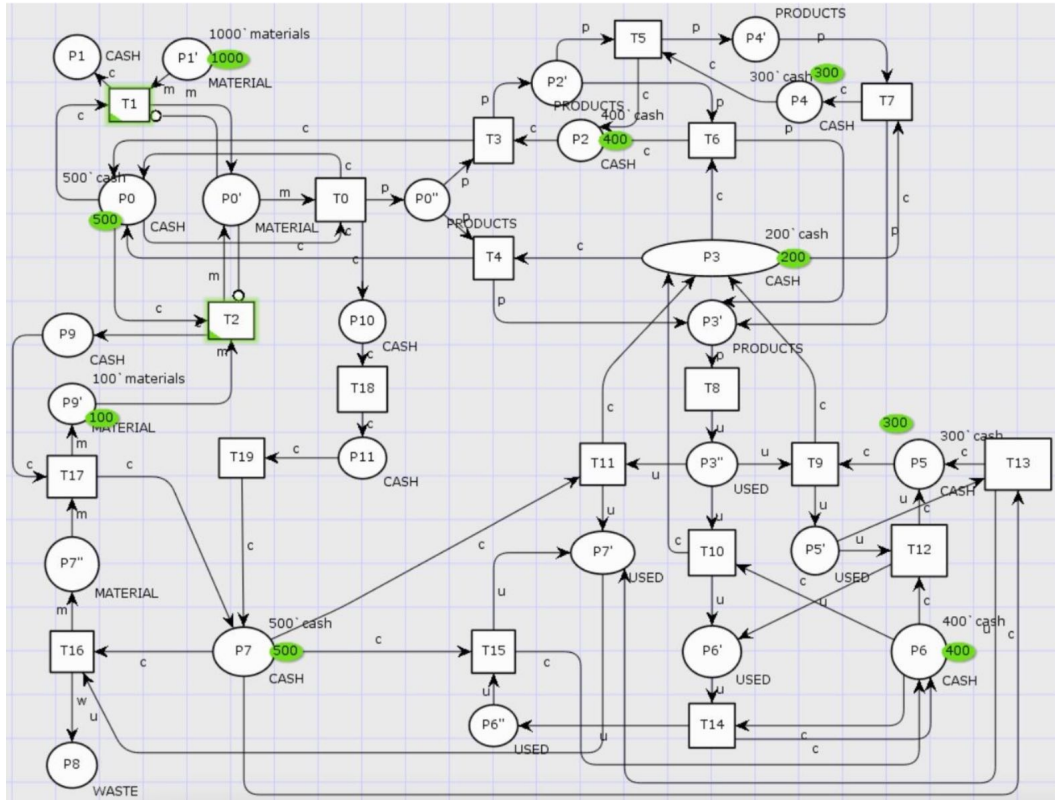


Fig. 2. Colored Petri Nets model of the green supply chain model

Table 2. Description of Places and Transitions

Places	Description	Trans.	Description
P0	Manufacturer's cashflow	T0	Production Process
P0'	Manufacturer's pre-production stage	T1	Manufacturer orders material from raw mat. supplier
P0''	Manufacturer's post-production	T2	Manufacturer buys material from secondary mat. market
P1	Raw material supplier cash flow	T3	Wholesaler buys products from manufacturer
P1'	Raw material supplier warehouse	T4	Customer buys products from manufacturer
P2	Wholesaler's cashflow	T5	Retailer buys products from wholesaler
P2'	Wholesaler with the product	T6	Customer buys products from wholesaler
P3	Customer's cashflow	T7	Customer buys products from retailer
P3'	Customer with the product	T8	Customer uses the products
P3''	Customer with the used/finished product	T9	Customer sends used products to collecting point
P4	Retailer's cashflow	T10	Customer sends used products to recycling plant
P4'	Retailer with the product	T11	Customer sends used products to disassembly plant
P5	Collecting point cashflow	T12	Collection point sends used products to recycling plant
P5'	Collecting point with the used products	T13	Collection point sends used products to disassembly pts
P6	Recycling plant cashflow	T14	Recycling point recycles the used products
P6'	Used products waiting to be recycled	T15	Recycling point sends used products to disassembly plant
P6''	Used products after recycling process	T16	Disassembly process
P7	Disassembly plant cashflow	T17	Disassembly plant sells materials to second. mat. market
P7'	Disassembly plant (used / recycled prod.)	T18	Manufacturer pays fee to govt environment agency
P7''	New materials obtained after disassembly	T19	Govt envt. agency subsidizes the disassembly plants
P8	Final disposal for waste		
P9	Secondary supply market cashflow		
P9'	Secondary supply market warehouse		
P10	Manufacturer's mandatory recycling fee		
P11	Government environment agency		

For the reverse supply chain, it seems that customers are balanced between sending the used products to the collecting points (T9, 1582 times), recycling plant (T10, 1523 times), or disassembly plant (T11, 1597 times). Finally the flow of products from collecting points to the

disassembly plant (T13) and to the recycling plant (T12) have the lowest number of firings.

The state-space analysis results are as follows. There are 20.252 possible states with 7.237 possible dead markings

```

▼Declarations
▼Color Set
▼colset CASH = with cash;
▼colset MATERIAL = with materials;
▼colset PRODUCTS = with products;
▼colset USED = with used;
▼colset WASTE = with waste;
▼Variables
▼var c : CASH;
▼var m : MATERIAL;
▼var p : PRODUCTS;
▼var u : USED;
▼var w : WASTE;

```

Fig. 3. Definition of color sets and variables

Table 2 Simulation results

Untimed Statistics			
Transitions Name	Count	Transitions Name	Count
T0	4703	T10	1523
T1	1000	T11	1597
T2	3703	T12	799
T3	2359	T13	783
T4	2344	T14	2321
T5	1183	T15	2320
T6	1176	T16	3659
T7	1183	T17	3659
T8	4702	T18	4702
T9	1582	T19	4702

on this model and 86.533 arcs that are connecting each and every states. The SCC (Strongly Connected Components) graph also has the same results which means there are no cycles or subgraph on this model. Also, after fairness analysis, it is found that there are no infinite occurrence sequences, which means eventually there will be no transitions available to be fired.

Table 3 State-space analysis results

Place	Upper Bound	Lower Bound	Place	Upper Bound	Lower Bound
P0	500`cash	492`cash	P5'	3`used	empty
P0'	1`materials	empty	P6	400`cash	397`cash
P0''	7`products	empty	P6'	3`used	empty
P1	8`cash	empty	P6''	2`used	empty
P1'	1000`materials	992`materials	P7	504`cash	497`cash
P2	400`cash	395`cash	P7'	3`used	empty
P2'	5`products	empty	P7''	1`materials	empty
P3	200`cash	195`cash	P8	2`waste	empty
P3'	5`products	empty	P9	8`cash	empty
P3''	3`used	empty	P9'	100`materials	92`materials
P4	300`cash	297`cash	P10	7`cash	empty
P4'	3`products	empty	P11	5`cash	empty
P5	300`cash	297`cash			

There is no home marking on this CPN, home marking is a marking which can be reached from any reachable marking, if there are no home marking, then it means that all markings are different each time. On our CPN model, all the places are bounded. While the lower bound explains the minimal number of tokens on the place in a reachable marking. Few of our places have lower bound of 0, this can

be explained as most of them have 0 token in the initial marking.

5. CONCLUSIONS

This paper has presented a Colored Petri Net approach to model and simulate a green supply chain system. A colored Petri net model of the green supply chain is developed and simulated with CPN Tools CPN Tools (2024), a dedicated software for CPN models. The simulation results as well as the state-space analysis results validate the correctness of the model. Future work will deal with the generalisation of the method to a class of Green Supply Chain Systems. Another future work will focus on the Reverse Supply Chain part and the strategies dedicated to it.

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