Review of simulation methods for analyzing closed loop green supply chains

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Abstract. The need for effective Closed Loop Supply Chain (CLSC) analysis is rising with the growing awareness of the environmental impact of product disposal. Companies like "Bol", the Dutch equivalent of Amazon, have already introduced options for returning replaced products to their manufacturers. However, the effective management approaches to these new supply chain routes, especially through data-driven methods like simulation, have not kept pace with the evolving demands. The focus of academic research regarding simulation methods is still focused on modelling Linear Supply Chains, while their application to CLSCs is lagging behind. Therefore, this paper evaluates whether simulation is still a useful method to analyse the characteristic concepts of CLSC. The analysis revealed that System Dynamics, Discrete Event Simulation and Timed Colored Petri Nets, are all suitable methods for simulating CLSC. However, their strengths and weaknesses trade off between the characteristics. This paper hence provides guidance on the circumstances under which it would be best to use each simulation method, or a combination of them.

Keywords: Closed Loop Supply Chain (CLSC) · Discrete Event Simulation (DES) · System Dynamics (SD) · Timed Colored Petri Nets (TCPN).

1 Introduction

The growing awareness of the environmental impacts of product disposal have prevailed the notion that businesses, but also consumers should use resources in a more responsible way. Many enterprises have since decided to restructure their logistics systems towards green supply chains. This is done by, integrating renewable practices into their supply chain management, with the goal of increasing resource efficiency and reducing the impact of manufacturing (Song & Gao, 2018). Closed loop green supply chains are a further extension of this concept that combines the environmental benefits of green supply chains and the economic benefits of closed loop supply chains (CLSCs) (Liu et al., 2023). Simulations can provide valuable insight in the complex nature of these systems through a structured set of rules and assumptions (Moroni et al., 2024). Liu et al. (2023) discussed the inability of green CLSC simulation in static environments to accurately analyse the system's performance. Focus of academic research has hence shifted towards dynamic environments. For this paper, three simulation methods to analyze have been chosen (1) System Dynamics (SD), (2) Discrete Event Simulation (DES) and (3) Timed Colored Petri Nets (TCPN). These simulation methods have all been used to model logistical systems and score well on system and process structures (Koch et al., 2012). DES and TCPN also score well on object structures. This paper questions whether these methods also can be deemed useful for the analysis of closed loop green supply chains and if so, what trade-offs are made under various circumstances.

1.1 Definition of concepts and structures

In literature closed loop supply chain (CLSC) and circular supply chain tend to unjustly be used interchangeably. For this review, the definition introduced in Moroni et al. (2024) is used, here they define CLSC as the process where value is recovered within the original Supply Chain by returning goods and packaging to the manufacturer. Closed Loop Supply Chain however, still produces waste throughout the supply chain. This is where the Circular Supply Chain is different as it defined as a zero-waste supply chain, where it designed to systematically restore and regenerate resources in both the full industrial and natural ecosystem it operates within. Note that due to the open loop (specifically cross-sector) characteristic, the definition of a simulation is much more complex than CLSC (see the difference in figure 1). The simulation methods to be discussed will therefore be evaluated on the immediate use in CLSC analyses.

To compare the three methods in the context of CLSC, a comprehensive assessment was conducted focusing on key characteristics of CLSCs. Definitions of these characteristics can be found in table 1.

Fleischmann et al., 2001 examined the ways in which stochastic elements like supply and demand uncertainty may affect the supply chain. *Supply uncertainty*

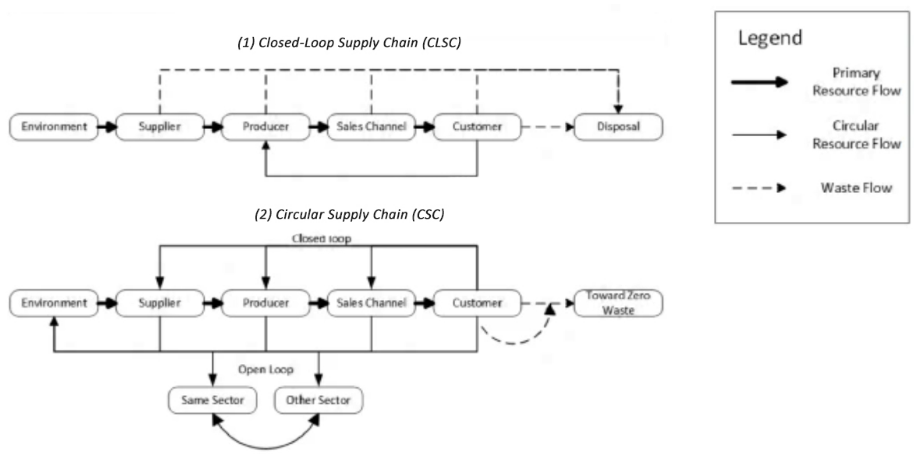

Fig. 1: Closed Loop Supply Chain, and Circular Supply Chain, Source: Adapted from Moroni et al., 2024

refers to the unpredictable variability in the availability, lead times, and reliability of inputs, such as raw materials or products. In their findings, the return process of reverse logistics can help stabilize demand uncertainty, but it increases supply uncertainty due to unknown conditions of availability and quality of the used products. Min et al., 2006 and S. Zhang et al., 2014 argue that the best way to account for these uncertainties is to include time delays in uncertain processes of the supply chain, such as remanufacturing. *Time delays* refer to the time interval between initiating an action (e.g., placing an order) and its realization (e.g., receiving goods), which can impact the efficiency of supply chain operations.

The distinguishing factor between CLSCs compared to standard Linear Supply Chains, is their inclusion of reverse logistics. This drastically increases the number of actors involved and thereby raises the complexity of the system (Guide Jr & Van Wassenhove, 2009). Complexity in a supply chain refers to the intricate interconnections among various stakeholders and processes, making it more challenging to predict and optimize operations. It is common practice when modeling CLSCs to organize these actors into a multi-echelon network structure, grouping them into hierarchical layers. For example, this can involve distinguishing between the forward chain (e.g., suppliers, customers, manufacturers) and the return chain (e.g., depots, recycling sites, secondary markets) (Garg et al., 2015; Kannan et al., 2009). *Multi-echelon network structures* refer to the layered organization of a supply chain, optimizing operations across multiple levels. Next to the organisation difficulty can the complexity make the supply chain computationally heavy to simulate. Therefore the *computational complexity* should also be considered a key concept. Computational complexity here, refers to the construction and run time before an organisation can start analyzing.

Products, along with crucial pieces of information, are constantly exchanged between the network of actors in a supply chain. *Product and information flows* refer to the movement of physical goods and the corresponding data that support decision-making. It is essential to track these exchanges to understand the system fully. However, as the cycle times tend to be longer in these processes, changes do not typically occur on very short time scales, making the use of continuous-time chains excessive in most cases (Min et al., 2006).

Table 1: Key concepts and definitions in Closed Loop Supply Chains

Concept	**Definition**
Supply uncertainty	The unpredictable variability in the availability, lead times, and reliability of inputs, such as raw materials or products.
Time delays	The time interval between initiating an action (e.g., placing an order) and its realization (e.g., receiving goods)
Multi-echelon network structures	The layered organization of a supply chain, operations across multiple levels.
Computational complexity	The construction and run time speed needed for the simulation model.
Product and information flows	The movement of physical goods and data between actors in the supply chain.

2 Methods

2.1 Research Approach

A comprehensive desk research was conducted, during which scientific studies were critically reviewed. Based on the literature review, various simulation methods were evaluated. The primary focus of this research is on exploring the possibilities for practical applications within the field of supply chain management.

2.2 Research Design

This study adopts a literature review approach, aimed at assessing the strengths and weaknesses of three prominent simulation methodologies: System Dynamics (SD), Discrete Event Simulation (DES), and Timed Colored Petri Nets (TCPN), specifically within the context of closed loop supply chain (CLSC) management. The primary objective is to evaluate the current state of knowledge on the application of these simulation methods. The focus mainly lies on their compatibility with the named concepts related to CLSCs. In this way, the study seeks to assess the effectiveness and efficiency of each approach when applied to CLSCs under a variety of circumstances.

2.3 Literature Selection

A systematic search strategy was employed across multiple academic databases, including Google Scholar, WorldCat, and Web of Science. The search terms utilized were combinations of keywords such as "simulation models", "closed loop supply chains", "circular supply chains", "System Dynamics", "Timed Colored Petri Nets", "Discrete Event Simulation" and "supply chain management.". Citation analysis was performed, assessing both the number of citations and the academic responses to these studies, to gauge the level of acceptance and impact within the scholarly community.

2.4 Data Analysis

The selected simulation methods were systematically analyzed by evaluating their compatibility with the key concepts surrounding CLSCs. For each of the key concepts the strengths and weaknesses of each modeling approach according to the literature review are gathered and tabulated. Subsequently a comparative analysis was conducted to determine which simulation methods performed best under which specific conditions. Additionally, the potential for combining different approaches was briefly discussed, based on the literature review, to assess whether a hybrid approach could yield more comprehensive results.

3 System Dynamics Modelling

System Dynamics (SD) was originally developed by Jay Forrester in the late 1950s as a method to understand and simulate industrial dynamics. Forrester's initial work focused on the application of SD to industrial processes, but over time, it evolved to address broader, complex systems like economics, business processes, and social systems (Forrester, 1987). The central concept behind SD is to model complex systems by focusing on stocks (representing accumulations of resources) and flows (representing rates of change). The use of feedback loops, both reinforcing and balancing, allows SD to simulate how changes in one part of the system propagate through the entire system.

System Dynamics (SD) approaches system complexity by focusing on several key aspects: (1) the accumulation and depletion of resources, (2) balancing and reinforcing feedback structures, (3) non-linearities, and (4) time delays (Franco, 2019). This methodology uses relatively simple differential and algebraic equations applied to stocks and flows, enabling users to model changes across macro, meso, and micro levels simultaneously. Given these capabilities, SD is frequently employed in the modeling of CLSCs and other systems related to sustainable development (Franco, 2019). However, the utility of SD is often questioned due to the complexity and the significant amount of high-quality data required for accurate modeling.

While SD is an effective tool for analyzing large-scale, complex systems, particularly those of an economic or environmental nature, it is less suited for simulating smaller interacting components (Alamerew & Brissaud, 2020). The framework excels in describing the inter dependencies between stocks (e.g., resources, products) and flows (e.g., production rates, consumption), but it struggles to capture the nuances of human decision-making and interactions within the system. According to Guzzo et al. (2022), although SD can assist decision-makers by providing "what if" scenarios and demonstrating patterns at various levels, it lacks the detailed complexity that approaches like Agent-Based Modeling and Discrete Event Simulation can offer. These other methods under which Timed Colored Petri Nets, are better suited for handling emergent behaviors and decentralized decision-making by individual agents within a system (Guzzo et al., 2022).

Some characteristics specific to the case of CLSCs and how SD is able to deal with them are discussed as following:

- **Supply Uncertainty**: SD can model supply uncertainty effectively through the use of stocks and flows, allowing the system to accumulate or deplete resources based on supply fluctuations. However, it is an aggregated view, SD typically requires a well-structured dataset to predict and model uncertainties accurately in comparison to models with more stochastic tools. The use of feedback loops can simulate how supply variations propagate throughout the system, but the need for accurate large-scale data presents limitations for systems with high volatility in supply (Alamerew & Brissaud, 2020).

- **Computational Complexity**: SD is particularly suited for high level systemic complexity. Due to the aggregation it is relatively intuitive and computationally light to construct, run and create fast insights into the dynamics at play. However, due to the high-level nature of SD models, detailed complexity might be underrepresented, such as the interactions of individual actors in the system (Guzzo et al., 2022).

- **Multi-Echelon Network Structure**: While SD is not inherently designed to represent hierarchical, multi-echelon structures, it can be adapted to simulate such networks by defining each echelon as a separate stock or flow. The ability to model feedback between different echelons helps visualize how disruptions or delays in one part of the supply chain affect the whole system. Nevertheless, for highly detailed networks, SD might oversimplify the structure (Franco, 2019).

- **Product and Information Flows**: SD provides a framework for modeling product flows through stocks and flows, where products move from one stage of the supply chain to another. The use of feedback loops also enables the modeling of information flow, helping to understand the impact of delays or information asymmetries in the system. The limitation of SD in this part is the level of detail needed, where SD will get messy when trying to incorporate too many detailed interactions in its high level perspective (Guzzo et al., 2022).

– **Time Delays**: One of the key strengths of SD is its ability to represent time delays. Delays are integrated directly into the feedback loops, providing a way to visualize the time interval between actions and their outcomes. This makes SD particularly effective for supply chain simulations that need to account for long-term dynamics and delayed feedbacks, such as those found in CLSCs (Franco, 2019).

4 Discrete Event Simulation

Discrete event simulation (DES) has for the past decades been one of the most used and well developed simulation methods (Robinson, 2005). Over time DES developed it's own tools, but subsequently also evolved to be a tool that is relatively easy to integrate other methods in. The method represents a system through the usage of a continuous time base with piece-wise constant trajectories. In DES, an event list is generated to schedule the order of the instantaneous events. This combination of characteristics make that DES is widely applied to the context of large complex systems to understand how such systems behave, and with that how the behavior changes over time under changing conditions (Robinson, 2005).

DES is widely used in the context of supply chains as it is well equipped to handle the stochastic elements that cause for supply uncertainty, through its ability to capture and evaluate changes at each timestep (Persson & Olhager, 2002). Here, it particularly excels in the ability to represent entities as individuals to which specific attributes can be assigned (Robinson, 2005). It has been suggested by various researchers that DES is only able to represent systems on the operational lower level, while missing out on the strategic higher level, which is ultimately crucial for effective supply chain management (Law et al., 2007).
Some characteristics specific to the case of CLSCs and how DES is able to deal with them are discussed as following:

– **Supply Uncertainty**: Robinson (2005) studied the ability of DES to represent both supply and demand uncertainty in supply chains. Here, they found that DES is quite capable of modelling uncertainty, and is one of the most prominent methods to assess operations of supply chains under uncertainty.

– **Computational Complexity**: DES is effective for simulating the stochastic complex linkages between components and individuals, making detailed complexity nicely representable. The downside of this is that higher-level flows of the system become computationally intensive (Manuj et al., 2009). The notion of *priority* also becomes more important in these systems as the sequencing constraints of events have to be clearly defined for same instant occurrences (Fujimoto, 1990).

- **Multi-Echelon Network Structure**: DES has been used as early as the 1960's to represent the multi-echelon structure of supply chains (Clark, 1960). It is still widely used for this case because it effectively provides the option to model hierarchies of a network as independent entities (Robinson, 2005).
- **Product and Information Flows**: DES can be used to model both material and process flows, but it in most cases seen as a less practical approach than SD. The reason for this is that DES can be very practical on small detailed, but missed the higher-level that is required for large complex supply chains (Oleghe & Salonitis, 2019). It has for this reason been proposed in many studies to apply hybrid simulation models (Jovanoski et al., 2012; Oleghe & Salonitis, 2019; Wen-li & Yao-wen, 2010).
- **Time Delays**: Lead times, processing times, and wait times at various stages in supply chains can be well represented as stochastic events in DES (Greasley & Chicksand, 2023).

5 Timed Colored Petri Nets

One of the methods to simulate CLSCs is the use of Petri nets. Originally Petri nets have been used to model asynchronous communication channels between automata (Petri, 1962). Over the years, numerous enhancements have been made on petri nets to increase their usefulness for simulation, like the creation of Colored Petri nets (CPN) (Jensen, 1994). With the emergence of CPN and the addition of time to petri net simulations, the method became particularly useful for simulating supply chains. Aalst (1992) showed that by using Timed Colored Petri Nets (TCPNs), uncertainty can be even more easily integrated by representing time delays as an interval rather then a value.

Since petri nets are naturally made to be asynchronous shows that it is possible to use petri nets for a model that can be parallelized, as well as extended without interrupting existing computations (Petri, 1962). Both of which can be of great use in a supply chain simulation model, which changes often and usually exists of a large and complex model (C. Zhang & Zhang, 2006). However, the low availability of good tooling for constructing TCPNs can cause loss of transparency and clarity, lowering the usability of TCPNs (Koch et al., 2012). While the use of good tooling, with libraries of commonly used petri nets for parts of the supply chain could help speed up the creation process (Aalst, 1992).

The use of TCPN simulations for supply chain management has become more important, since there is a increasing demand on formal models representing systems with a lot of unknown variables (Mahjoub et al., 2021). CPN have been used to model CLSCs with a forward and reverse supply chain. In (Kaiyandra et al., 2024) an implementation of such a model has been explained. Their model is made in CPN tools, a tool to create colored petri nets. The paper states that the CPN approach is useful to create such a model, however more research is needed to create a good formalism for CLSC. In Liu et al. (2023) generalized stochastic petri nets are used to model a CLSC. For their case it proved useful, however they also state the limitations of the simulation, in that it is still rather simple and that it might be hard to represent the complexity of a real system through the same approach.

Some characteristics specific to the case of CLSCs and how TCPN are able to deal with them are discussed as following:

- **Supply Uncertainty:** Uncertainty can be hard to describe and take into account for discrete event simulations, the same applies for supply uncertainty. Petri nets however have strong tools to model and deal with uncertainties (Aalst, 1992) (Mahjoub et al., 2021).

- **Computational Complexity:** Petri nets provide a way with which any type of detail wanted could be modelled if desired (Aalst, 1992). The main problem being that the model might turn out to be too big to run efficiently. In essence, the states used in the petri net model can be as detailed up to the state of a single digit in the whole simulation, however it would decrease efficiency to simulate the overall system. Aside from that it can take a long time to create the simulation (Aalst, 1992). Aside from the time it can take to create the model, good tooling is needed to run the simulation efficiently. CPN is just as powerful as DES, although there is less tooling available, since it is less used by industry (Koch et al., 2012).

- **Multi-Echelon Network Structure:** Logistical systems and especially closed loop supply chains are extremely complex. Multiple hierarchical levels to model within the simulation are required, which can be done using Colored Petri Nets (Jensen, 1994). Petri nets showing network structures naturally within the simulation. Since the way petri nets work, they show connections between the different states the model could be in. This way, all complicated connections within the model can be visible during the simulation. This is also one big downside, since this also means that a lot of connections between states have to be modelled before the simulation can be ran and keeping track of all of those connections is cumbersome (Liu et al., 2023).

- **Product and Information Flows:** Using tokens in a petri net simulation creates a natural way to create products in the simulation. Petri-nets can model the different flows in a logistical system, including information flows, combining all information in one model (Aalst, 1992).

- **Time Delays:** The timed aspect of petri nets naturally causes the tokens of the simulation to stay within a state for a certain amount of time, as in the simulation actually naturally works with delays. With the extension using intervals delays in time are easily modelled within the petri net simulation (Aalst, 1992).

6 Discussion

So far, three simulation methods have been described and several aspects of green closed loop supply chains have been discussed. An overview of the strengths and weaknesses identified in the review is presented in table 2. Note that all of the simulation methods can be used to simulate a green closed loop supply chain, but each has characteristics for which they perform better and worse. Therefore it is advisable, to make an informed decision considering the trade-offs.

Comparing the three different simulation methods, several trade-offs can be mentioned. In Kleijnen (2005) a comparison between SD and Discrete-event dynamic systems (DEDS) has been made, where DEDS is a discrete event simulation that can handle uncertainty. It states that SD uses aggregated flows, while DEDS is all about individual events with uncertainties like random time intervals. The study showed that SD can be used well in a supply chain to create an overview of the different stakeholders and show effects between them. If you want more detailed information on probabilities of a certain goal, for example a fill rate that is met within a certain time frame, SD will not do the trick. DEDS is however perfect for this job, since it is much better fit for handling uncertainties, so it will create better estimates. We find that the same applies for using DES and TCPN for the simulation of a supply chain. Both methods handle uncertainty in timing well and can create individual events, just like DEDS.

The level of detail and the size of the supply chain heavily affect the practicality of each method. The high precision of detail that is represented in TCPN can be very useful for small systems, but quickly becomes obsolete for large systems that require a multi-echelon network structure, as it takes too much time for most users to specify each part. This is where especially SD, but also DES thrive as they are effective methods that can function on a higher level. For all simulation methods is computational complexity traded off against the precision of system details. Noting which elements of a complex system need the precision and for which it not necessary will be vital as system grow. Then one could opt for integrated SD, DES model or multiple levels integrated DES models (Franco, 2019). Note that due TCPN also has a lot of strengths to bring in such a hybrid model, but construction and integration difficulties with limited tooling support make this a less obvious choice.

Table 2: Comparison of Simulation Methods Based on the Characteristics of Sustainable Supply Chains

Characteristics	**System Dynamics**	**Discrete Event Simulation**	**Timed Colored Petri Nets**
Supply Uncertainty	Stochasticity not implementable, Needs high quality data to show dynamics	Well equiped to handle uncertainty through stochasticity	Strong tools available to model uncertainty
Computational Complexity	Can do fast and effective high level simulation, detailed interacting effects are difficult	Effective for modeling the stochastic complex linkages	Takes a lot of time to create and good tooling is required to run the model well
Multi-Echelon Network Structure	Feedback between different layers well implementable, danger of oversimplifying complex structures	Able to represent hierarchies of a network as independent entities	Can show all connections in any level, can be hard to keep oversight of the whole simulation
Product and Information Flows	Using stocks, flows and feedback loops an intuitive logical structure can be build	Practical for small details but misses a higher level for large complex systems	Very strong, naturally through tokens, can show anything
Time Delays	Can be directly specified and integrated in feedback loops	Represented as stochastic events	Timed elements of TCPN naturally delays tokens, with intervals even variation can easily be modelled

When analysing flows and time delays another trade-off emerges. SD modelling excels at testing "what-if" scenarios and observing how changes propagate through the supply chain. This can provide rapid and valuable insights, especially when considering additional loops such as in a close-loop supply chain. DES on the other hand, lacks straightforward high-level insights but is able to represent stochastic, individual events. This allows emergent behaviors, such as additional delays, to surface. Phenomena that may be overlooked in the aggregation typical of SD models. TCPN offers the best of both worlds, easily handling variation in flows and delays. Additionally, TCPNs work well at both high and low levels, making them the preferred method for these particular characteristics.

7 Conclusion

As mentioned in the introduction, the main goal for this paper is to answer whether these simulation methods can be useful for the analysis of a closed loop supply chain and if so, under which circumstances they are best utilized and with what trade-offs. The short answer is, it depends. Multiple papers have shown that all three simulation methods can be used to simulate a closed loop supply chain, each with their own characteristics and trade-offs (Koch et al., 2012). System dynamics is great to get an overview of closed loop green supply chains and the interaction between the different components. If you want to take a look in greater detail at the processes within the different systems in the supply chain, it might be better to use Timed Colored Petri Nets instead. The main trade-off there is the amount of detail to simulate against the amount of time it will take to create the simulation, since a TCPN model will take a large amount of time. If you rather have an easier time creating the model and visualizing the model, while still creating more detail then SD can, it might be better to use a DES simulation instead.

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