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An Event-Driven Computational Framework for Mining Ecological Processes in the Venice Lagoon

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Article info

Article history: Received 2nd Sept 2025, Revised 18 Nov 2025, Accepted 4th Dec 2025, Published Dec 2025

Keywords: Ecosystem; Food Chain; Models, Biological; Petri Nets; Plankton; Process Mining; Population Dynamics

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Citation: Bhatt Shaifali, Gupta Abhinav, Chouhan Usha. 2025.An Event-Driven Computational Framework for Mining Ecological Processes in the Venice Lagoon.Curevita Innovation of BioData Intelligence. 1,2,73-97.

Publisher: Curevita Research Pvt Ltd

Abstract

Marine ecosystems integrate biotic and abiotic processes increasingly disrupted by human activities. We present a Petri net–based computational framework integrated with process mining to quantify respiration, assimilation, and mortality in Venice Lagoon compartments: phytoplankton, bacterioplankton, microzooplankton, Manila clam (Ruditapes philippinarum), and detritus. Using literature flux ranges, synthetic event logs were analyzed with the α-algorithm, inductive miner, and fuzzy miner; token-based replay exposed bottlenecks. Lower-trophic compartments (detritus, phytoplankton, bacterioplankton) exhibited higher throughput than higher-trophic compartments (clam, microzooplankton). Event-level diagnostics explained low microzooplankton assimilation when predators were absent and elevated phytoplankton mortality from unmodeled grazers; bacterioplankton/phytoplankton deviations reflected structural invariants and grazing assumptions. Fuzzy-miner abstractions clarified dominant pathways. Coupling advances ecosystem diagnostics and pinpoints intervention points for biodiversity conservation and climate resilience.

Article Highlights

- Venice Lagoon trophic models emphasize steady-state fluxes and aggregate relations.
- Disruptions from overfishing, pollution, and development alter marine energy flows.
- A Petri net and process-mining framework captures stage-wise process behavior.
- Event-level diagnostics identify bottlenecks and conditions for ecological stability.

Introduction

Ecosystems are complex, adaptive systems in which biotic communities interact with abiotic conditions through nutrient cycles and energy flows. Producers, consumers, and decomposers jointly govern the movement and transformation of matter; by mineralizing organic detritus, decomposers return carbon and nutrients to forms that primary producers can readily use(Samaranayaka & Fletcher, 2010). Over recent decades, industrialization, urbanization, overfishing, pollution, and the introduction of exotic species have altered many marine systems, raising concerns about resilience, stability, and the long-term capacity of ecosystems to absorb disturbance. Conservation planning in such contexts requires tools that quantify not only aggregate fluxes but also how process level changes propagate through trophic networks.

Mathematical and computational ecology has advanced the representation and analysis of trophic interactions in the Venice Lagoon and related systems (Murata, 1989). Petri nets provide a rigorous formalism for discrete, concurrent processes and have been used to represent trophic networks by mapping ecological compartments to places and ecological processes (e.g., biomass or energy transfers) to transitions(Simeoni et al., 2018), (Page & Wohlgemuth, 2010). Complementary work integrates discrete-event simulation and material-flow networks within environmental management information systems to assess throughputs, utilizations, bottlenecks, and environmental impacts within a unified modelling environment(Parsons et al., 2014). Other strands introduce dynamic parameterizations to analyze, evaluate, and forecast aquatic environmental quality in reservoirs, lakes, and seas (Guseynov and Aleksejeva). Despite these contributions, much of the literature emphasizes steady-state balances or aggregate relationships and therefore does not fully characterize the stage-wise vitality of cooperative ecological processes - especially respiration, assimilation, and mortality or how local adjustments cascade across dependent and cooperating compartments. The compartmental structure of the trophic network is shown in Figure 1.

The Venice Lagoon is a well-studied planktonic trophic system that serves as an instructive testbed (Page & Wohlgemuth, 2010). The compartments typically considered include phytoplankton (PHP), bacterioplankton (BPL), microzooplankton (MIZ), mesozooplankton (MEZ), Ruditapes philippinarum (TAP), and detritus (DET). For each compartment, throughput—the total flux per unit time—provides a measure of activity, while consumption, assimilation (consumption minus faeces), respiration, and mortality are often evaluated as percentages of consumption. Two broad groups commonly emerge: lower-trophic-level compartments (DET, PHP, BPL) display higher throughput, whereas higher-trophic-level compartments (TAP, MIZ, MEZ) exhibit lower throughput, consistent with general metabolic and growth-rate differences across trophic levels(Vezina & Pace, 2011), (Reinthaler et al., 2005) . In this setting, literature ranges indicate, for example, respiration typically $(\geq 20\%)$in zooplanktonic compartments and assimilation within $(\sim 40-80\%)$ for MIZ/MEZ, while bacterial assemblages can exhibit respiration near or above $(\sim 20\%)$, with assimilation often approximating consumption (Vezina & Pace, 2011), (Van Der Aalst et al., 2004). Prior analyses of the Venice Lagoon network have highlighted deviations linked to structural assumptions: MEZ can show assimilation near the lower bound when predators are not modelled; adding external predation raises MEZ assimilation toward values observed for TAP and MIZ. PHP may exhibit comparatively low respiration coupled with elevated mortality, plausibly reflecting the absence of grazers commonly present in lagoon systems. Low respiration estimated for MIZ, BPL, and PHP has also been attributed to a small number of minimal I/O invariants constraining these compartments, while PHP mortality appears high when certain grazers are omitted (Page & Wohlgemuth, 2010).

These findings underscore both the promise and the limitations of Petri-net-based ecosystem models. Structural or continuous Petri nets can reproduce key ecological processes at steady state and provide visual clarity on how one progresses from initial conditions through sequences and parallel branches to specific outcomes. They can identify mandatory paths and illuminate network topology. However, Petri nets alone do not render visible the fine-grained influence that each process exerts on others during execution, particularly under perturbations that deviate from steady state. In real ecosystems, dynamic changes in one process propagate to dependent, cooperative, and networked processes, producing compensatory adjustments that may preserve function or failures to compensate that impair function. Capturing these temporal adjustments is essential when evaluating system vitality, diagnosing emerging bottlenecks, and designing interventions that favour convergence toward stability.

To address this gap, we combine Petri net modelling with process mining to analyze the Venice Lagoon trophic system at the level of events. Petri nets furnish the structural and dynamical scaffold of compartments and flows; process mining extracts, from event logs, temporal ordering, causal dependencies, and variability in execution (Conover, 1966). Using the ProM framework, we apply discovery algorithms $(the\ \alpha\ algorithm, inductive\ miner)$ to reconstruct block-structured control-flow models and token-based diagnostics to evaluate conformance and reveal slow or obstructed segments indicative of resource constraints. We also employ the fuzzy miner, which weights significance and correlation to aggregate low-significance behaviour and clarify dominant pathways. Event logs are generated with a Process Log Generator (PLG) (Vezina & Pace, 2011), (Baldan et al., 2018) by executing the Petri-net model under literature-consistent conditions to reflect trophic interactions and parameter ranges documented for the Venice Lagoon (Sorokin & Giovanardi, 1995), (Ezparza & Nielsen, 1994).

Within this framework, we pursue three objectives. First, we quantify process vitality - respiration, assimilation, and mortality—at the event level, extending beyond endpoint fluxes to the temporal structure of process execution. Second, we trace interdependencies among cooperating processes, showing how local changes in availability or allocation propagate through trophic and detrital pathways. Third, we identify bottlenecks and intervention points, i.e., stages at which slow token movement or weakly correlated paths indicate constraints on system vitality, thereby clarifying conditions under which energy flows converge toward stability or diverge from it. By retaining literature-based parameter ranges for comparison while instrumenting the same ecological setting with event-level diagnostics, the analysis directly links established trophic understandings with process-oriented evidence. Flux magnitudes and directions used for parameterization are annotated in Table 1.

Figure 1 provides the structural context for subsequent process analysis, clarifying how planktonic and detrital compartments are connected before parameters and event-level behavior are examined. Nodes denote compartments (PHP, BPL, MIZ, MEZ, TAP, DET) and directed edges represent trophic transfers; abbreviations are defined in the text. As shown in Table 1, the annotated fluxes summarize steady-state expectations that anchor comparisons with event-level results recovered by process mining in later sections. Numbers on directed edges indicate literature-derived fluxes used to guide parameter ranges for throughput, assimilation, respiration, and mortality.

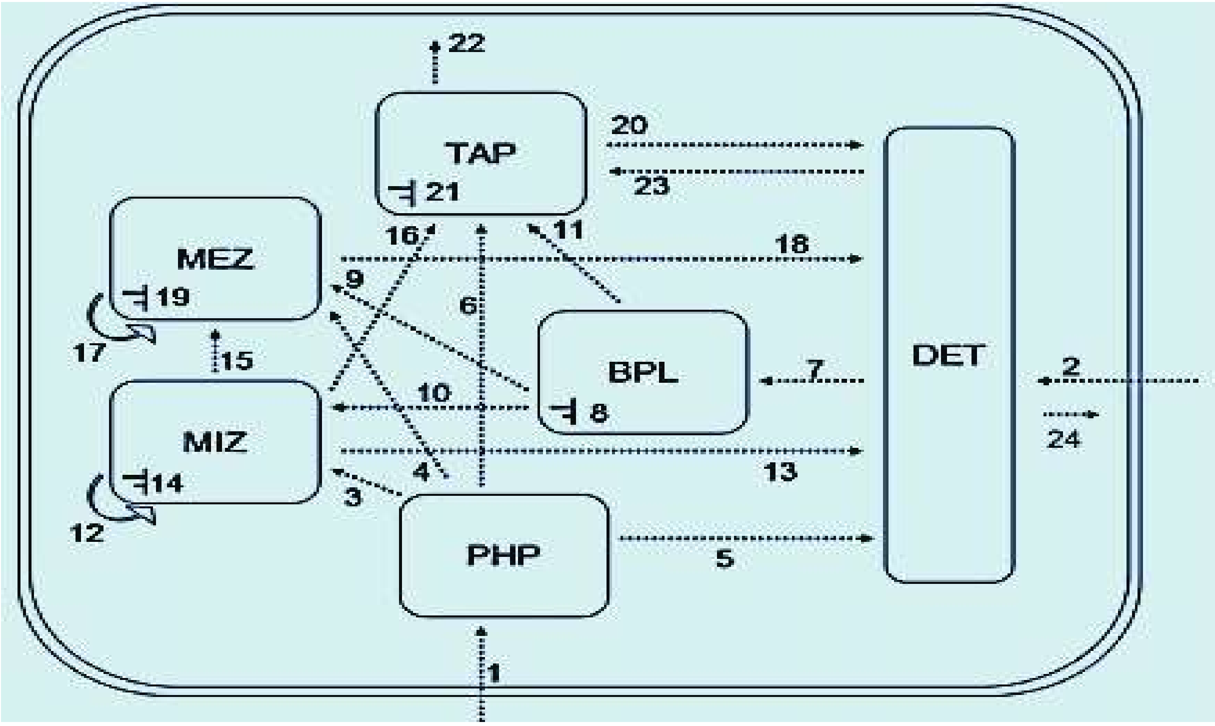


Figure 1. *Planktonic trophic system of the Venice Lagoon*

Table 1. Flux annotations (numbers on arrows) for the Venice Lagoon trophic network.

No.	Flux
1	CO2 → PHP
2	input → DET
3	PHP → MIZ
4	PHP → MEZ
5	PHP → DET
6	PHP → TAP
7	DET → BPL
8	BPL → CO2
9	BPL → MEZ
10	BPL → MIZ
11	BPL → TAP
12	MIZ → MIZ
13	MIZ → DET
14	MIZ → CO2
15	MIZ → MEZ
16	MIZ → TAP
17	MEZ → MEZ
18	MEZ → DET
19	MEZ → CO2
20	TAP → DET
21	TAP → CO2
22	TAP → Harvesting
23	DET → TAP
24	DET → Export

Methods and Materials

This work develops a computational framework that couples Petri net modelling of a trophic network with process mining of event logs to examine stage-wise behaviour of key ecological processes in the Venice Lagoon (Reinthaler et al., 2005), (Ezparza & Nielsen, 1994). The analysis focuses on respiration, assimilation, and mortality and their interdependencies across compartments, using literature-based flux information to parameterize the model (Vezina & Pace, 2011), (Van Der Aalst et al., 2004). No new experiments were conducted. The trophic network comprises phytoplankton (PHP), bacterioplankton (BPL), microzooplankton (MIZ), mesozooplankton (MEZ), Ruditapes philippinarum (TAP), and detritus (DET), following the Venice Lagoon case study (Baldan et al., 2018). For each compartment, we consider throughput (total flux per unit time) as a measure of activity; consumption; assimilation (consumption minus faeces); and respiration and mortality, reported as percentages of consumption. Parameter ranges were drawn from the literature and used to guide model structure and comparison. Table 1 lists representative literature ranges and model-comparable values for the continuous Petri net representation reported in prior work.

We model the trophic system as a place/transition (P/T) net

$$N = (P, T, W, M0)$$

(Simeoni et al., 2018). Places represent ecological compartments; transitions represent processes (e.g., ingestion, assimilation, respiration, mortality, detrital routing); arc weights encode flow multiplicities; the initial marking assigns tokens to places. A transition t is enabled at marking M if each input place p satisfies

$$M(p) \geq W(p,t).$$

When t fires, tokens are removed from input places and added to output places according to the arc weights, yielding a new marking. This captures discrete movements of biomass/energy tokens through the network. Structural soundness and basic invariants follow standard Petri net properties (Simeoni et al., 2018), (Mitsyuk et al., 2017). CPN Tools was used for graphical modelling and simulation. To analyze stage-wise behaviour, we generated event logs by executing the Petri net using a Process Log Generator (PLG) (Van Dongen et al., 2005). Each case represents a realization of trophic activity across the network; each event records an executed transition with its case identifier and timestamp. Multiple cases $(e.g., 1{,}000)$ were produced to assess variability consistent with literature-based constraints. The resulting logs capture sequences, concurrency, and loops implied by the net, enabling discovery of causal and temporal relations in the process-mining step.

Event logs were analyzed in ProM(Cumming, 2003). The $\alpha - algorithm$ recovers a workflow net from partial-order relations (direct succession, causality, concurrency). The inductive miner yields block-structured models with clearer split/join semantics. The fuzzy miner produces significance/correlation - weighted abstractions that collapse low-significance behaviour, clarifying dominant pathways and bottlenecks. Token-based replay assessed fitness and highlighted slow or obstructed segments indicative of resource constraints.

Mapping of ecological processes to transitions: Transitions encompass ingestion/consumption, assimilation, respiration, mortality, and detrital routing. Lower-trophic compartments (DET, PHP, BPL) serve as dominant sources of flow, while higher-trophic compartments (TAP, MIZ, MEZ) aggregate inflows and channel outflows via respiration and mortality. The mapping is consistent with throughput groupings and parameter ranges reported in prior analyses (Baldan et al., 2018), (Sorokin & Giovanardi, 1995). We retain literature-derived expectations to anchor the interpretation of mined behaviour: respiration ($\geq 20\%$)in zooplanktonic compartments, assimilation ($40-80\%$) in MIZ/MEZ, and assimilation ≈ consumption in BPL and PHP under certain steady-state assumptions. Deviations known from the Venice Lagoon (e.g., lower MEZ assimilation when predators are unmodelled; elevated PHP mortality) are treated as structural consequences that process-mining diagnostics make visible at event level. This study uses previously published trophic structures and literature-based parameter ranges; no human or animal subjects are involved.

Ethical approval and registration: This computational study used previously published trophic structures and literature-based parameter ranges; no human or animal subjects were involved. Ethical approval and informed consent were not required. Registration: not registered (non-clinical research).

Results and Discussion

Petri-net model of the Venice Lagoon trophic network

We first instantiated the trophic network for the Venice Lagoon as a place/transition Petri net in CPN Tools as shown in figure 1, representing ecological compartments as places phytoplankton (PHP), bacterioplankton (BPL), microzooplankton (MIZ), mesozooplankton (MEZ), Ruditapes philippinarum (TAP), and detritus (DET)—and processes (e.g., ingestion /

consumption, assimilation, respiration, mortality, detrital routing) as transitions. Arc weights encode flow multiplicities, and the initial marking reflects literature-consistent steady-state constraints for throughput, assimilation, respiration, and mortality. This model provides the structural scaffold for event-log generation and subsequent process-mining diagnostics. Places (circles) represent compartments (DET, PHP, BPL, MIZ, MEZ, TAP); transitions (rectangles) represent processes (consumption, assimilation, respiration, mortality, detrital routing); arc weights encode flow multiplicities; initial tokens specify the starting marking. Built in CPN Tools.

The explicit mapping of compartments to places and processes to transitions enables token-based interpretation of biomass/energy transfer. In the ecological reading, token movement along consumption and assimilation transitions reflects the uptake and internalization of biomass, while respiration and mortality transitions redistribute tokens to external sinks or the detrital pool. This structural clarity is essential for analyzing where stage-wise compensation occurs and where bottlenecks emerge.

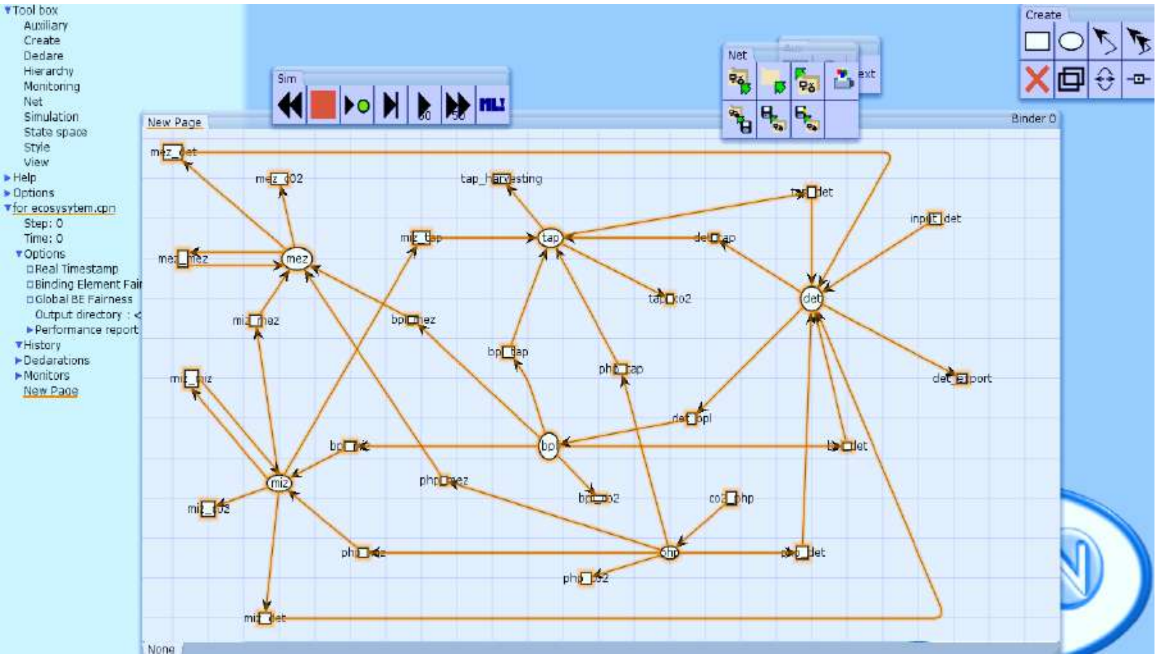


Figure 2. Coloured Petri Net of the Venice Lagoon trophic system.

Event-log characteristics and case structure

To analyze stage-wise behaviour, we executed the Petri net using a Process Log Generator (PLG) to create synthetic event logs. Each trace (case) records a realization of trophic activity across the network; each event corresponds to a transition execution with timestamps and case identifiers. We generated 1,000 cases as shown in figure 3 to support the discovery of dominant control-flow patterns and assessment of variability consistent with literature constraints for the Venice Lagoon network.

Key data

Processes 1
Cases 1000
Events 9525
Event classes 26
Event types 1
Originators 1

Events per case

Min 4
Mean 10
Max 22

Event classes per case

Min 4
Mean 7
Max 14

Log info

Start date
Wed Dec 31 16:00:00 PST 1969
End date
Thu Jan 01 11:00:00 PST 1970

Figure 3. Case set overview $(n = 1{,}000)$ in ProM.

Summary statistics include trace counts, average/median events per trace, and start/complete timestamps; intended to support control-flow discovery and diagnostics. Across the 1,000 traces, we observed stable coverage of the core trophic processes with expected concurrency and looping (notably, repeated detrital routing). The spread in trace lengths reflects natural variability in repeated assimilation-respiration cycles. These properties provide sufficient support for control-flow discovery and conformance diagnostics without overfitting to rare patterns.

Dominant classes correspond to consumption/assimilation at lower trophic levels (DET, PHP, BPL) feeding higher-level processes (MIZ, MEZ, TAP), with respiration and mortality forming recurrent sinks as shown in figure 4. The event-class distribution confirms the ecological expectation that lower-trophic compartments dominate inflows. High frequency of consumption and assimilation at PHP and BPL, coupled with repeated detrital routing, is consistent with the literature-reported grouping: higher throughput at lower trophic levels and lower throughput at higher levels (TAP, MIZ, MEZ). Deviations such as lower MEZ assimilation are investigated next via discovery and performance diagnostics.

Instances
case_934
case_87
case_891
case_789
case_657
case_842
case_593
case_998
case_483
case_345
case_595
case_395
case_905
case_527
case_451
case_882
case_624
case_938
case_825
case_953
case_98
case_542
case_602
case_635
case_776
case_816
case_714
case_822
case_981

case_934
8 events
input_det
#1
31.12.1969 16:00:00.000
co2_php
#2
31.12.1969 16:00:00.000
det_tap
#3
31.12.1969 17:00:00.000
co2_php
#4
31.12.1969 17:00:00.000
tap_harvesting
#5
31.12.1969 18:00:00.000
co2_php
#6
31.12.1969 18:00:00.000
php_tap
#7
31.12.1969 19:00:00.000
tap_harvesting
#8

Attributes for case case_934
LITERAL TYPED
conceptname: case_934

Figure 4. Event-class distribution by case.

Log Summary

Total number of process instances: **1000**
Total number of events: **9525**

Figure 5. Log summary dashboard (ProM).

The log summary shows balanced coverage of core transitions without single-activity dominance that would compromise discovery as shown in figure 5. Duration statistics (where recorded) indicate slower segments aligned with respiration/mortality and with resource-dependent transitions at higher trophic levels, foreshadowing the bottlenecks identified by token-based replay.

Discovered control-flow models

We applied the α-algorithm to recover a workflow net describing the causal skeleton of the process. While $\alpha-miner$ can be sensitive to noise, it provides an interpretable baseline showing essential ordering relations among consumption, assimilation, respiration, mortality, and detrital routing.

Alpha Miner
S.J. van Zelst, B.F. van Dongen, L.M.A. Tonnaer (s.j.v.zelst@tue.nl)

Animate Event Log in Fuzzy Instance
H. Verbeek (h.m.w.verbeek@tue.nl)
Fuzzy

Conformance Checking of DPN
F. Mannhardt, M. de Looni (f.mannhardt@tue.nl, m.d.looni@tue.nl)
DataAwareReplayer

Conformance Checking of DPN

lpha Miner
uthor: S.J. van Zelst, B.F. van Dongen, L.M.A. Tonnaer
ategories: Discovery

The Alpha Miner Plugin implements a collection of algorithms, all belonging to the "Alpha Family". All algorithms take an event log as an input and result in a Petri net with an initial marking. The algorithms are based on the following papers:
- Alpha (Classic): "Workflow Mining: Discovery Process Models from Event Logs": Aalst, W.M.P. van der, Weijters, A.J.M.M., and Maruster, L.
- Alpha+: "Process Mining for Ubiquitous Mobile Systems: An Overview and a Concrete Algorithm", Medeiros, A.K.A. de, Dongen, B.F. van, Aalst, W.M.P. van der, and Weijters, A.J.M.M.

Figure 6. Control-flow model discovered with the α-algorithm.

The $\alpha - miner$ model shows the canonical sequence from consumption to assimilation, diverging into respiration and mortality with feedback into detritus. Parallelism reflects simultaneous processing in different compartments. Given ecological variability, we complemented $\alpha - miner$ with inductive mining for a robust, block-structured view as shown in Figure 6.

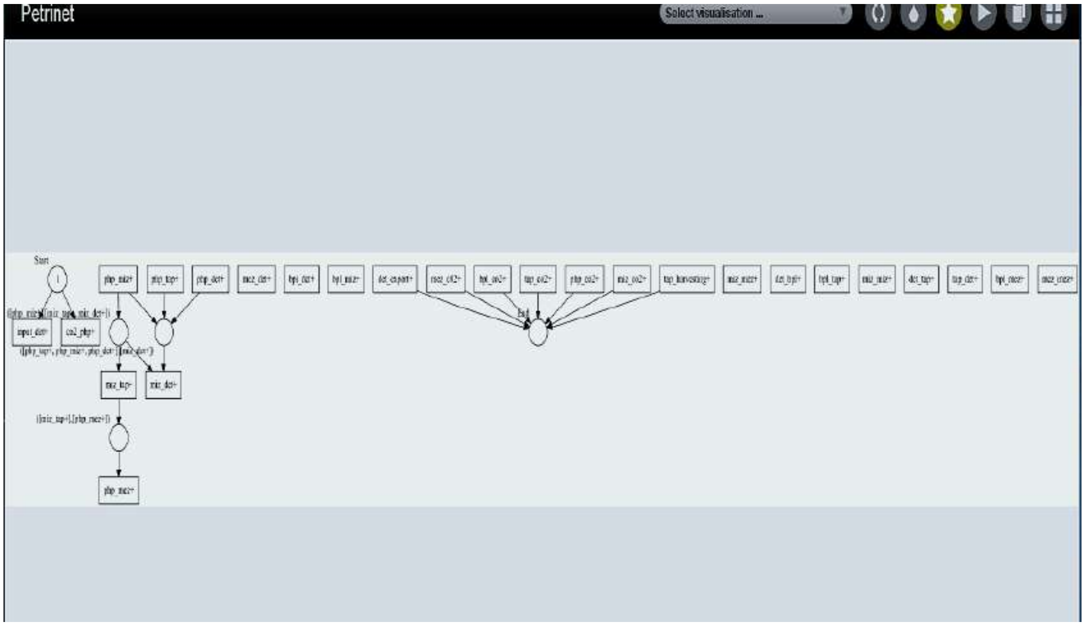


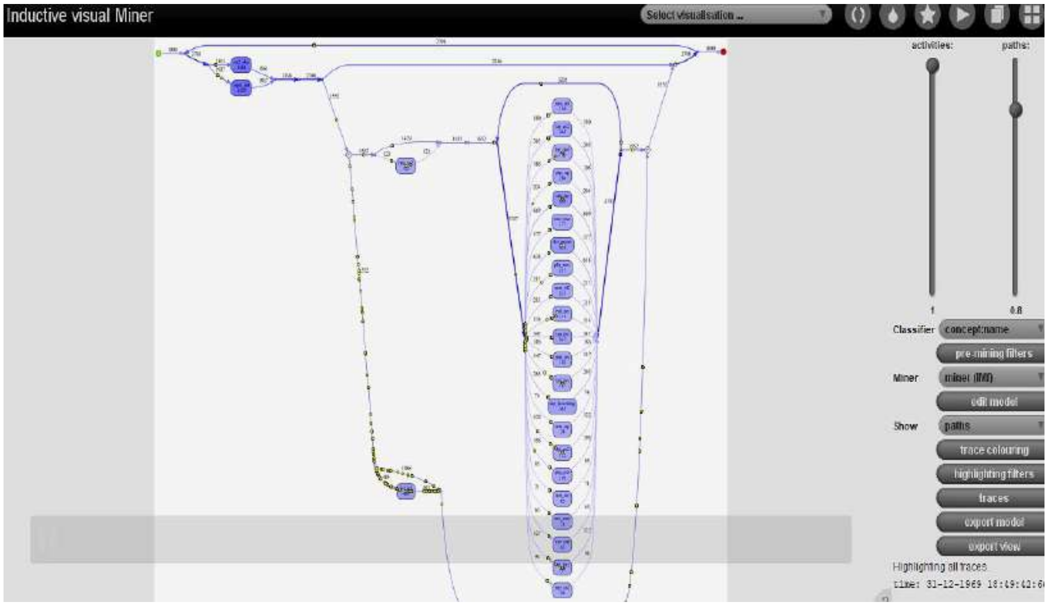
Figure 7. Inductive miner model and event footprint.

The inductive miner as shown in figure 7 retains the core pathways while clarifying split/join structure and loops, enabling more reliable token-based replay. The activity footprint highlights strong follows relations from lower-trophic consumption/assimilation to higher-trophic processes, with respiration/mortality forming terminal branches.

Performance and conformance diagnostics (token movement)

Token-based replay on the inductive model exposes slow or obstructed segments that align with resource constraints or structural assumptions.

Ecologically, these appear where predator-mediated inflows are weak (e.g., MEZ without predators) or where grazing on PHP is under-represented, producing low respiration but elevated mortality and detrital accumulation. Performance traces in figure 8 show that when predator links to MEZ are absent, tokens accumulate upstream, depressing MEZ assimilation towards its lower bound while increasing detrital routing. Conversely, adding predation in scenario runs rebalances flows, raising MEZ assimilation towards values typical of TAP/MIZ as reported in the literature—illustrating how small structural changes can propagate system-wide.



Classifier concept:name
Miner miner (IMf)
Show paths
Highlighting all traces
time: 31-12-1969 18:49:42:6

Figure 8. Token-based replay: movement and delays.

Abstraction of dominant pathways (fuzzy miner)

To emphasize dominant behaviour, we applied the fuzzy miner. Significance–

correlation weighting collapses peripheral segments and retains high-throughput routes. This aids in discerning the minimal set of pathways governing system vitality and in distinguishing compensatory detrital loops from primary trophic transfers, as shown in figure 9. The abstraction highlights consumption → assimilation → (respiration | mortality) as the central backbone, with detritus serving as a recurrent compensatory sink. Lower significance on certain higher-trophic branches corresponds to the limited inflows under predator scarcity, consistent with earlier performance findings.

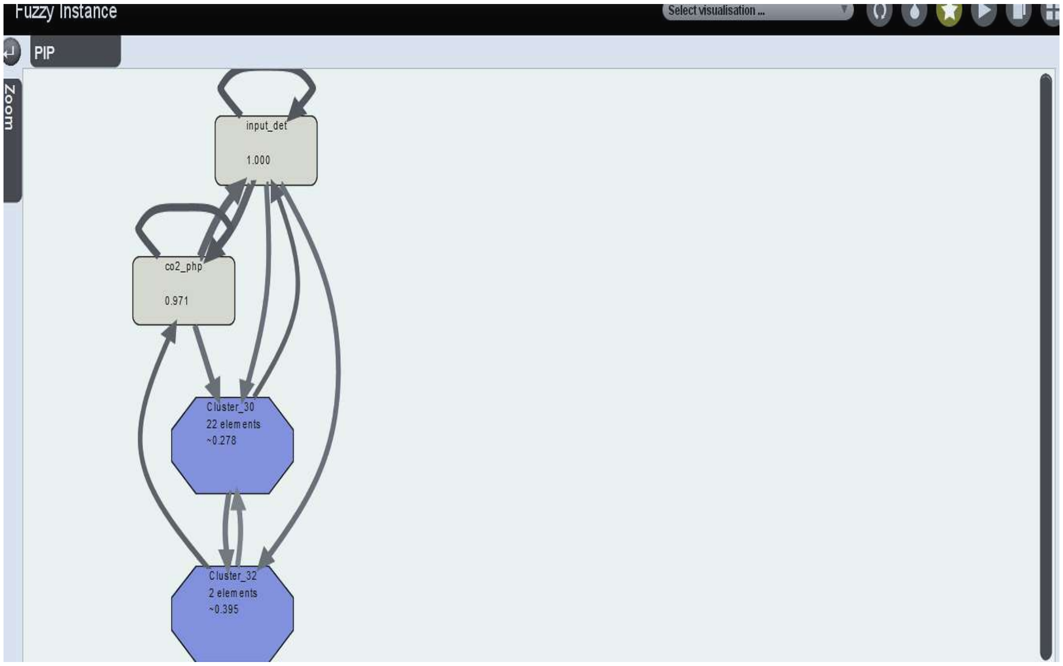


Figure 9. Fuzzy miner abstraction of the trophic process.

Parameter-focused modelling of respiration, assimilation, and mortality

To make parameter dependencies explicit, we constructed a focused Petri-net view for respiration, assimilation, and mortality across compartments, using consumption rate as the driver for event-log synthesis (values derived from the Venice Lagoon literature ranges). This complements the whole-network models by foregrounding the three processes central to ecological vitality.

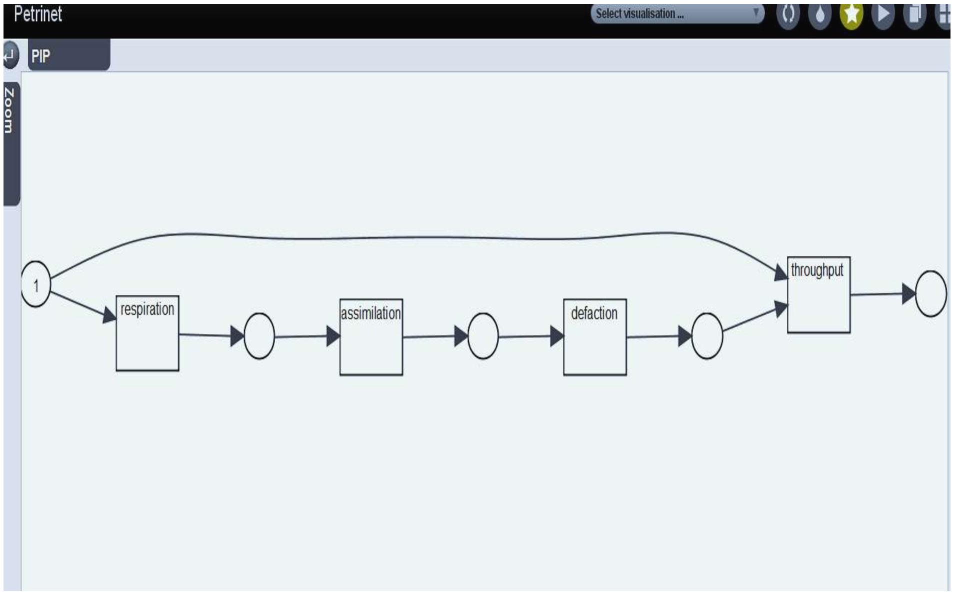


Figure 10. Petri-net view emphasizing respiration, assimilation, and mortality.

Process-focused as shown in figure 10 net highlighting process-specific transitions per compartment; used to generate targeted event logs for parameter-level mining. The parameter-focused view supports direct comparison with literature-based expectations. As summarized in Table 2, TAP respiration (∼36%) and assimilation (∼73%) lie within or slightly above reported ranges; MEZ assimilation (∼39%) trends low in the predator-free structure; MIZ assimilation (∼78%) lies near the upper range; PHP respiration is low (∼2%) with comparatively high mortality (∼22%), and BPL respiration (∼17%) is just below common thresholds—patterns consistent with earlier ecological analyses of the Venice Lagoon.

Table 2 consolidates literature ranges and model-comparable values for each compartment (TAP, MEZ, MIZ, BPL, PHP, DET). These values contextualize the process-mining results, showing where event-level behaviour aligns with, or departs from, prior steady-state inferences.

Table 2. Literature values and measured values for the continuous Petri net model of the case study

Compartment	Throughput	Literature values	Model values
TAP	41	Respiration>=20%(Ezparza & Nielsen, 1994) 37%<=assimilation<=70%(Ezparza & Nielsen, 1994)	Respiration=36% Assimilation=73% Mortality=27%
MEZ	28	Respiration>=20%(Reinthaler et al., 2005) 40%<=assimilation<=80%(Vezina & Pace, 2011), (Baldan et al., 2018)	Respiration=37% Assimilation=39% Mortality=61%
MIZ	37	Respiration>=20%(Reinthaler et al., 2005) 40%<=assimilation<=80% (Vezina & Pace, 2011), (Baldan et al., 2018)	Respiration=14% Assimilation=78% Mortality=22%
BPL	41	Respiration>=20% assimilation=consumption(Reinthaler et al., 2005), (Van Der Aalst et al., 2004)	Respiration=17% Assimilation=consumption Mortality=2,4%
PHP	49	10%<=Respiration>=30% assimilation=consumption(Vezina & Pace, 2011)	Respiration=2% Assimilation=consumption Mortality=22%
DET	58	Not relevant	Not relevant

Limitations

This work employs a computational representation of the Venice Lagoon ecosystem and synthetic event logs derived from literature-based fluxes. While this enables precise interrogation of stage-wise behaviour, it inherits assumptions embedded in the trophic structure (e.g. simplified predator–prey links) and in parameter ranges compiled from heterogeneous sources. Event-log generation reflects these structural choices and may under-represent rare or context-specific interactions. The analysis focuses on respiration, assimilation and mortality and does not incorporate exogenous drivers (e.g. temperature, salinity or contaminant pulses). Consequently, findings should be interpreted as process-level diagnostics consistent with published ranges rather than as direct measurements. Future work could relax structural assumptions, integrate observed time series and evaluate robustness under alternative parameterisations.

Conclusion

This study introduces a Petri net–based computational framework, integrated with process mining, to analyze stage-wise ecological processes in the Venice Lagoon trophic network. By coupling structural representation (places as compartments; transitions as processes) with event-level inference (discovery, abstraction, and token-based diagnostics), the framework reveals how respiration, assimilation, and mortality interact across compartments and how local perturbations propagate through cooperative pathways. The results confirm the established pattern of higher throughput in lower-trophic compartments (DET, PHP, BPL) relative to higher-trophic compartments (TAP, MIZ, MEZ) and show that deviations from literature ranges—for example, low MEZ assimilation under predator scarcity and elevated PHP mortality in the absence of grazers—can be traced to identifiable structural features. Event-level diagnostics illuminate where compensations maintain function and where slow or obstructed segments indicate potential instability, thereby clarifying conditions under which energy flows converge toward or diverge from stability. In doing so, the framework complements steady-state trophic analyses by making the temporal vitality of processes observable, interpretable, and comparable against literature anchors. The approach provides a rigorous, generalizable basis for ecosystem diagnosis, supporting conservation decisions that depend on balanced energy flows and predator–prey relations.

Declarations

Funding

The authors received no specific funding for this work.

Conflicts of interest

The authors declare no competing interests.

Ethics approval

Not applicable. This computational study uses previously published trophic structures and synthetic event logs; no human or animal subjects were involved.

Registration

Not registered (non-clinical computational research).

Data availability

PLG-generated event logs and ProM configuration files supporting the findings are provided in the Supplementary Materials or available from the corresponding author on reasonable request. Source trophic structures are drawn from the published Venice Lagoon literature cited herein.

Acknowledgments

We thank the developer communities of CPN Tools and ProM for software that enabled model editing, simulation, and process mining.

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