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# Use of timed automata and model-checking to explore scenarios on ecosystem models

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ABSTRACT

The interest to build ecosystem models is well acknowledged in order to improve the understanding of the sophisticated linkages between humans and natural species embedded within variable local and global environmental contexts. It is especially true when a complex temporal evolution intervenes as in population regulations. Ecological modellers usually resort to numerical models supported by accurate data and extensive knowledge on biological processes. Unfortunately, the task becomes more difficult to model ecosystems with limited data and knowledge. Qualitative models may be more suitable for designing data-poor systems in a decision-aid context. We propose a new qualitative approach for ecosystem modelling based on timed automata (TA) formalism combined with a high-level query language for exploring scenarios. TA rely on a discrete-event system formalism to reproduce the temporal dynamics of a system. Combined with model-checking techniques, TA enable the exploration of system properties in response to a wide range of scenarios based on a temporal logic. Our applicative case concerns the evolution of different fish biomass along time according to fishing policies, especially when exogenous environmental issues may also be considered. We have developed this approach to model a simplified marine ecosystem subject to different fishing policies. Using predefined query patterns, we show that TA and model-checking are relevant tools to query timed properties of a fishery system in response to different management options. This modelling approach may be especially useful for fostering better discussion among all stakeholders involved in fisheries management.


## 1. Introduction

Ecosystem simulation models are useful for assessing critical system properties in response to various management options in which time remains a key element but difficult to consider. As noted by Rykiel (1989), ecological modellers typically use mathematical equations to build numerical models to express such systems; yet, they look well-suited when appropriate data and knowledge are available. Unfortunately, in the case of many marine ecosystems, their representation suffers from a lack of data and knowledge. Furthermore, real data on all species are difficult to get and their interactions remain insufficiently known to be expressed through mathematical equations. Ecological interactions and feedbacks are often too complex to be tackled by the simple use of quantitative approaches, which impedes policy and decision making in the context of ecosystem management.

In contrast, qualitative modelling (Kuipers, 1994; Weld and de Kleer, 1989) offers a good alternative to model complex and large systems in a poor data context. This approach allows to represent a system under an abstracted way. Indeed, the different states of a system are simply represented by a list of qualitative attributes corresponding to a range of possible values, either numeric or symbolic. The change from one state to another is operated by some qualitative events that are assumed to drive or modify the behaviour of the system. This abstracted representation of complex processes constitutes the central idea of qualitative reasoning. According to Travé-Massuyès et al. (2003), qualitative models rely on solid theoretical foundations and provide a reliable abstraction of real-valued models. Most qualitative models are exploited to simulate a scenario. A user must launch a set of desired simulations with appropriate parameters, and later analyzes the results

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provided. Qualitative approach simulations have been promoted in various biological fields such as biomedical domain (Bellazzi et al., 2001; de Jong et al., 2003; Ironi and Panzeri, 2009), plant physiology (Rickel and Porter, 1997; Vercesi et al., 2010), watershed and stream pollution (Salles et al., 2006; Tullos and Neumann, 2006; Guerrin and Dumas, 2001; Beaujouan et al., 2001; Cordier et al., 2005) or terrestrial ecosystems (Guerrin and Dumas, 2001). In ecology, (Puccia and Levins, 1985) introduced loop analysis to depict trophic webs and to predict responses of community facing perturbations. Loop analysis is today the most common reference in the literature to evaluate the stability of aquatic systems (Dambacher et al., 2002; Dambacher et al., 2003a,b; Montaño-Moctezuma et al., 2007; Metcalf et al., 2010).

In our paper, we focus on qualitative models within decision-aid contexts. Qualitative simulations deal with trends rather than precise output values, which provides a more intuitive interpretation and fit well to resource management. A decision maker who wants to exploit a qualitative simulation model must face two well-known difficulties. The first one is to translate a general problem-oriented query into the design of a set of adequate simulation inputs. The second one is to filter the useful information from a large amount of simulation results (Trajanov, 2010). We argue that combining a high-level qualitative modelling with a powerful query language (i.e. a set of predefined queries used in exploring ecosystem dynamics) can provide an efficient tool in this context.

The main idea that underlies *model-checking* (Clarke et al., 2002) is to verify the behaviour of large transitions-graphs and then check if dynamical properties, expressed as logical statements, are satisfied by the model. Model-checking can be efficiently performed on systems modelled as finite-state automata. Of particular interest for ecosystem management, the modelling formalism that we propose is based on timed automata (TA) approach (Alur and Dill, 1994). As a discrete-event system formalism, this approach suits model system dynamics and allows explicit temporal constraints (Cordier and Largouët, 2001; Helias et al., 2004). In this formalism, the states of the system are described by qualitative attributes and represent either equilibrium states or transient states.

Recent studies have also emphasized the great interest of coupling qualitative model with model-checking techniques. Thus, Shults and Kuipers (1997) propose to use the qualitative simulation tool QSIM to verify properties expressed in the temporal logic CTL* (Clarke et al., 2002). More recent studies applied model-checking for analyzing regulatory networks (Bernota et al., 2004; Batt et al., 2005; Monteiro et al., 2009; Batt et al., 2010). Compared with these works dedicated to the verification of system properties, our approach proposes a new perspective to give temporal predictions of a marine ecosystem facing various perturbations.

The key point of this approach is to provide, without performing any simulation, an efficient way to explore the model. Prediction problems are expressed as statements in temporal logic and the proposed framework invokes a model-checking algorithm to infer the ecosystem behaviour. Since models of ecological systems can induce many possible alternative trajectories, the systematic analysis is often not tractable with limited available resources. Hence, to overcome the state-explosion problem we propose to use *symbolic model-checking* (Burch et al., 1992) as powerful techniques to verify large state-transition graphs. Despite the efficiency of model-checking techniques, writing temporal logic requirements is challenging and reserved to experts (Dwyer et al., 1999). Based on temporal logic, a high-level language expresses some requirements a user wants to verify, in a form that is similar to a database query. Query patterns, i.e. a set of predefined queries, have already been defined for the verification of industrial applications (Dwyer et al., 1999) or biological systems (Monteiro et al., 2008). Up to now, translating scenarios of changing ecosystem in query patterns has not been studied. Here, a scenario means a hypothetical story to help a user to understand possible ecosystem trajectories depending on its dynamics. We propose query patterns corresponding to the main questions that fisheries managers may want to ask. Each pattern can be qualified in terms of reachability or safety properties that can be checked by model-checking. Using these query patterns, model-checking techniques allow to verify ecosystem properties that are in the scope of management purposes. Thus, a user may explore the ecosystem model, starting by an initial query, getting a result, and then entering an interactive process until he gets a better understanding of the system and the possible consequences of the decisions he had in mind.

Our present work aims at introducing TA and model-checking as a potential modelling tool to support decision process in ecosystem management. It is motivated by the current needs in the management of fisheries, especially for small-scale, artisanal fisheries operating in poorly documented ecosystems. For this purpose, we developed an integrated approach allowing to build a qualitative model of ecological interactions that can be explored by the verification of predefined queries that adequately fit usual management questions. In particular, these queries address both predictive (what is going to occur?) and proactive (what must be made to reach or avoid a given situation?) management scenarios. The fundamental principles of TA and model-checking are first illustrated by using a theoretical predator-prey system that can either be disturbed by anthropogenic pressures (fishing) or climatic events. We then present some preliminary results when this modelling approach is applied to a real-case study, a coral-reef fishery in a remote atoll in New Caledonia. Our purpose is to highlight the ability of TA and model-checking techniques to explore a wide array of policy scenarios and to inform stakeholders about the effect of various fishing efforts.

Our paper is structured as follows. Section 2 introduces the theoretical predator–prey system used as an example of the modelling approach. Section 3 provides the basics of the timed automata formalism and model-checking techniques. Section 4 details the qualitative model of the theoretical system. Section 5 focuses on the various types of query patterns that can be processed to address management questions. Section 6 introduces the EcoMata software, an integrated platform for building a TA model of an exploited marine system and for exploring management scenarios through model-checking. Section 7 describes the results of the TA modelling approach on the theoretical system and the coral-reef fishery. Finally, capacities and limitations of this approach are discussed in section 8 along with perspectives and ongoing work.

## 2. A theoretical ecosystem example

A theoretical ecosystem of interacting species under fishing pressure is presented in Fig. 1. This system is made of four fish species (*Species*0 called *SP*0 to *Species*3 called *SP*3), two fishing pressures (*PP*0 and *PP*1) and two environmental disturbances (sudden disaster and long-term warming sea) occurring at different temporal scales.

The species are considered as trophic compartments that exchange biomass flows via predator–prey relationships. The biomass flow from the prey *SP*1 to the predator *SP*0 is labelled by the symbol "*a*" whereas the biomass inflow of *SP*1 is denoted by "*b*". This inflow mostly comes from *SP*2 (indicated by the symbol $++$ in Fig. 1) and to a lesser extent from *SP*3 (symbol $+$). In addition to the trophic structure, two fishing pressures have been included and are applied on *SP*0 (for *PP*0) and *SP*1 (for *PP*1). In this ecosystem, fishing pressures are considered as supra-predators. The environmental disturbances are external events that affect *SP*2 for the disaster (hurricane) and *SP*3 for the warming sea.