Mitigating Biomass Supply Chain Uncertainty Through Discrete Event Simulation

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Abstract

Forest management and forest operations planning are complex topics requiring a holistic approach combining knowledge of the domain, optimization and simulation approaches, weather forecasting models, and state-of-the-art technology. Our research focuses on valuing biomass through more efficient management of its operations. Removing forest residues from piles is essential to mitigate fire risk. On the other hand, it is a way of valuing a by-product which can be used for heating, energy production, and even the production of biomaterials. There is significant variability in the availability of forest residues, biomass demand, and the productivity of operations, particularly in the forest-to-bioenergy supply chain. This work proposes a simulation framework to support the decision-making by combining plans generated by a resource allocation model with the analysis of a set of disruptive scenarios generated by discrete event simulation. The model addresses uncertainty in demand and variability in supply, resulting from fires. The obtained results provide essential managerial insights for the case study of a biomass supplier in the central region of Portugal and offer prescriptive recommendations to increase the efficiency and robustness of this chain in response to uncertainty. An extension of the methodology to other sectors appears, therefore, quite promising.

Keywords
Biomass supply chain; Resource allocation; Discrete-event simulation; Uncertainty modelling; Supply chain management

1. Introduction
The success of a company strongly depends on having a mindset centered on continuous improvement and a competitive strategy. Such a strategy should be based on the coordination between suppliers, production resources, and clients, allowing supply chains to be as flexible as possible, with a focus on versatile design and planning to improve effectiveness.

Energy generated by biomass, being clean and sustainable, will play a significant role in the future, providing a real alternative to fossil fuels. This industry goes on growing and is very attractive, given the abundance of raw material, the storage convenience, and the possibility of production worldwide. It is, however, still not very profitable. The biomass volume also depends on external factors such as weather phenomena or geographical restrictions (Sun and Fan 2020). In many countries, it is expectable that biomass will become the third source of energy, requiring the development of intelligent decision support systems to improve supply chains' efficiency (Demirbas et al. 2009).

Supply chain (SC) management is recognized as being fundamental to containing costs and responding to unexpected events, while ensuring demand fulfillment. A considerable part of a supply chain cost is related to transportation and "chipping" (the transformation process of the wood into smaller particles called "chips"). Therefore, in what concerns supply chain configuration, it is vital to specify the locations, capacities, routes, and processes, along the chain to ensure lower costs and higher robustness to variability, making this kind of energy source a viable alternative (Tymoszuk et al. 2019). The difficulty in storing and transporting solid biomass is still a disadvantage in producing this type of energy. In addition to its moisture content and low bulk density, the forest biomass has specific characteristics, such as seasonal availability and uncertainty related to weather variability, leading to complex supply chain, difficult to design and manage (Sun and Fan 2020).

The main motivation for this research is the practical need for a reliable and cost-efficient supply chain design, acknowledging the complexity and uncertainty of biomass logistics processes. There is uncertainty on when each wood pile will be available and, on the quantity, and quality of raw material in that pile. In addition, the operating scales are technically restricted by the amount of available biomass and economically constrained by the cost of delivered biomass to the bioenergy centrals (Cambero and Sowlati 2014). It is crucial to deal with this variability in supply, demand, and machine breakdowns with a flexible supply chain layout. In this research, we combine the opening of intermediate warehouses with the postponement of chipping operations from piles to these intermediate warehouses, in order to gain economies of scale and reduce costs.

This paper presents a simulation-based methodology to evaluate the impact of unexpected events on biomass SC performance. To support the chain configuration, a GIS (Geographic Information System) module is used for the supply chain nodes' location and the usage of intermediate warehouses to store biomass (as a way to deal with demand or supply uncertainty). Moreover, in terms of SC planning, the proposed approach uses previously computed resource allocation plans as input to evaluate the impact of unexpected events, such as fire occurrence on the chain' KPIs (Key Performance Indicators). This analysis is performed through interactive dashboards.

The main contributions of this work are: i) guidelines on how a simulation-based methodology can be used to enhance biomass supply chain designing and planning; ii) a set of procedures to allow automatic configuration of a SC in a parameterized simulation model; and iii) the validation of the approach in a real case study.

After this introduction, in section 2, a literature review is provided regarding SC structure and simulation models in the biomass context. Section 3 presents the problem and describes the case study. In section 4, the adopted methodology is detailed. Section 5 present discusses the main results of the approach. Finally, section 6 presents some general conclusions and possible extensions of the work, with special focus on the potential replication of this work to other supply chains.

2. Literature background

In this brief literature survey, section 2.1 describes the main features, gaps, and opportunities associated with designing and planning biomass supply chains, considering the specific features of biomass supply chains. Section 2.2 briefly explains how Discrete Event Simulation (DES) can be used to support this type of decisions, with examples of application from the literature.

2.1 Biomass for energy supply chain

These particular supply chains encompass several stages with different entities, such as farmers, transportation, storage, and final consumers. The performance of the supply chain depends on its design, planning, and operation, requiring high levels of coordination and optimization (Akhtari et al. 2018; Marques et al. 2018). When planning the bioenergy production from biomass, planners should consider each stakeholder along with the SC concerning six sectors: logging (which is the harvesting and collection of wood); storage of biomass; transportation along the supply chain; pre-treatment stations (also called intermediate warehouses); energy production; and distribution of the energy to the final customers (Sun and Fan 2020).

The biomass SC is, in fact, composed of two segments: downstream and upstream. The upstream segment encompasses the processes before the power plant and focuses on biomass harvesting, transport, and storage. This paper addresses this segment's problems, where biomass supply is uncertain, periodic, and limited by land opportunity

(Ekşioğlu et al. 2009). Cambero and Sowlati (2014) also refer the problems associated with biomass piles' geographic location and uncertainty in their available quantity.

Harvesting encompasses a set of operations such as "baling" (tie up something tightly into round or square bales) and "chipping". In this phase several types of constraints need to be considered concerning the quantity of accessible biomass, seasonality, weather conditions, and the need for tree plantations (Nunes et al. 2020). There are several difficulties to satisfy the energy demand when dealing with restricted access conditions for the operation of trucks and chippers (Gold and Seuring 2011).

Storage solutions are also essential for supply chain logistics and very important to accommodate demand variability. There are several options for warehouses from open-air, covered, or even equipped with fans (Zandi Atashbar et al. 2017). Warehouses also vary from roadside warehouses (suitable for the farmers to have their own space along the road) and intermediate warehouses (terminals or satellite depositories)(Ebadian et al. 2013). This paper addresses the case of intermediate warehouses, used to store biomass from several piles and allowing the execution of "chipping". Here the main challenge relies on determining their location and capacity to satisfy the energy demand.

In terms of logistics, challenges emerge when defining the transportation routes between network points, thus affecting the SC design (Sun and Fan 2020). In this industry the most common mode of transportation is the truck mainly because of the involved short distances and great flexibility of road transport compared to other modes (Rentizelas et al. 2009). However, mode choice depends on several factors such as required distances and times, biomass density, load capacity, speed, and vehicle availability. Using optimization algorithms, the distance and time of the route can be minimized by scheduling and synchronizing resources, thus reducing operational costs (truck waiting time and chippers idle time) (Marques et al. 2018).

2.2 Discrete Event Simulation (DES)

Simulation models are usually used to analyze stochastic environments, as a way to anticipate and study the impacts of certain events on complex systems (disruptions, stockouts, machine failures). Simulation models also allow the evaluation of different operational scenarios and the performance of different planning and scheduling decisions before implementation (Borshchev and Filippov 2004; Andersson et al. 2011), thus acting as a decision support tool.

In this work, discrete event simulation (DES) models have been developed. Such models generate a sequence of "events", i.e., changes of system states that are relevant for the decision-making processes being studied. In order to address some challenges presented in the biomass supply chain literature, simulation-based methods, combined with GIS and optimization models, were surveyed. Ayoub et al. (2007) present a decision support system developed for planning and implementing an expansion of bioenergy production. A combined optimization (a genetic algorithm), and simulation methodology, incorporated with a GIS module, helps decide the biomass collection points and the optimal location for warehouses and power plants. Zhang et al. (2016) also propose an integrated methodology by combining GIS with simulation and optimization methods. The number, location, and capacity of biofuel production facilities were determined by a Mixed Integer Linear Program (MILP) model. The GIS module allows the consideration of factors such as country borders, road networks, distribution of cities, and biomass accessibility. However, they do not consider the variability of biomass over a period. According to that study, the demand increases dramatically in both delivered feedstock and the overall cost.

In this work, we have used the Flexsim software which is a powerful simulation engine with years of improvement and one of the most used for simulation modeling and analysis (Dias et al. 2017). However, the GIS module on Flexsim is very recent (August 2021), and we believe this work can also help consolidate and tune some features of this module. The practical application found in this literature survey clearly show the relevance of combining simulation with optimization and with a GIS component, in addressing biomass supply chain problems.

3. Biomass supply chain case study

This research addresses the inefficiency problems of forest biomass suppliers and aims at providing a tool to support their operations planning activities. The biomass supplier has the chipping equipment needed to transform forest residues into biomass and must fulfill two types of contracts: one with forest owners to clean all residues from the piles; and another with the bioenergy plants for the supply of forest biomass. In this context, planning activities may be quite complex, as there is a vast spatial and temporal variability in forest residues' availability and the demand for biomass.

3.1 Case study description

In the case under study, we address the problems of a biomass supplier company operating in the biomass supply chain in Portugal. The company is responsible for shipping and transporting wood chips to fulfill the power plants' expected demand for each of the months. For this purpose, the company makes contracts with forest owners who provide forest residues to produce biomass. These residues (leaves, branches, and barks removed from tress) are transported to the forested roadside, to make them more accessible to trucks and chippers.

Operations take place only between March and November, in order to avoid possible rainy periods. However, the summer period directly affects the SC planning due to the risk of occurrence of fires. In addition, the piles are geographically dispersed all over the region, as there are many harvesting locations. For this reason, the company has multiple resources such as chippers, specialized operators, and trucks to complete these operations. However, the number of trucks was considered to be unlimited, and the chipper are limited to three.

In this study, the planning horizon is nine months (“macro” periods). Each month has 24 working days, and each day has eight hours of standard work (“micro” periods) and the possibility of eight hours of extra work (“micro” periods). The company adopted two decision levels, “long-term” and “short-term” decisions, associated to months and days, respectively. In the “long-term”, the company wants to plan the piles to be hired in the coming months to match the contracted demand, along with the chippers, and intermediate warehouses available for the entire horizon. The “short-term” planning consists of: allocating and deploying chipper; determining the biomass transportation routes; defining the number of hours the chippers operate each day.

The biomass supplier has a set of teams and equipment (chippers which are the machines that crush forest residues, transforming them into forest biomass) to carry out the processing, and trucks to transport the biomass, and he has some locations where he can open intermediate warehouses. These nodes can perform the function of stockyards and processing centers. In this work, we use some plans (produced by a previously developed Mixed-Integer Programming model) for opening intermediate warehouses, selecting the chippers to use, define the flows between piles and bioenergy centers, perform allocation of teams and equipment, and define stocks and working hours.

In this work we call the “simulation base model” a virtual representation of a supply chain assuming an “optimal scenario”, without the occurrence of disruptive events. Three plans are used as input for the simulation model. Plan 1 considers that all the demand is satisfied and there is no biomass in the piles at the end of the planning horizon The chippers can process the biomass both on the intermediate warehouse or on the piles. In this plan at the end of the planning horizon, the intermediate warehouses only have unprocessed biomass. The other two plans guarantee that all forest residues have been processed by the end of the planning horizon. In Plan 2, the chippers can process the biomass in piles or intermediate warehouses, and Plan 3 can only process in the intermediate warehouses.

3.2 Demand uncertainty and supply variability

After analyzing the base model, we have considered some disruptive events, in order to study the suitability of the plans, and to increase the robustness and flexibility of the chain accordingly. Two scenarios will be analyzed, one causing the biomass to increase and another increasing the demand.

In the first scenario, a common and unpredictable situation is considered: the occurrence of a fire in the forest, which can cause the amount of available biomass in each pile to increase. This increase happens because biomass residues come mainly from the wood industry, so if the wood is completely burned, the wood companies cannot use it, and therefore, more residues can be used. Furthermore, the number of piles can increase with occurrence of fires, and plans should be able to incorporate these piles. This scenario has three parameters that can define how the fire happens: the period in which the fire occurs; the quality of the forest; and the intensity of the fire that influences which piles are affected.

The second scenario is related to the quantity of biomass to deliver. During the nine months of the planning horizon, the power plants can request more biomass than initially contracted. For this scenario, the following parameters have to be considered: the number of power plants affected; the period (month) when the increase happens; and the percentage of demand increase (or simulating this increase, a normal distribution with mean from up to 20% and a 2% of standard deviation).

For both demand increase and fire occurrence scenarios, the following assumptions were made:

- After a fire event, extra biomass needs to be transported and processed. Several factors determine its amount: fire intensity; forest quality in the affected piles; and whether the affected piles are new or already had biomass to be treated.
- The extra biomass is transported to the nearest available terminal.
- In case the processed biomass in the intermediate warehouse is enough to cover the demand increase, an extra order of transportation, moving biomass from the terminal to the power plant, is triggered. If demand continues unfulfilled and the unprocessed biomass at the intermediate warehouse is higher or equal to the biomass to deliver, a new chipper deployment is activated.
- The pre-defined plan defines how chippers will behave initially. After a disruption, chippers have the following behavior: i) if chippers already operate at the intermediate warehouse, a supplementary processing is planned on the same day using extra hours; ii) if there is still biomass to process, 5 to 6 days at the end of each month hold extra deployments of the chippers and processing - in this case, each chipper can only do one deployment (the first available chipper is deployed to the terminal and operates up to 16 extra hours each day until the end of the current month).

4. Simulation-based methodology

This section describes the developed simulation model by outlining its main elements and emphasizing its capabilities. Designing and planning the biomass SC requires the use of non-deterministic data. Disruptions, supply or demand uncertainty, or resource unavailability directly affect the network KPIs (Key Performance Indicators). In this context, the adopted simulation-based approach allows the decision-maker to predict the impact of disruptive events on the network configuration and on the plan feasibility, providing suggestions for the SC redesigning and replanning.

The adopted DES simulation model uses plans generated by a previously developed optimization algorithm. However, the model has been designed in such a way that inputs from other planning procedures can be easily considered. Figure 1 below shows the main phases of the methodology, and the correspondent input data, that can be summarized as follows:

- **Biomass Supply Chain (BSC) Network Points & Location** – file in the JSON format, containing data related to Biomass SC network; it is specific to the case under study and has the geographic location of piles, intermediate warehouses, and power plants.
- **Resource Allocation Plan** – file exported from optimization algorithm using SOL format (used for solutions to mathematical programming problems) comprising the chippers allocation, working hours, stocks, flows, and strategic decisions related to chippers selection and intermediate warehouse opening.
- **Flexsim GIS Map configuration** – related to the setup of the network on the simulation software:
    - **Piles, Intermediate Warehouses, and Power Plants Location** - instantiation of the network points on the Flexsim GIS Map with the associated geographic coordinates.
    - **Travel Routings** – possible routes connecting piles, intermediate warehouses, and power plants.
    - **Chippers Creation** – instantiation of the chippers and their association to nodes.
    - **Flow Data Tables Creation** – conversion of data coming from the input files to data tables used for missions' assignment (transportation, processing, and deployments).
    - **Biomass Supply & Demand** – conversion of data coming from the input files used for piles supply and power plants demand.
- **Scenarios Definition** – parameters setting using a global data table and used to move quickly between pre-defined scenarios, without the necessity of changing the model.
- **Simulation Execution** – execution of the simulation model for a pre-defined time horizon.
- **Results Analysis** – evaluation of network KPIs; if statistic distributions are being used, the results of different replications can be compared.

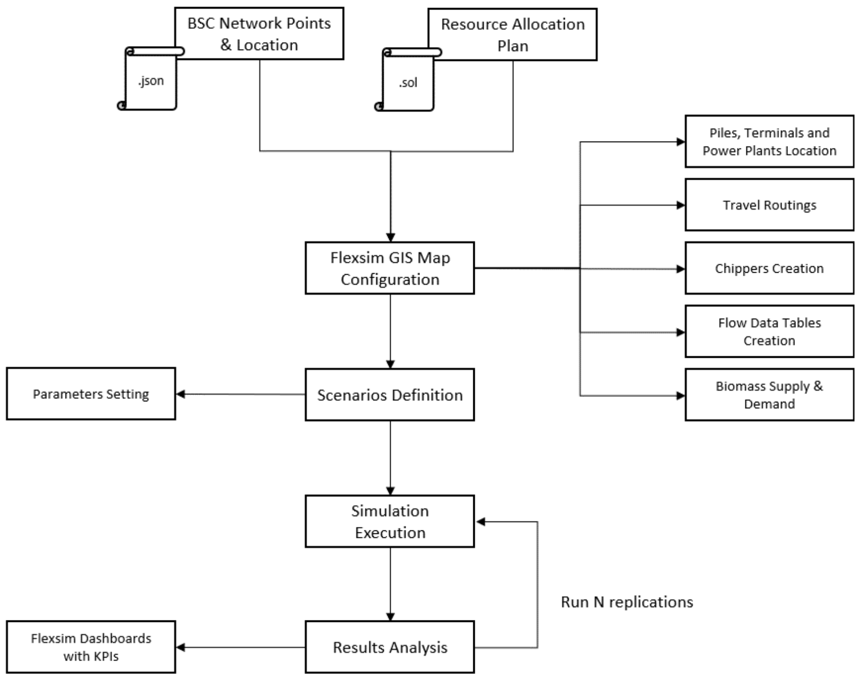

Figure 1 - The simulation approach

4.1 Application to the case study

The model presented in this work has been implemented in the Flexsim simulation software. This model has a high level of detail and allows the planner to configure a supply chain quickly and evaluate its' KPIs (costs, resources utilization, service level, biomass generated and consumed).

For setting up network setup, and using the "Flexsim Process Flow", dynamic scripts (programmed with Flexscript language) are used to configure the Flexsim GIS Map. Besides "loops" and "if-else" programming, these scripts also use the following methods (from the Flexsim code repository):

- **createinstance()** - to create the GIS Map, resources (chippers and trucks), and each network node based on the biomass SC Network Points & Location file;
- **setvarnum()** - to set latitude and longitude of the points, on the GIS Map;
- **contextdragconnection()** - to connect one network node to another node or resource (for example, to create a route between a pile and a terminal);

Running the developed scripts, the transportation and resource allocation plans are loaded automatically on Flexsim data tables. These scripts only need to run if there are changes in the input data, avoiding unnecessary processing. After the network setup, the GIS Map on Flexsim displays the SC points and routes (Figure 2).

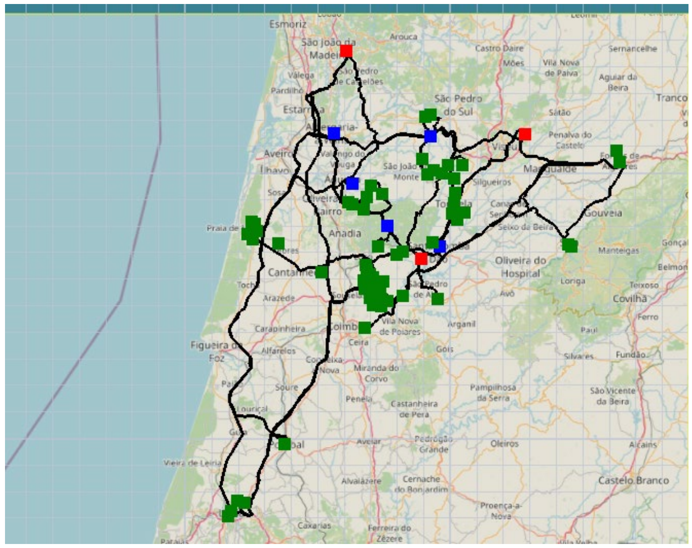

Figure 2. Network setup in the Flexsim simulation model

Additionally, a parameters data table is used for testing and evaluating scenarios. Parameters are variables or expressions used to change the model logic and behavior efficiently. After the network configuration and scenario definition have been performed, the execution of the base model can star. Dynamic dashboards collect performance indicators for the decision planner analysis.

In order to consider disruptive events (scenarios), the Flexsim experimenter tool is used, allowing to perform multiple trials and replications for each scenario. For the "fire" scenario, we used a simulator that generated multiple instances based on two factors: intensity, which indicates the piles affected; and in which month the fire occurs. A fire is more likely to happen in the summer months than at the beginning or the end of the planning horizon. The other factor that is relevant for this scenario is the age of the forest. A probability is therefore assigned to the cases "young" or "adult" forest, thus affecting the biomass available after a fire occurrence.

For the "variation of demand" scenario, the simulation model generates the number of powerplants with demand increment, according to the value of a specific parameter. A second parameter defines the biomass percentage that increases, using a normal distribution with a mean from 0 to 20% and a standard deviation of 2%. Finally, a third parameter randomly generates the month of demand growth.

5. Results analysis and discussion

The main purpose of the computational experiments is to evaluate the performance of the three generated plans and to highlight and understand the deviations of the simulation results from the original plans obtained by the optimization procedure. These deviations should, in some sense, reflect the uncertainty and variability dimensions added by the simulation model. In addition, the simulation will retrieve a set of KPIs about the flexible procurement planning options to be adopted in different scenarios of raw material disruption and variability.

5.1 Simulation model validation

After running the simulation base model (without the occurrence of disruptive events), simulation and "theoretical" (optimization model) results were compared using Plan 1. Table 1 provides breakdown costs obtained with these two approaches, for an instance of 52 piles and three power plants. The allocation plan produced by the "optimization model" uses four intermediate warehouses and two chippers (already purchased by the company). Together the chippers would operate for around 2300 hours, and at the end of nine months, there is no processed biomass in the intermediate warehouses.

Table 1 – Cost comparison between the "optimization" plan and the simulation base model

Cost	**Theoretical**	**Simulation**
Fixed	Intermediate Warehouses: 12 000 € Chippers: 7 500 €	Intermediate Warehouses: 12 000 € Chippers: 7 500 €
Chippers	Chipper 1: 1726h * 170 € = 293 420 € Chipper 2: 605,67h * 100 € = 60 567 € Deployments: 20 * 250 € = 5 000 €	Chipper 1: 1726h * 170 € = 293 420 € Chipper 2: 605,67h * 100 € = 60 567 € Deployments: 20 * 250 € = 5 000 €
Routes	146 529 €	244 810 €
Total cost	**525 016 €**	**623 297 €**

The difference between the total costs is due to the fact that the approaches compute "distances" in a different way. The optimization model uses the Euclidean distance (considering the coordinates of the locations) while the Flexsim GIS module considers more realistic route distances. Despite some minor differences between the simulation and the "theoretical" results, the logic and behavior of the simulation model can be considered validated. Taking advantage of the dashboards developed on the simulation model, the relevant KPIs can be analyzed by the planner, providing relevant insights for the decision-making process.

Figure 3 presents a Sankey diagram indicating the biomass flow rate at all points in the network. The segments on the left reflect the piles, the segments in the center represent the intermediate warehouses, and on the right, the power plants (expect the bottom segment representing an intermediate warehouse). In this example, by running the simulation model using Plan 1, we may conclude that Terminal 1 has a higher amount of biomass fed by several piles. Moreover, Power Plant 1 receives the larger amount of biomass among the Power Plants, most of it coming from Terminal 1. In terms of resources, the Gantt Chart of Figure 4, presents the allocation of the chippers throughout time, where the chippers had been allocated.

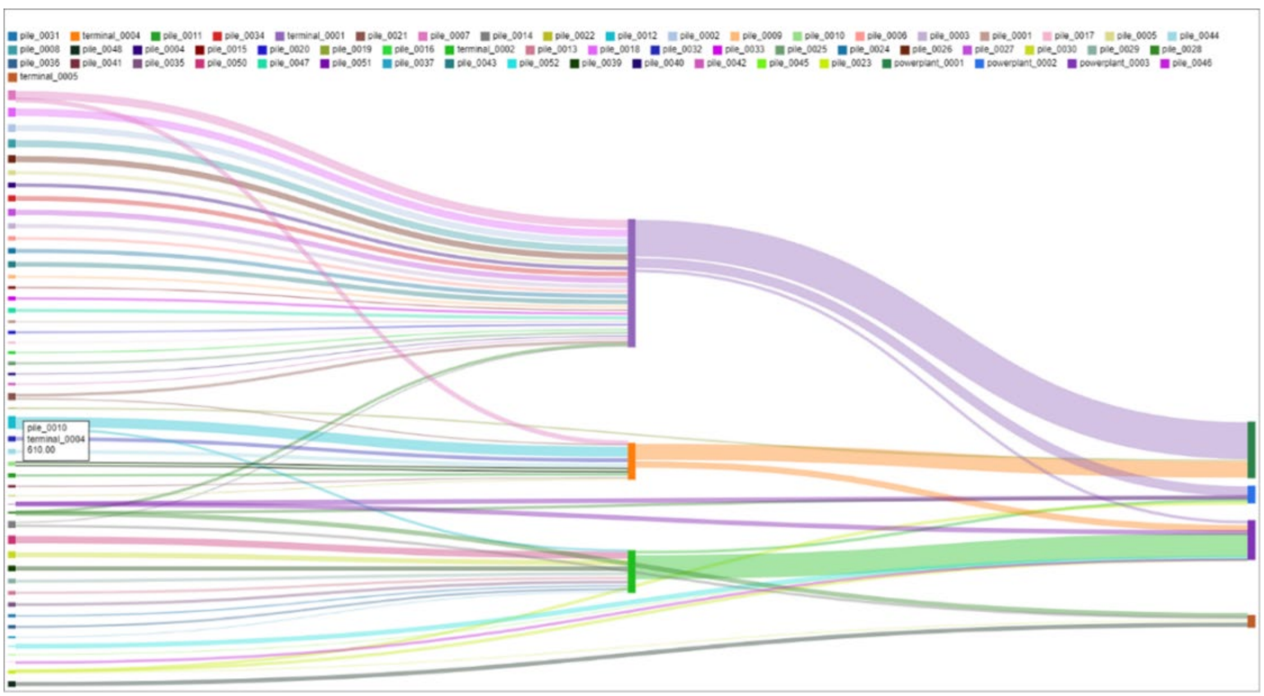

Figure 3. Sankey diagram for simulation run of Plan 1

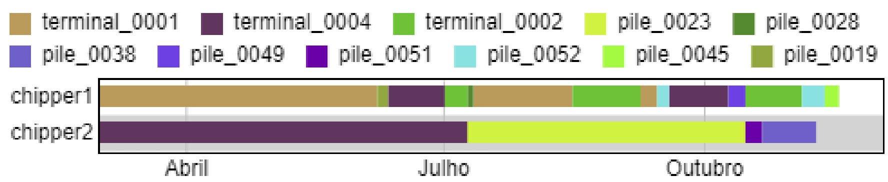

Figure 4. The allocation of chippers for simulation run of Plan 1

5.2 Analysis of scenarios

After the above analysis of the base model, this section presents and discusses the results of running two illustrative scenarios: a fire occurrence and a demand increase.

The fire scenario used a "fire simulator" generating 36 instances varying the piles that are affected by the fire. The results obtained by fire period (month when the fire occurs), considering success as be able to process the generated extra biomass for all instances, were:

- Period 3 - plans 1, 2 and 3 were 100% successful;
- Period 4 - plan 1 was 80.6% successful; plans 2 and 3 were 100% successful;
- Period 5 - plan 1 was 75% successful; plan 2 was 100% successful; plan 3 was 97% successful;
- Period 6 - plan 1 was 58% successful; plan 2 was 97% successful; plan 3 was 89% successful;
- Period 7 - plan 1 was 30.6% successful; plan 2 was 94% successful; plan 3 was 86% successful.

Analyzing these results, Plan 2 seems to be more prepared for fire events once it always obtained near 100% of success for all instances. Plan 3 is the second next in terms of ranking, being successful in almost 100% for periods before 6. Plan 1 showed to be the less prepared for fire events and was only able to accomplish 100% for period 3.

Table 2. Sample of results for the "fire scenario" in period 7, using 3 instances with 10, 14, 24 piles affected

Plan	Number of affected piles	Biomass increase (tons)	Forest Residues (tons)	Chippers (C) extra hours	Total cost (€)	Service level (%)
1	10	9 055	0	C1: 372,8 C2: 160	826 664	100
2				C1: 256 C3: 196,9	906 022	
3				C1: 248,7 C2: 408	936 204	
1	14	12 700	3 155	C1: 357,2 C2: 240	814 393	75,2
2			0	C1: 351,5 C3: 283,5	940 980	100
3				C1: 333,3 C2: 603,5	978 033	
1	24	23 195	12 500	C1: 440 C2: 189,5	905 137	46,1
2			4 024	C1: 392 C3: 566,8	1 121 156	82,7
3			9 220	C1: 478,8 C2: 440	1 067 070	60,3

Table 2 shows a sample result in fire period 7 using 3 instances with 10, 14, 24 piles affected. All plans use four intermediate warehouses and two chippers. However, Plan 2 uses chippers 1 and 3, while the others use 1 and 2. The first and second columns of Table 2 present the selected plan and the number of affected piles by each instance, respectively. The third column shows the biomass increased quantity with the occurrence of a fire and the fourth presents the unprocessed biomass quantity at the end of the horizon. The fifth column presents the number of extra hours operated by each chipper for biomass processing. Column six shows the overall cost of the supply chain. Finally, column seven presents the service level (total processed biomass divided by total biomass available).

In this example, we can see that the cost dramatically increases because of the price cost of extra hours, with 40-50% higher when compared with the base model. Moreover, the service level seems to be affected by the number of piles affected and Plan 2 has the better service level.

For the "demand uncertainty" scenario, Table 3 presents a sample of the model simulation results for four instances tested for the three plans, with 52 piles. The first five columns show the instance setup, including the plan, the power plants affected, the month of the increment (occurring only once), the percentage increased quantity, and the extra total amount needed to satisfy the delivery nodes. Column six includes the total amount of biomass not delivered to the power plants, column seven presents the periods when the demand was not satisfied, and the last column provides the total costs. For the three plans, multiple instances were tested and analyzed. However, Plan 3 always satisfies the increase of biomass, being more resilient and flexible in this case. For this reason, Table 3 only includes Plans 1 and 2.

Table 3 - Sample of results for the "demand increase" scenario

Plan	Affected Power Plants	Raise Month	Demand Raise (%)	Increased Biomass (tons)	Non-Delivered Biomass (tons)	Demand Not Satisfied	Total Cost (€)
1	[1,2,3]	[4,5,5]	20	1 004	1 004	[4,7]	623 408
2				1 006	1 006	[5]	708 870
1	[1,2,3]	[2,5,8]	15	784	784	[2,3,7]	625 663
2				784	468	[2]	714 392
1	[2]	[5]	10	548	548	[6,7]	624 768
2				548	0	-----	717 075
1	[3]	[9]	20	953	0	------	644 261
2				953	0	------	712 919

Analyzing the overall results, we can see that Plan 1 cannot fulfill the demand if there is a demand increase before period 7. Nevertheless, if the raise happens at period 9 in power plant 3, demand is always met regardless of the increasing percentage. For Plan 2, if the increase is 20% and occurs in one of the first four months affecting power plant 1, the demand is not fulfilled. If the growth is 15%, it can only fulfil the raise for the first two months of the planning horizon. Finally, the plan is feasible if the increase is 10%, except if this increase occurs in the first month.

6. Conclusions

The main objective of this work was to develop a simulation-based methodology capable of estimating the impacts of disruptive events in a biomass supply chain (that forms, in fact, a network). After defining the main features of the network, a simulation model was built that includes dashboards to visualize KPIs and cost breakdowns, to support the analysis and decision-making processes. The implementation of "intermediate nodes" aims at facilitating the management of biomass stocks. Moreover, using these warehouses will help the biomass supply chain be more flexible to disruptive events.

The dashboards added value to the system developed, providing supply chain managers with information about the cost structure and main KPIs in a visual format and easy to understand. The simulation model helped portray the results of the theoretical optimisation model by representing the system over time and evaluating stochastic scenarios with uncertainty, much representative of reality. In this work, three different plans (produced by a previously developed optimization model) are tested and compared in terms of the robustness of the supply chain.

Regarding the plan performance, Plan 2 seems to be more prepared for the fire scenario justified by the usage of chipper 3 (higher processing power) instead of 2. Plan 3 has shown to be more suitable for the demand increase scenario because the chippers are always located at the intermediate warehouses, ready to process. Focusing on the fire period, as closer it occurs to the end of the horizon, the success rate tends to decrease since there is less time to process all the extra biomass. Furthermore, in terms of demand increase month, as it approaches the end of the horizon, the success rate tends to increase, justified by the biomass already in the intermediate warehouses able to correspond to the increment.

In terms of overall conclusions, the framework developed in this work seems able to support the assessment and selection of operational plans, taking into account the occurrence of disruptions in a biomass supply chain. The framework also provides insights about the cost breakdown, the number of overtime work, number of deployments, or quantity of biomass not delivered or processed.

The proposed simulation-based methodology was developed for the forest-to-bioenergy sector. However, the performed experiments show it is possible to replicate the methodology in terms of network setup and develop new simulation models for other sectors. Future studies could be conducted to validate this methodology in other industries and for different types of uncertainty such as breakdowns, machine deterioration, and transport delays. On the other hand, it would be interesting to integrate other constraints such as perishability, penalties for unsatisfied deliveries, and the time it takes for the supply chain to recover from different types of disruptions, through higher levels of resilience. Finally, it would also be essential to include a new study on the robustness of the model considering the decision makers' risk attitude.

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