A MATHEMATICAL MODEL OF WASTE MANAGEMENT AND FOOD LOSS ALONG THE AGRIFOOD CHAIN

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RESEARCH ARTICLE

Abstract

The waste management in the agrifood chain is a complex component within the agrifood industry system. In this matter, modeling and simulating processes within the system can lead to the determination of the impact of the actions made in the system for optimization purposes. The most important part of waste management is the optimization of food loss and waste (FLW) phenomenon, either by a quantitative or qualitative point of views. This paper presents a model of waste management within the agrifood chain built based on the distributed systems approach, specifically using Petri nets. The formal algebraic notation of the Petri net is described, as well as the pictorial representation. Also, a simulation of a primary form of a Petri net is run and the results are analyzed. The model leads to the determination of several interpretations which can be used further for waste management optimization.

Keywords: food waste, food loss, distributed system, agrifood chain, Petri nets.

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INTRODUCTION

Computational practices are nowadays used at a large scale for every domain, including production systems (Kutyauripo et al., 2023). A model based on distributed systems (Gaudio et al., 2023) for the management of waste and food waste in the agrifood chain is an effective way to analyze, simulate and optimize the processes related to the production, processing, distribution and consumption of food products. This analysis can be made on any type of food system, such as in wine, cassava (Alade et al., 2023) or meat (Botilias et al., 2023). The main purpose of such a model, built using, for example, the blockchain technology (Liu et al., 2023; Omar et al. 2023) or, for this paper, Petri nets (Chen et al., 2015; Zhang et al., 2011), is to represent and analyze the complexity of the agrifood chain, focusing on food waste and waste management. The complexity will determine sustainability practices (Joshi et al., 2023) within the chain (Iakovou et al. 2021). The model can help to understand the processes, linkages and economic and ecological (Liu et al., 2023) impact of these aspects. The model can be used to develop and evaluate practical solutions for reducing food waste, for effective waste management (Roy et al., 2023) and for improving sustainability and ecological issues (Maesano et al., 2022) in the agrifood industry.

This paper presents a modality of determining waste management in respect to food loss and waste using specific distributed system modelling tools, such as Petri nets. Petri nets refer to a mathematical modeling language used for the description and analysis of systems. Petri nets are used in a wide variety of fields such as computer science, engineering, economics theory or behavioural economics and they are used for modeling, simulation, and verification of systems with concurrent and distributed components, such as the agrifood chain. The result of this kind of modelling instruments consists in a graphical and mathematical representation that helps in understanding and analyzing the dynamic behavior of complex systems. While their primary usage is directed to computer science models, they are also used for modeling and analyzing the behavior and patterns of concurrent systems, such as distributed systems, communication protocols, and manufacturing processes.

The waste management is extremely important in the agricultural and agrifood chain and is extended to all the processes and phases of the chain. Agrifood chains are complex systems with various stages, from production and processing to distribution and consumption. The role of modelling and analysis given by the usage of Petri nets is related to the development of models and analysis of the dynamic interactions and dependencies between different stages. In this way, they provide insights into waste generation, disposal, and potential optimization points.

MATERIAL AND METHOD

Waste management during the agrifood chain can be considered a distributed system in some aspects, although it may not fully show all the characteristics of traditional distributed computing systems. Distributed systems are a type of computing system in which components or nodes, located on different machines or at various geographical locations, work together to achieve a common goal. Although their main usage is related to computing contexts, the distributed systems are also used in other areas, such as food production. The distributed nature of waste management in the agrifood chain arises from the fact that various stages of the chain involve multiple participants, locations, and processes. Thus, the main characteristics of a waste management system seen as a distributed system are related to:

- geographical distribution of agrifood chain;
- the variety of participants (farmers, food processors, distributors, consumers);
- concurrent processes (harvesting, packaging etc.);
- data and information sharing alongside agrifood chain;
- resource allocation for waste management (waste collection, recycling etc.).

While these characteristics suggest a distributed aspect to waste management along the agrifood chain, it's important to note that it may not have the same technical and computational complexities as traditional distributed computing systems. Nevertheless, information systems and technologies can play a role in optimizing waste management practices in the agrifood chain by providing tools for tracking, reporting, and optimizing waste-related processes.

In order to model the waste management with the emphasize on the food loss and waste, methods and instruments which are usually applied to model distributed systems were considered. For the specific nature of waste circuit, the most suited instrument was considered a Petri net. The main impact of the usage of Petri nets is the optimization of resource usage by modeling the flow of resources, energy, and waste through the system. This can assist in aspects such as increasing the efficiency of the processes, reducing food loss and waste, and improving sustainability in the agrifood chain. Also, Petri nets can be used alongside alternative modeling approaches, such as life cycle assessment (LCA) or environmental impact assessment. Based on this integration, they provide a more comprehensive view of the environmental implications of waste management strategies in the agrifood chain. The motivation of the usage of Petri nets was related to the usage of these instruments in complex systems, such as production ones. In this matter, Petri Nets are a graphical way of modeling and analysing processes and systems, especially those involving concurrency, parallelism, and synchronization. A usual Petri net is formed of two main elements:

- places, which represent states or conditions of the system;
- transitions, which represent actions or events that can change the system states.

Other important components of a Petri net are constituted by tokens. They are entities situated in places which shows system states or resource quantities within the system. The places and transitions are connected by arcs, which direct the tokens in specific places and they can carry restrictions to reach a specific state. Connected to arcs we can consider arc functions, which determine the behaviour of the tokens from one place to another.

The main purpose of the study is related to the determination of waste cycle within an agrifood chain, with emphasize to food loss and waste, in order to establish good practices related to food waste within the agrifood industry. In this matter, the methodology follows the next path:

1. the determination of the components of the model;
2. the description of the mathematical model of the system;
3. the determination of the primary Petri net using specific software (CPN Tools and CPN IDE);
4. the run of tests and simulations related to the obtained Petri net.

RESULTS AND DISCUSSIONS

Petri nets have specific forms which can be used to model complex systems. In order to build and run the model, we have to determine the main components of the model: the places, the transitions, the arcs and the tokens. The places which represent states of the agrifood system are shown in Table 1.

Table 1

The places considered for the agrifood system

No.	Place	Title
1.	S1	Raw material on farm
2.	S2	Raw material on processing phase
3.	S3	Processed products
4.	S4	Distributed products
5.	S5	Consumed products
6.	S6	Food waste

The determined places are related to food status on the agrifood chain. The transitions show system changes related to states. The transitions list is shown in Table 2.

Table 2

The transitions considered for the agrifood system

No.	Transition	Title	Short description
1.	T1	Agricultural production	Raw material harvesting process in the farm
2.	T2	Raw material transport	The transportation of raw material from farm to processing unit
3.	T3	Processing	Transforming raw material in product
4.	T4	Transportation	Product transport process from processing to selling points
5.	T5	Purchase	The product acquisition by consumers
6.	T6	Disposal	Food disposal as waste
7.	T7	Farm recycling	The process of recycling waste raw material on farm
8.	T8	Processing recycling	The process of recycling waste products and raw material at processing units
9.	T9	Raw material purchase	The acquisition of raw material at farm by customers
10.	T10	Processed product purchase	The acquisition of products directly from the processing unit
11.	T11	FW generation – farm	The generation of food waste from farm
12.	T12	FW generation – raw material transportation	The generation of food waste from raw material primary processing processes
13.	T13	FW generation – processing	The generation of food waste from processing
14.	T14	FW generation – distribution	The generation of food waste from product transportation
15.	T15	FW generation – consuming	The generation of food waste from consumers

The arcs are determined as connection links between specific places and transitions. For example, T1 is connected to S1, representing the fact that the raw material is generated from the agricultural processes and the food state in the agrifood system is "Raw material on farm". As for tokens, for the primary form of the Petri net built in the study we have established that the resources found in the system (food) are found in units. In the updated form of the actual Petri net, the tokens will be considered as various resources and expressed in their respective measurement units.

Now, we will represent the formalized mathematical model of the system.

Definition 1. The considered agrifood system may be represented as a Petri net PN, which is considered to be a quintuple $PN = (S, T, A, F, M_0)$, where:

- $S = \{S_i, i = 1,6\}$ is the set of places;
- $T = \{T_i, i = 1,15\}$ is the set of transitions;
- $A = \{(T_i, S_j), i = 1,15; j = 1,6\}$ is the set of arcs (edges);
- $F = c \times S_i \xrightarrow{T_k} p \times S_j, i, j = 1,6; k = 1,15$ is the arc function;
- $M_0 = \{T_1\}$ is the initial state of the Petri net, with the default tokens of 1.

Observation 1. The arc function is a multiplicity function. The variable *c* establishes the minimum number of tokens needed in the state S_i in order to activate the transition T_k. When the transition is fired, the state S_j produces *p* tokens. The function is established as a multiplicity function due to the fact that waste quantity is considered as a fraction of the entire generated food quantity at each agrifood chain level. For this study, the variables *c* and *p* have values of 1 for the agrifood chain transitions ($T_k, k = \{1,2,3,4,5,9,10\}$) and *p* value remains the same, while *c* has random values for the waste management transitions. The arc function will be subject to other updates in future research papers.

Observation 2. The tokens (resources quantity) used for the initial state will be determined based on agricultural production, based on the fact that the tokens will have various configurations for future papers. In this matter, coloured Petri nets will be used to differentiate various stages of food resources (raw material, products wasted food etc.).

The obtained pictorial notation described by the algebraic notation of the considered Petri net is shown in Figure 1.

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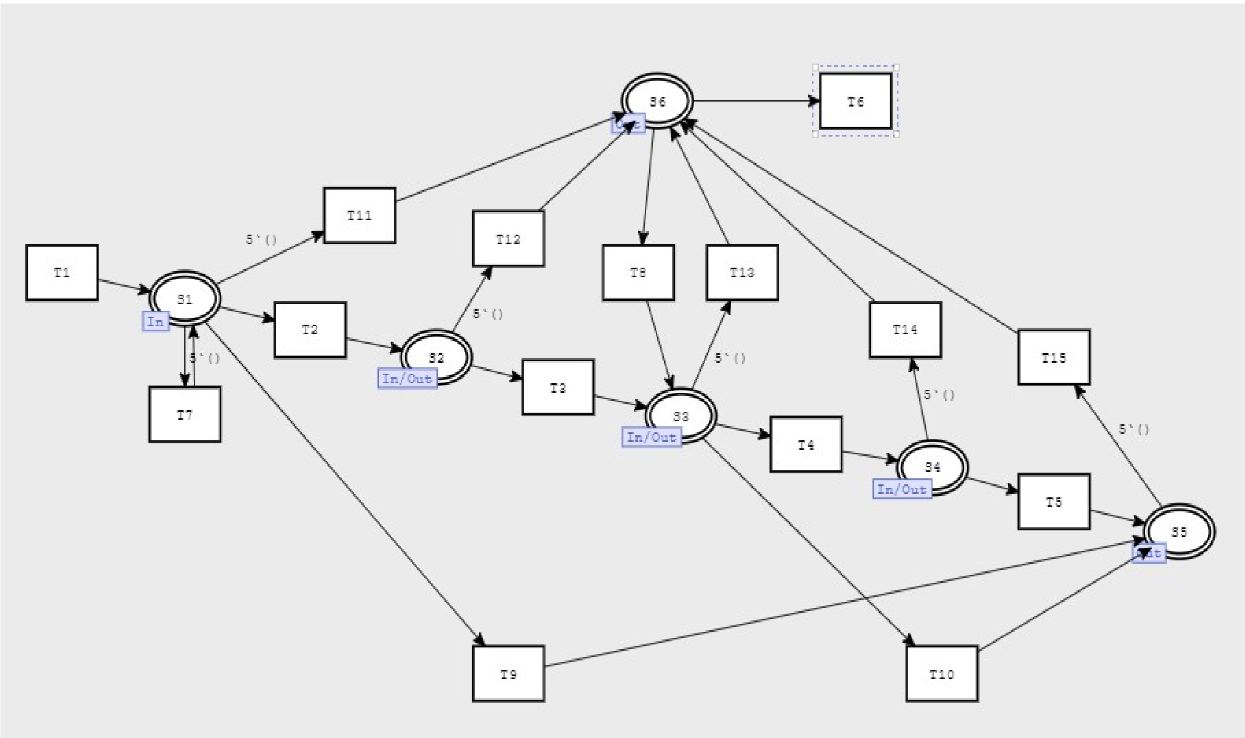

Figure 1 **The pictorial notation of the obtained Petri net**

The pictorial notation was obtained using the software tool CPN Tools. The transitions were represented as rectangles, while the places were noted by circles and the arcs as arrows between the transitions and arcs. In this matter, we can observe the dynamic of the agrifood chain processes and the fact that states within this chain are established as In\Out states, except for the S1 (In) and S5 (Out) states.

In order to establish the behaviour and dynamics of the Petri net, we have run a simulation of the net. The nature of the obtained net was non-deterministic, i.e., for a given state and an active transition, there are several paths that can be used for the transition. We have obtained the post-simulation configuration presented in Figure 2.

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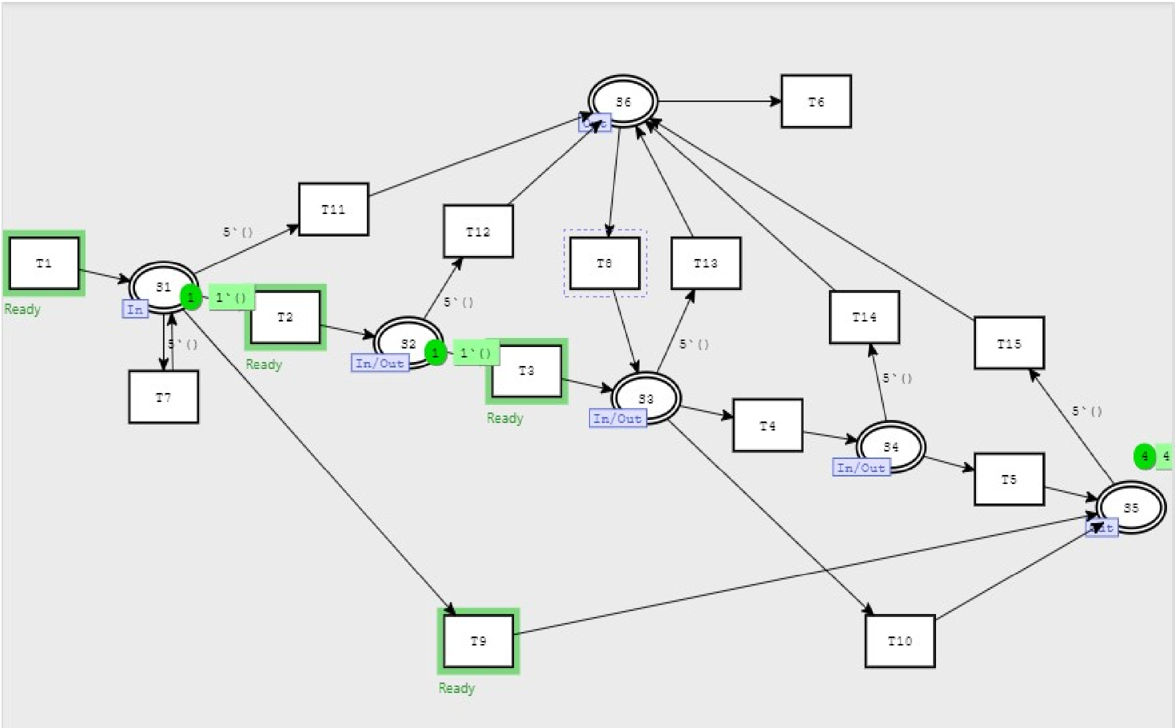

Figure 2 **The configuration obtained after an instance of simulation**

The simulation was run for 100 steps. We can observe that active transitions at the 100th step are T1, T2, T3 and T9, with 1 token in S1 and S2 and 4 tokens in S5, with T6 firing for a limited number of times.

The economic interpretation of the mathematical model resides in the behaviour of the Petri net components, showing that waste management can be optimized during the agrifood chain. One of the main interpretation directions is related to operational efficiency, which is obtained by the identification of the weak points where waste is generated in massive quantities. A second interpretation aspect is related to recycling processes within the system. The model contains specific states related to recycling processes, at the farm and processing levels, showing the importance and quantifying the impact of the recycling processes. Another important aspect is related to food waste costs and benefits, due to the impact of the recycling and waste reduction.

CONCLUSIONS

In conclusion, a Petri net-based model for managing food waste and waste in the agri-food chain provides a powerful approach for analyzing and optimizing these critical aspects of the food industry and supply chain. The model provides data for assessing the economic and ecological impact of changes in waste management and reducing food waste. It can contribute to increasing sustainability in the agrifood industry.

Future research papers will focus on aspects related to the determination and integration of real-data inputs into the model. To make the model relevant, it needs to be fed with real data or parameter estimates, such as product quantities, degradation rates, waste management costs. In this matter, several aspects related to arc function determination and coloured Petri nets (CPN) development of the current algebraic and pictorial notation will be made, including various modalities of the net representation.

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