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Three Essays on Agent-Based Modelling and Adaptation to Climate Change

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Many times you hear researchers that justify their work saying that they were moved by curiosity: they like to start their lectures with statements, which they believe are funny and intrinsically right, that sound like: "Why I did this? ... Because I'm curious". Well, I believe that people should jump on their seats when they hear such an egoistic and anachronistic motivation.
We, as human race, are now facing, more than ever, the urgency of driving our resources to save our species, and research is one of the most powerful instruments to reach this purpose.
Research must be ethically driven, not at all for the sake of curiosity, but by the aspiration of finding the ways to deal with the complex problems that surround us.
Research must be morally driven by the idea of serving the present and the future generations to let them leave in a healthy and equitable world.
In other words, curiosity is no longer enough.

Three Essays on Agent-Based Modelling and Adaptation to Climate Change

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SHORT ABSTRACT

The dissertation is a collection of three essays. The first essay is a survey of relevant literature that aims at responding to two research questions: (1) is agent-based modelling an appropriate methodology to study adaptation to climate change? and (2) how have some relevant concepts of this methodology been previously treated according to the state of the art? The second essay develops a conceptual agent-based model of the tourism system of an alpine winter destination. It is envisioned for the assessment of alternative and infrastructure-oriented strategies of future local development that are considered to be capable of dealing with possible scenarios of climate change. The third essay concerns the implementation of the conceptual model into a computer simulation software and its analysis, also taking into account the authentication process with the local stakeholders involved.

ESTRATTO

La tesi è una composizione di tre saggi. Il primo saggio è un'analisi della bibliografia principale sui modelli ad agenti che intende rispondere a due domande di ricerca: (1) i modelli ad agenti sono una metodologia adeguata per lo studio dell'adattamento ai cambiamenti climatici? e (2) come sono stati precedentemente trattati alcuni elementi fondamentali di questa metodologia nella letteratura considerata? Il secondo saggio sviluppa un modello concettuale ad agenti che rappresenta il sistema turistico di una destinazione invernale alpina, con lo scopo di considerare strategie di sviluppo turistico alternative che potrebbero essere in grado di far fronte a possibili scenari di cambiamento climatico. Il terzo saggio riguarda l'implementazione del modello concettuale in un software che permette di sviluppare simulazioni al computer. L'analisi dei risultati di queste simulazioni tiene in considerazione l'opinione dei portatori d'interesse coinvolti in una sorta di processo di autenticazione dello strumento utilizzato.

LONG ABSTRACT

There is a growing awareness that global environmental change dynamics and the related socio-economic implications involve a degree of complexity that requires an innovative modelling of combined social and ecological systems (SES).
SES are complex and adaptive systems (CAS) where social (human) and ecological (biophysical) agents are interacting at multiple temporal and spatial scales. CAS are dynamic networks of many agents (which may represent cells, species, individuals, firms, nations) acting in parallel, constantly acting and reacting to the behavior of other agents. Since the study of CAS is an attempt to better understand systems which are difficult to grasp analytically, often the best available way to investigate such them is through computer simulations. When decision are of major importance and hugely permeated by imperfect knowledge and deep uncertainty, an improved understanding of the use models is needed. One way is to move towards exploratory modelling, whereby ensembles of scenarios are used to represent possible futures of the system under study and criteria such as resilience and stability are used to compare the robustness of alternative policies.
Past research on computer science has shown how CAS can be represented by means of multi-agent systems (MAS). MAS is a concept derived from distributed artificial intelligence (DAI), which firstly used it in order to reproduce the knowledge and reasoning of several heterogeneous agents that need to coordinate to jointly solve planning problems. Typically MAS refers to software agents and it is implemented in computer simulations.

Pure MAS, as conceived in DAI, are not fully relevant for modelling SES, which are real systems based on the law of physics and on human social interactions. However, including the fundamental contribution of past research on artificial life, individual-based modelling and social simulations, we are provided with a very promising framework for the innovative modelling of combined SES and policy-making in the context of sustainable development. Although this methodology has assumed many names, we adopted the umbrella term agent-based modelling (ABM) which we regard as any systemic and agent oriented modelling approach that employs computer simulations.
ABM can explicitly represent the sources of social and biophysical complexity accounting for interdependencies, both in space and time, heterogeneity and nested hierarchies among agents and their environment. The main advantages of ABM are found in its abilities to: (a) couple social and environmental systems, linking social and environmental processes; (b) model individual decision-making entities, taking into account the interactions between them and incorporating social processes and non-monetary influences; (c) incorporate the influence of micro-level decision making into the system dynamics, linking these micro-scale decisions to macro-scale phenomena; (d) study the emergence of collective responses to changing environment and policies. Moreover, agent-based models can be constructed and validated in the participatory setting, fostering the process of social learning and, while integrating factual and local knowledge, they can provide assistance for specific decision making.
Since recently, ABM has been increasingly combined with empirical methods. This study is conceived to follow this stream of research, applying an agent-based approach to the analysis of adaptation to climate change and sustainable development in a local and case-specific context: a winter tourism destination in the Alpine Region.

The thesis is divided in three papers. In the first paper a quite comprehensive review of past applications of this methodology to similar issues is performed. In the second paper the conceptual model is presented with particular attention to its methodological development. In the third paper the implemented version of the model is analyzed.

The Alpine Region in Europe is among the areas that are most rapidly affected by climate change. In general, the mean temperature of this region has increased up to +2°C for some high altitude sites over the 1900-1990 period against +0.78°C in the last 100 years at a global level. With a certain degree of local variability, glaciers have lost 50% of their volume since 1850 and snow cover is decreasing especially at the lowest altitudes and in fall and spring. A clear signal of climate change about precipitations is not detectable yet, but increasing risks of extreme events have been projected including floods, debris flows, avalanches, glacial hazards, and mountain mass movements. The main expected impacts on the Alps concern the hydrological conditions and water management, forests and biodiversity, agriculture, energy management, and eventually tourism, which is the focus of this paper. While summer tourism is most probably going to be favored by climate change, the World Tourism Organization started warning about the possible negative implications for winter tourism and sports since 2003. Nowadays already 57 of the main 666 ski resorts of the European Alps are considered to not be snow-reliable. However, climate change is also an opportunity for those resorts that are snow-reliable, as they will face less competition in the future.

AuronzoWinSim is a conceptual model included in a European research effort that considers the possible impacts of climate change on tourism in the Alps. The ClimAlpTour project, which is under the EC Alpine Space Programme, brings together institutions and scholars from the Alpine arch to analyze multiple pilot sites and to produce a framework of joint recommendations in view of comprehensively dealing with this crucial issue. The all AuronzoWinSim idea has been conceived as an exploratory and case-specific application of a spatially explicit agent-based model (ABM), capable of gathering heterogeneous but incomplete information, to produce computer simulations about possible futures, and discuss them with local stakeholders. The model is an original concept in the sense that, to our knowledge, this is the very first application of agent-based modelling to investigate adaptation to climate change of winter tourism at a local level. The model, which has been firstly developed in unified modelling language (UML), is meant to be fully tailored on the case study, the municipality of Auronzo di Cadore, located in the Dolomites. However, it has the potential to be generalized and eventually become an ontology of a generic winter tourism destination, especially for what concerns its conceptual structure in classes.

AuronzoWinSim 1.0 is the software application deriving from the conceptual model which has ultimately been programmed in the NetLogo 4.1 modelling environment. AuronzoWinSim 1.0 is an agent-based tool capable of producing simulated data about relevant socio-economic indicators, linked to environmental implications, of the tourism system of Auronzo di Cadore. These have been used to assess alternative tourism development strategies across scenarios of climate, society and competition for the period 2011-2050. Results show that investing on the dimensions of winter tourism that are detached form the activities based on snow seems like the safest way to proceed for a destination with the characteristics of Auronzo di Cadore.

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INTRODUCTION TO THE DISSERTATION

Agent-based models (ABM) can explicitly represent the sources of social and biophysical complexity accounting for interdependencies, both in space and time, heterogeneity and nested hierarchies among agents and their environment. The main advantages of ABM are found in its abilities to: (a) couple social and environmental systems, linking social and environmental processes; (b) model individual decision-making entities, taking into account the interactions between them and incorporating social processes and non-monetary influences; (c) incorporate the influence of micro-level decision making into the system dynamics, linking these micro-scale decisions to macro-scale phenomena; (d) study the emergence of collective responses to changing environment and policies. Moreover, agent-based models can be constructed and validated in the participatory setting, fostering the process of social learning and, while integrating factual and local knowledge, they can provide assistance for specific decision making.
Since recently, ABM has been increasingly combined with empirical methods. This study is conceived to follow this stream of research, applying an agent-based approach to the analysis of adaptation to climate change and sustainable development in a local and case-specific context: a winter tourism destination in the Alpine Region.

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AuronzoWinSim is a conceptual model included in a European research effort that considers the possible impacts of climate change on tourism in the Alps. The ClimAlpTour project, which is under the EC Alpine Space Programme, brings together institutions and scholars from the Alpine arch to analyze multiple pilot sites and to produce a framework of joint recommendations in view of comprehensively dealing with this crucial issue. As a matter of fact, climate change is already significantly affecting the European Alpine Region beyond the average temperature signals that have been registered at a global level. The all AuronzoWinSim idea has been conceived as an exploratory and case-specific application of a spatially explicit agent-based model (ABM), capable of gathering heterogeneous but incomplete information, to produce computer simulations about possible futures, and discuss them with local stakeholders. The model is an original concept in the sense that, to our knowledge, this is the very first application of agent-based modelling to investigate adaptation to climate change of winter tourism at a local level. The model, which has been firstly developed in unified modelling language (UML), is meant to be fully tailored on the case study, the municipality of Auronzo di Cadore, located in the Dolomites.

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REVIEWING AGENT-BASED MODELLING OF SOCIO-ECOSYSTEMS: A METHODOLOGY FOR THE ANALYSIS OF CLIMATE CHANGE ADAPTATION AND SUSTAINABILITY[1]

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Abstract

The integrated - environmental, economic and social - analysis of climate change calls for a paradigm shift as it is fundamentally a problem of complex, bottom-up and multi-agent human behavior. There is a growing awareness that global environmental change dynamics and the related socio-economic implications involve a degree of complexity that requires an innovative modelling of combined social and ecological systems. Climate change policy can no longer be addressed separately from a broader context of adaptation and sustainability strategies. A vast body of literature on agent-based modelling (ABM) shows its potential to couple social and environmental models, to incorporate the influence of micro-level decision making in the system dynamics and to study the emergence of collective responses to policies. However, there are few publications which concretely apply this methodology to the study of climate change related issues. The analysis of the state of the art reported in this paper supports the idea that today ABM is an appropriate methodology for the bottom-up exploration of climate policies, especially because it can take into account adaptive behavior and heterogeneity of the system's components.

Keywords

Review, Agent-Based Modelling, Socio-Ecosystems, Climate Change, Adaptation, Complexity

[1] A shorter version of this essay is published in the International Journal of Agent Technologies and Systems (IJATS) 2, no. 4: 17-38, October – December 2010.

1. INTRODUCTION

1.1 Global change and complex systems

There is an increasing awareness that global change dynamics and the related socio-economic implications involve a degree of complexity which is not captured by traditional economic approaches that employ equilibrium models. In particular, such a top down analysis of the human-environment system doesn't consider the emergence of social behavioral patterns. This eventually leads to a flawed policy making process which relies on unrealistic assumptions (Moss, Pahl-Wostl, and Downing 2001). Yet, the ultimate source of anthropogenic climate change is the agency of human individuals grouped in social networks and their interaction. At the same time, the responses to climate change, in terms of mitigation of greenhouse gases emissions and in terms of adaptation to climatic variability and slow changes in mean conditions, have to be found in human behavior.
In our global system where human activities prevail and endlessly modify the environment, climate change is providing the chance to concretely understand how the environment responds, suggesting a change in human behavior, both at a local and global level. Climate change can no longer be addressed separately from a broader context of systemic sustainability and adaptation strategies.

The endogenous feedbacks between socio-economic and biophysical processes and the co-evolution of the human-environment system are precisely those kind of dynamics included in the notion of social-ecological systems, or socio-ecosystems (SES). SES are complex and adaptive systems where social (human) and ecological (biophysical) agents are interacting at multiple temporal and spatial scales (Rammel, Stagl, and Wilfing 2007). This definition emphasizes the adoption of a single integrated approach for the analysis of both social and economical agents and the natural components of the ecosystem. It postulates the fact that SES are non decomposable systems, because they emerge from the dynamic interplay between the social and ecological components. SES show specific properties such as: (a) non linear dynamics, alternate regimes and thresholds; (b) adaptive cycles; (c) multiple scales and cross scale effects, (d) adaptive capacity and transformability (Gunderson and Holling 2002).

Given such properties SES have to be considered as complex and adaptive systems (CAS). CAS are dynamic networks of many agents (which may represent cells, species, individuals, firms, nations) acting in parallel, constantly acting and reacting to the behavior of other agents. The control of a CAS tend to be highly dispersed and decentralized. If there is to be any coherent behavior in the system, it has to arise from competition and cooperation among the agents themselves. The overall behavior of the system is the result of a large number of decisions made every moment by many individual agents (Waldrop 1992).
CAS display an ever changing dynamic equilibrium, which fluctuates between chaotic and ordered states. On the edge of chaos, these systems are very sensitive to any perturbation from the individual components (Holland 1992). CAS are inherently unpredictable as a whole: “their futures are not determined and their global behaviors emerge from their local interactions in complex, historically contingent and unpredictable ways” (Bradbury 2002).

Since the study of CAS is an attempt to better understand systems which are difficult to grasp analytically, often the best available way to investigate such them is through computer simulations (Gilbert and Troitzsch 1999). As a matter of fact, when dealing with CAS, one has to cope with uncertainty (Perez and Batten 2006). When decision are of major importance and hugely permeated by imperfect knowledge and deep uncertainty, an improved understanding of the use models is needed (Funtowicz and Ravetz 1995). One way is to move towards exploratory modelling, whereby ensembles of scenarios are used to represent possible futures of the system under study and criteria such as resilience and stability are used to compare the robustness of alternative policies (Lempert 2002).

1.2 Introducing agent-based thinking

Past research on computer science (e.g. Wooldridge and Jennings 1995; Ferber 1999; Huhns and Stephens 1999; Weiss 1999) has shown how CAS can be represented by means of multi-agent systems (MAS). MAS is a concept derived from distributed artificial intelligence (DAI), which firstly used it in order to reproduce the knowledge and reasoning of several heterogeneous agents that need to coordinate to jointly solve planning problems. Typically MAS refers to software agents and is implemented in computer simulations.

According to the DAI derived definition of Ferber (1999) a MAS is a system composed with the following elements:

1. an environment (E), often possessing explicit metrics;
2. a set of passive, located objects (O). These objects can be located, created, destroyed or modified by the agents;
3. a set of active agents (A). Agents are particular objects that constitute the active entities of the system;
4. a set of relationships (R) linking objects and/or agents together;
5. a set of operators (Op) allowing the agents to perceive, create, use, manipulate or modify the objects.

Agents are virtual entities that demonstrate: (i) autonomous actions within their environment, (ii) communication with other agents, (iii) limited perception of their environment, (iv) bounded representation of their environment (if any) and (v) decision making process based on satisfying goals and incoming information (Ferber 1999).

Pure MAS, as conceived in DAI, are not fully relevant for modelling SES, which are real systems based on the law of physics and on human social interactions. However, including the fundamental contribution of past research on artificial life (AL) (e.g. Reynolds 1987; Holland 1992; Langton 1992); individual-based modelling (IBM) (e.g. Huston et al. 1988; Grimm 1999) and social simulations (e.g. Schelling 1978; Axelrod and Hamilton 1981; Epstein and Axtell 1996), we are provided with a very promising framework for the innovative modelling of combined SES and policy-making in the context of sustainable development (Boulanger and Bréchet 2005).

Although this methodology has assumed many names, we adopted the umbrella term agent-based modelling (ABM) which we regard as any systemic and agent oriented modelling approach that employs computer simulations.

ABM can explicitly represent the sources of social and biophysical complexity accounting for interdependencies, both in space and time, heterogeneity and nested hierarchies among agents and their environment (Parker et al. 2003).

The main advantages of ABM are found in its abilities to: (a) couple social and environmental systems, linking social and environmental processes; (b) model individual decision-making entities, taking into account the interactions between them and incorporating social processes and non-monetary influences; (c) incorporate the influence of micro-level decision making into the system dynamics, linking these micro-scale decisions to macro-scale phenomena; (d) study the emergence of collective responses to changing environment and policies (Hare and Deadman 2004; Matthews

et al. 2007).
Moreover, agent-based models can be constructed and validated in the participatory setting, fostering the process of social learning and, while integrating factual and local knowledge, they can provide assistance for specific decision making (Barreteau, Bousquet, and Attonaty 2001; Guyot and Honiden 2006; Pahl-Wostl 2007).

1.3 Further expansion of ABM

To date, ABM has been used to reformulate some main issues of social and natural science (Bousquet and Le Page 2004). In fact, there exists a consistent body of work on ABM in sociology and social processes (e.g. Conte et al. 2001; Macy and Willer 2002; Gilbert and Troitzsch 1999), economics and finance (e.g. LeBaron 2000; Tesfatsion 2002) and in a set of environmental issues including land use and cover change (e.g. Parker et al. 2003; Veldkamp and Verburg 2004) ecology and natural resource management (e.g. Lansing and Kremer 1993; Bousquet and Le Page 2004), agriculture (e.g. Balmann 1997; Berger 2001), urban planning (e.g. Torrens and O Sullivan 2001; Batty 2005), and archaeology (e.g. Kohler and Gumerman 1999). Altogether these various applications constitute the rich breeding ground for moving towards a new approach to the analysis of climate change issues.

However, there are limited useful publications on ABM in the arena of climate change. Some of them stand a very epistemological level stating the usefulness of the methodology without applying it (e.g. Moss, Pahl-Wostl, and Downing 2001; Patt and Siebenhüner 2005). Few applications explicitly aim at analysing climate change at a theoretical level (e.g. Janssen and de Vries 1998) or at a more empirical level (e.g. Bharwani et al. 2005; Ziervogel et al. 2005; Berman et al. 2004; Werner and McNamara 2007; Barthel et al. 2008; Entwisle et al. 2008). In contrast, there are several ABM applications which generically include climate change elements in their system modelling (e.g. Dean et al. 1999; Barthel et al. 2008; Hasselmann 2008; Filatova 2009; Mandel et al. 2009; Beckenbach and Briegel 2009). Such a few available publications are evidence of an immature area of research. This field of application, only recently, started to rapidly develop, with many research project forthcoming[2], with potential publications in the future.

The justification of this late development can be found in the intrinsic characteristics of the methodology.
Given ABM ability to capture complexity and represent detail, the model has to be built at the right level of description, with just the right amount of detail to serve its purpose. Therefore, the purpose has to be clearly stated in order to try hard to limit the model complexity. The reason is that, as computer models are less constrained technically, their design can still be too complex compared to classical models (Grimm and Railsback 2005). General purpose models aiming at representing a system rather than a problem, which are common in the climate change arena, cannot work.
Moreover, ABM may face challenges of parametrization and validation (Parker et al. 2001). This is particularly evident when one desires to build an empirically grounded model. ABM involves soft factors, difficult to quantify, calibrate and sometimes justify (Bonabeau 2002). Assumptions necessary for statistical verification and validation, such as normality and linearity can be at odds with models designed to accommodate complex behaviors caused by sensitivity to initial conditions, self-organized criticality, path dependency and non linearities (Arthur 1990; Manson

[2] For instance at Global Cities Institute of RMIT University and CSIRO in Australia, University of Hohenheim, in Germany, Tyndal Centre in UK, Natural Resources Canada, etc.

2001; Perez and Batten 2006).
Also the communication phase is more difficult, because the model has to be described in words, other than the universal language of mathematics, and this turns very often to be less efficient (Grimm et al. 2006).
Finally, ABM is not well suited to make quantitative deterministic predictions about how a system will function in the future, or about how to make the system function better in the future, which seems like the issue for the mainstream climate change economics devoted to top-down "hard science". The outcome of a simulation should be interpreted at a more qualitative level, depending on the degree of accuracy and completeness in the input to the model (Bonabeau 2002).
ABM has, to date, had limited impact in policy making, because it has been predominantly used in deterministic rather than exploratory mode, while it should be used in conditions of deep uncertainty, where there is no agreement between stakeholders on correct decisions (Lempert 2002).
Eventually, ABM is object of renewed interested, fuelled by the recent developments on uncertainty analysis applied to climate change (Barker 2008; Weitzman 2009).

The analysis of climate change calls for a paradigm shift (Bousquet and Le Page 2004; Martens 2006; Voinov 2008) as it is fundamentally a problem of complex, bottom-up and multi-agent human behavior, which involves the entire socio-ecosystem.
This paper aims at integrating the existent know-how on ABM from different scientific communities in order to clarify whether or not this could be an appropriate methodology for modelling the dynamics of SES exposed to climate change and assessing the related policies within the context of adaptation and sustainability.
In the second section we define some core notions of ABM, we clarify the terminology in use, and briefly describe the main scientific domains and research communities applying this methodology. We approach the different domains making reference to the three fundamental dimensions of sustainability identified by the social, the economic and the environmental systems.
We than go deeper into the subject by elucidating how the concepts of agent, environment, emergence, interaction, heterogeneity, space and time, behavior and validation are treated, including the computing languages, tools and platforms used for the simulations. We reviewed those applications that, in our opinion, better fit the idea of modelling SES and include climate change related elements.
In the fourth section we conclude discussing the main results.

2. ABM AND COMPLEXITY IN THE THREE SPHERES OF SUSTAINABILITY

2.1 ABM and the dimensions of complexity

Nowadays ABM constitutes a broad and interdisciplinary movement. Different terms are used to define subtly different approaches to ABM: agent-based simulation modelling (e.g. Berman et al. 2004), individual-based modelling (e.g. Grimm and Railsback 2005), multi-agent-based simulation (e.g. Perez and Batten 2006), agent-based social simulation (e.g. Gilbert 2004), multi-agent simulation (e.g. Bousquet and Le Page 2004), multi-actor modelling (e.g. Barthel et al. 2008), etc. According to Hare and Deadman (2004) a key difference, which justifies this terminological diversity, stands in the complexity of the interactions to be modelled. When emphasis is placed on modelling interactions, and agents can be simplistic, the AL and ecological roots of ABM prevail. When interactions spawn from the deliberations of the agents and the deliberative social cognition is most important, then the DAI roots are prevalent.
In general there are three types of interaction: direct interaction among agents, which can be physical (grow, push, eat) or by communication, and interactions mediated by the environment (Bousquet and Le Page 2004). By means of interactions, interdependencies exist among agents and their environment, across time and across space.

In the following paragraphs we argue that there are more sources of complexity, which also influence the terminology in use.
Heterogeneity is another major source of complexity. ABM can consider heterogeneous system's components situated in dedicated heterogeneous spaces. Agents' diversity may depend on their experience, values, abilities and resources but also on their spatial position. In fact, heterogeneity may also be present across the environment, space and time (Parker et al. 2003).
Complex interactions and heterogeneity combined typically build up a high degree of spatial and temporal complexity, exemplified in cross-scale interdependencies and nested hierarchies.

Emergence is a central tenet of ABM and the search for emergence is explicitly mentioned in most of the modelling efforts (Parker et al. 2001). An emergent property may be defined as a macroscopic outcome resulting from synergies and interdependencies between lower level system components. Emergence characterizes a complex system, the capacities of whom are greater than the sum of the system. The emergent qualities of a system are not analytically tractable from the attributes of internal components (Baas and Emmeche 1997).
The concept of emergence and the concept of cross-scale hierarchies are related. Identifying emergence, therefore, may require understanding important cross-scale interactions and deliberately building interactions across topological, temporal and structural levels, rather than limiting modelling and analysis to a single scale. Unfortunately this potential to explicitly represent cross-scale interactions and feed backs, both bottom-up and top-down, has been minimally exploited in agent-based models to date (Parker et al. 2001).

Very much linked to the complexity of the interactions is the behavioral complexity that derives from the agents' internal world, their mental model or architecture, which describe their cognition and learning capacity. Often agents are endowed with bounded cognition. They have a limited perception of the environment and derive information from it, which they use to make assumptions about its state. Agents are not meant to be omniscient and fully rational utility maximisers as, for instance, the homo economicus (Gintis 2000). Models of bounded rationality have been used as an alternative in economics (Simon 1955). Furthermore, borrowing concepts from psychology,

behavioral economics has included dimensions of economic agents such as emotions, motivations and perceptions (Camerer 2003). In ABM is also possible to incorporate the salient characteristics of actual human decision-making behavior (Tesfatsion and Judd 2006), including the agents capacity of learning from past experiences.
The combination of behavioral complexity with the complexity related to interactions and heterogeneity allows the representation of adaptation in agent-based models at both micro and macro scales. The behavior built into the decision making structure at the individual agent level, which is influenced by the system dynamics, is in turn embedded in the systemic adaptive mechanisms.

2.2 ABM and the triple bottom line of sustainability

In applications of agent-based models to social processes, agents represent people or groups of people and agent relationships represent processes of social interaction (Gilbert and Troitzsch 1999). The fundamental assumption is that people and their social interactions can be credibly modelled at some reasonable level of abstraction, for at least specific and well defined processes (Macal and North 2005).
After Schelling (1978), Epstein and Axtell (1996) extended the notion of modelling human agents to growing artificial societies through agent simulations, with their ground-breaking Sugarscape model. Social science computation is now a consolidated subfield of sociology (Gilbert and Abbott 2005). However, sociological ABM is much more concerned with theoretical development and explanation than with exploratory analysis. These models do not necessarily aim to provide an accurate representation of a particular empirical application (Macy and Willer 2002). Instead, their goal is to enrich the understanding of fundamental processes that might appear in a variety of applications (Axelrod 1997).

In ABM applications to economic systems agents can be both organization and individuals, while the design of interactions aims at performing a natural description of the system, taking into account both the topological and behavioral dimensions of the components' activities (Bonabeau 2002).
Some of the main classical assumption of microeconomics can be relaxed, leading to a more realistic representation of economic systems. Firstly, drawing on behavioral economics, agents are not rational optimizers (Smith 1989). Secondly, agents are not homogeneous. A key observation of complexity science is that agents' diversity universally occurs in the real world (Arthur 1999). Thirdly, there can be increasing returns to scale underlying dynamic processes of rapid exponential growth. Such positive feedback loops can create self-sustaining processes that quickly take the system away from its starting point to a faraway state (Arthur 1990). Lastly, the long run equilibrium state of the system might not be the primary information of interest. Transient states may be crucial. Furthermore, not all systems come to an equilibrium (Arthur 2006).
The field of agent-based computational economics (ACE) has grown up around the application of ABM to economic systems. ACE is the computational study of economies modelled as evolving systems of autonomous, adaptive and interacting agents (Tesfatsion 2002).

In environmental applications of ABM agents can be both an individual human or biological organism or, more generically, any biophysical entity, as a reservoir of a natural resource or a part of it.
In biology, ABM has been used to model the possible emergent structures resulting from molecular self-assembly (e.g. Troisi, Wong, and Ratner 2005) and the self-organization of bacterial colonies (e.g. Krawczyk, Dzwinel, and Yuen 2003) but also to model bacterial behavior and interaction at

multiple scales (e.g. Emonet et al. 2005).
However, in the environmental domain, ABM applications were initially developed in ecology at the end of the 1980s following the IBM paradigm (e.g. Huston et al. 1988; Grimm 1999), which introduced the notion of the individual to understand the role of heterogeneity. In ecology an agent is necessarily an individual and scarce emphasis is given to the decision making process of the agents and to the social organization in which these individuals are embedded (Bousquet and Le Page 2004).
In contrast, in ABM applications to ecosystem management an agent can represent any level of organization, while the decision making process and the social organization are crucial. Frequently, these studies examine questions of collective problem solving related to the management of a common natural resource. ABM of ecosystem management is often included in the categories of agent-based land use models (ABLUMs) (Matthews et al. 2007) or as multi-agent systems for land use and cover change (MAS/LUCC) (Parker et al. 2003). In fact, most of the research on ABM and natural resources management overlaps with ABLUMs. This is because many of the environmental applications of ABM have a crucial spatial component and are very often spatially explicit, making use of abstract grids, cellular automata (CA), and, when case specific, maps from geographical information systems (GIS). So the landscape very frequently coincides with the environment where the physical space, the agents and the resources are represented delineating the system's boundaries and its organization.

2.3 Shared streams of research in ABM

The short overview of section 2.2 suggests that the definition of agent cannot be reduced to a specific one, because there are different realms of applications and processes with different agent characteristics, that can be successfully modelled with ABM. As suggested by Goldspink (2000) it's worth defining the minimal agent as “a natural or artificial entity with sufficient behavioral plasticity to persist in its medium by responding to recurrent perturbations within that medium so as to maintain its organization”. The medium is what Ferber (1999) defines as the environment and can be the background environment, *in strictu sensu*, or the substrate of a social system, and may contain active and/or passive agents. The latter are what Ferber (1999) calls objects. Starting from this any model can add new agent's features.
In the spirit of the interdisciplinary approach we are interested in the points of convergence between different scientific disciplines and a framework to classify them. Building on Macy and Willer (2002), Bonabeau (2002), Tesfatsion (2003), Bousquet and Le Page (2004) and Janssen (2005) we identified some main streams of research that can be found in each of the three scientific domains constituting the triple bottom line of sustainability.
Within *self-organization and co-evolution of the system* the focus of agent-based models is on the self-organizing capabilities of the system under study, in particular how agents' behavioral rules influence their co-evolution and, ultimately, the system's structure. These models study in evolutionary terms how the decision making at the micro-level affect the macro-structure.
The stream of research *diffusion processes and networks formation* is interested on how micro-level interactions and transmission of information lead to the emergence of specific structural phenomena such cultural convergence, diffusion processes and endogenous formation of networks. Models often employ learning algorithms like artificial neural networks. As networks are a particular way of representing the structure, this second stream can be considered a specification of the first one.
In the stream of research *modelling organizations, cooperation, and collective management* the focus of agent-based models is on how the system's topology and structure influences its behavior, and in particular which structure stimulate cooperation in the benefit of the collective.

In *parallel experiments* we include those applications that compare computational and empirically observed agents and structures in order to improve the representation of the system under study. This stream has strong linkages with the issue of model validation.

Agent's architecture deals specifically with behavioral complexity. The main issue is how to represent the decision making of the agents and, ultimately, evolution and learning both at a micro- and macro-level.

Programming is necessarily a main cross-cutting issue given the shared computer based approach. OOP techniques (Cox 1986) are often advocated as a crucial mean for constructing an environment in which users can easily tailor models designed to suit their own particular research agendas. In general there remains a certain duality between general purpose languages and more or less specific packages.

While the first three streams define the main research questions of an ABM application and, therefore, tend to be mutually exclusive, the remaining three can be understood as necessary accessories and tools among the ABM movement. We classify some relevant ABM studies belonging to various disciplines in Table 1 in order to show that a huge part of the ABM past research can find its proper allocation in this framework.

Table 1. Classification of ABM according to scientific domain and stream of research

ABM Streams \ Domains		Social	Economic	Environmental
ABM Main Research Questions	**Self-organization and co-evolution of the system (SOCES)**	Schelling (1971) Epstein and Axtell (1996)	Marks (1992) Arthur et al. (1996) Bower and Bunn (2001) Hommes (2002)	Bousquet et al. (1993) Deadman and Gimblett (1994) Kohler and Carr (1996) Balmann (1997) Torrens (2001) Parker and Meretsky (2004)
	Diffusion processes and networks formation (DPNF)	Latane (1996) Nowak and Vallacher (1998) Rosenkopf and Abrahamson (1999)	Albin and Foley (1992) De Vany and Lee (2001) Tesfatsion (2001) Janssen and Jager (2002)	Rouchier et al. (2001) Berger (2001) Deffuant et al. (2002)
	Modelling organizations, cooperation and collective management (MOCCM)	Axelrod and Hamilton (1981) Cohen et al. (2001) Takahashi (2000) Cecconi and Parisi (1998)	Prietula et al. (1998)	Lansing and Kremer (1993) Barreteau and Bousquet (2000) Becu et al. (2003) Feuillette et al. (2003) Mathevet et al. (2003)
ABM Accessories and Tools	**Parallel experiments (PE)**	Lomi and Larsen (1998) Carley (1996)	Arthur (1993) Chan et al. (1999)	Bousquet et al. (1999) Barreteau et al. (2001) Guyot and Honiden (2006)
	Agent's architecture (AA)	Rumelhart and McClelland (1986) Holland (1992)	Booker et al. (1989) Dawid (1996) Chattoe (1998) Gintis (2000) Vriend (2000) Bell (2001) Luna (2002)	Reynolds (1987) Drogoul and Ferber (1994) Wooldridge and Jennings (1995) Grand and Cliff (1998) Deffuant et al. (2000) Manson (2005)
	Programming (P)	Terna (1998) Gilbert and Bankes (2002) Tobias and Hofmann (2004)	Luna and Stefansson (2000)	Savage and Askenazi (1998) Le Page et al. (2000) North et al. (2006) Railsback et al. (2006)

2.3.1 Self-organization and co-evolution of the system

In sociology this stream of research is concerned with the emergent structure in terms of structural differentiation as, for instance, social segregation (e.g. Schelling 1971). Models often investigate spatial clustering using CA. Agents can change location and behavior in response to selection pressures. Adaptation is based on evolution, which modifies the frequency distribution of strategies across the population of agents (e.g. Epstein and Axtell 1996).
In economics this stream of research deals with the self-organizing capabilities of specific types of market processes and the co-evolution of firms (Tesfatsion 2002). The most successful studies are those on financial markets (e.g. LeBaron 2000). Evolutionary models can explain important stylized facts such as fat tails, clustered volatility, and long memory, of real financial series (Hommes 2002).
In environmental ABM applications of this stream the focus is on how the behavioral rules of interacting agents lead to the self-organization of the ecosystem's structure and to the state of the common natural resource.

2.3.2 Diffusion processes and networks formation

In sociology these models investigate imitation (e.g. Latane 1996) and diffusion (e.g. Rosenkopf and Abrahamson 1999). Adaptation operates via social influence and is based on learning, which modifies the probability distribution of strategies in each agent's repertoire (Nowak et al. 1998).
In economics these models investigate the dynamics of interaction networks and diffusion processes. Relevant examples of applications focus attention on the endogenous formation of trade networks (e.g. Albin and Foley 1992). A further kind of network issue is represented by the transmission of information as occurs with bank panics and stock market crashes (e.g. De Vany and Lee 2001).
In environmental applications of this stream of research both interaction networks and diffusion processes are present. Rouchier et al. (2001) investigated the formation of networks in a field study that focus on seasonal mobility (transhumance) among nomadic cattle herdsmen. Berger (2001) studied the diffusion of agricultural technologies based on the concept of early and late adopters. Deffuant et al. (2002) simulate adoption of organic farming practices as a consequence of governmental policy.

2.3.3 Modelling organizations, cooperation, and collective management

In sociology, studies dealing with emergent order focus attention on the ways in which network structures affect the viability of cooperative behavior. For example, they can show how egoistic adaptation can lead to successful collective action without either altruism or global (top-down) imposition of control, according to the network properties (Macy and Willer 2002).
In economics, organizations can be seen as CAS (Tesfatsion 2002). One can model the organization's activities by looking at what every actor does. Therefore, it is possible to model the emergent collective behavior of an organization or of a part of it in a certain context or at a certain level of description (Bonabeau 2002). Studies of firms in the ACE framework have tended to stress the effects of a firm's organizational structure on its own result behavior (e.g. Prietula et al. 1998). Cooperation and coordination are a prerequisite to achieve an efficient overall performance.
In environmental applications this is a prime issue for the research on management of common pool resources. These models investigate how the system topology and structure influences the collective behavior towards the common natural resource trying to identify what type of institutional rules may direct individuals to act in the benefit of the collective (Parker et al. 2003). The irrigation

system in Bali is an early example of the use of ABM to understand self-governance (Lansing and Kremer 1993).

2.3.4 Parallel experiments

In sociology, organizational life histories generated by simulations are compared with those observed in empirical populations (e.g. Carley 1996; Lomi and Larsen 1998).
In economics, human subject behavior is used to guide the specification of learning processes of computational agents and computational agent behavior is used to formulate hypothesis about the root causes of observed human agent behavior (Tesfatsion 2002).
Both the cited sociological and economic applications adopt an *a posteriori* approach. In contrast environmental applications tend to adopt an iterative approach by means of participatory techniques, such as role playing games, where human subject experimentation is used to test and ameliorate the computational simulations in an iterative process. In the spirit of adaptive management (Holling 1978) several researchers[3] have developed their agent-based models together with the stakeholders of the problem under concern, improving the acquisition of knowledge, the model construction, the model validation and the model application to decision making (e.g. Bousquet et al. 1999; Barreteau et al. 2001; Guyot and Honiden 2006).

2.3.5 Agents' architecture

In sociology there seems to be a clear distinction between learning and evolution. Learning modifies the probability distribution of strategies in each agent's repertoire. Learning architectures are based on artificial neural networks (Rumelhart and McClelland 1986). Evolution modifies the frequency distribution of strategies across the population of agents. In this case architectures are based on evolutionary algorithms such as genetic algorithm (Holland 1992).
In economics learning is used as a comprehensive term. The learning issue is particularly crucial due to the numerous anomalies discovered in laboratory experiments between actual human-subject behaviors and the behaviors predicted by traditional rational-agent economic theories (Gintis 2000) A broad range of algorithms is used to represent the agents' learning processes including reinforced learning algorithms (e.g. Bell 2001), neural networks (e.g. Luna 2002), genetic algorithms (e.g. Dawid 1996) and classifier systems (Booker, Goldberg, and Holland 1989), genetic programming and a variety of other evolutionary algorithms (e.g. Chattoe 1998) that attempt to capture aspects of inductive learning (Tesfatsion 2003). Vriend (2000) put more emphasis on the learning level, which can be individual, meaning on the basis of own experience, or social, in which every agent's experience is considered
In environmental applications various agent's architectures are drawn from computer science in order to represent behavioral complexity (Bousquet and Le Page 2004). Most are based on the evolutionary metaphor, as the genetic algorithm (e.g. Manson 2005). Others are defined architectures for competitive tasks, whereby choices are made by agents when they receive several stimuli which activates different tasks (e.g. Drogoul and Ferber 1994). Neural networks are employed in order to place emphasis on the agent's learning capacity: the perception-action relation is modelled by a network whose connections evolve (e.g. Grand and Cliff 1998). Agent's decisions may also be expressed in terms of parametrized functions by means of vector calculation describing the addition of physical forces (e.g. Reynolds 1987), linear programming describing processes of

[3] We defined these researchers as the "French school" of ABM as they are all more or less related to the Centre de coopération internationale en recherche agronomique (CIRAD) of Montpellier and to the Cormas ABM platform.

optimization more or less bounded (e.g. Balmann 1997), multi-criteria analysis (e.g. Deffuant et al. 2000), etc. One last way to model cognitive agents is the belief-desire-intention (BDI) architecture (e.g. Wooldridge and Jennings 1995) where agents memorize the space and the resources in a sort of mental map but also other agents' reputation when it comes to the moment of interaction.

2.3.6 Programming

In sociology, applications are more oriented towards ad-hoc platforms. Gilbert and Bankes (2002), provide a comprehensive enumeration of available languages and tools without identifying the best options. According to Tobias and Hofmann (2004), who evaluated four freely available and JAVA based programming libraries, Repast is the most suitable simulation framework for the applied modelling of social interventions based on theories and data. In contrast, Terna (1998) focuses on Swarm, which is the ground breaking and most dated tool of this type.
In economics, there remains a considerable gap between powerful general purpose languages and packages easy learned (Tesfatsion 2002). On the one hand, significant programming skills are needed in order to master general purposes languages such as C++ and Java, where applications are built from scratch. On the other hand there is a proliferation of ad-hoc packages, often not powerful enough for many economic applications, which can't communicate with each other and don't facilitate an easy sharing and comparison of modelling features. Economic applications often opt for a programming language or a generic but powerful software as NetLogo or Swarm (e.g. Luna and Stefansson 2000).
Also environmental applications are more oriented towards ad-hoc packages. Bousquet and Le Page (2004) survey some platforms developed with OOP distinguishing between generic softwares (e.g. Swarm and NetLogo), those dedicated to social and ecological simulation (e.g. Ecosim, Repast and Cormas), and specific platforms for ad- hoc applications (e.g. Manta, Arborscapes). According to Railsback et al. (2006) NetLogo is highly recommended, compared to Mason, Repast and Swarm, even for prototyping complex models. Cormas is a well tested software for ecosystem management which supports participatory processes (Le Page et al. 2000). Repast is well considered for its flexibility but requires higher programming skills.
Many of the packages which have not been cited in this section can be found in the appendices of Tobias and Hofmann (2004) and in Schut (2007).

3. ABM OF SOCIO-ECOSYSTEMS AND CLIMATE CHANGE

In the past 10 years there have been few studies that modelled socio-ecosystems and included climate change elements related to mitigation or adaptation issues. In this section we review those papers that, in our opinion, are suitable to this purpose and are already published or close to publication. However, we suggest to look at the following comparative analysis as a first attempt to envision, in a comprehensive manner, the issue of climate change through the lenses of ABM. Several research projects, which are currently developing new relevant studies for this same issue, are expected in the near future[4].

Janssen and de Vries (1998) are specifically concerned with the behavioral aspects of ABM applied to climate change adaptation. Agents are groups of decision makers who operate at the international level and have different world-views and management styles towards climate change.
Dean et al. (1999), Werner and McNamara (2007), Entwisle et al. (2008) and Filatova (2009) deal with ABM and land use. Dean et al. (1999) is an early example of ABM of a local socio-ecosystems, which include climate change elements in order to simulate human responses and the outcome of adaptation. The model represents the behavior of culturally relevant agents on a defined landscape in order to test hypothesis of past agricultural development and settlement patterns. Werner and McNamara (2007) investigate how the economic, social and cultural factors surrounding the human response to river floods, hurricanes and wetlands degradation affect a city landscape. Entwisle et al. (2008) focus on the responses to floods and drought at a regional level in terms of agricultural land use and migration, explicitly taking into account social networks. Filatova (2009) incorporated climate change related risks in an agent-based land market for coastal cities, which simulates the emergence of urban land patterns and land prices as a result of micro scale interactions between buyers and sellers.
Berman et al. (2004), Bharwani et al. (2005) and Ziervogel et al. (2005) are the only published empirical field studies, which explicitly aim at exploring local adaptation in the context of climate change and sustainable development by means of ABM. As Bharwani et al. (2005) and Ziervogel et al. (2005) refer to the same research project, we chose to review Bharwani et al. (2005) for its more comprehensive model description. Grothmann and Patt (2005) is a useful socio-cognitive model that can be used in ABM of this kind where is important to capture the most significant behavioral determinants of adaptation. It has been tested in similar studies but not applied in the reviewed paper and therefore it is not present in Table 2. Berman et al. (2004) assess how scenarios associated with economic and climate change might affect a local economy, resource harvest and the well-being of an existing community. Bharwani et al. (2005) investigate whether individuals, who adapt gradually to annual climate variability, are better equipped to respond to longer-term climate variability and change in a sustainable manner.
Barthel et al. (2008) developed an ABM framework for water demand and supply future scenarios where the socio-ecosystem is enabled to react and to adapt to climate change.
Hasselmann (2008), Beckenbach and Briegel (2009) and Mandel et al. (2009) concern macroeconomic models which employ, more or less explicitly, an agent-oriented framework in dealing with growth and climate change at a regional to global level. Hasselmann (2008) introduces few representative actors in a macroeconomic model of coupled climate-socio-economic system conceptualized following a system dynamics approach. The focus is on the evolution of this coupled system according to behavior of the agents pursuing different goals while jointly striving to limit global warming to an acceptable level. Mandel et al. (2009) developed an agent-based model

[4] See also Acosta-Michlik and Espaldon (2008).

of a growing economy where growth is triggered by the increase of labor productivity proportionally to investments. Beckenbach and Briegel (2009) investigate the relationship between innovations, economic growth and carbon emissions.

Building on Parker et al. (2001) and Grimm et al. (2006) we review the cited papers according to the following categories:

1. in *stream of research* we show how is possible to associate any of them to one of the streams in Table 1;
2. in *system under study* and *climate issue* we describe the object of the model, it's physical boundaries and the climatic problem at stake;
3. in *agents* and *environment* we define how the respective concept are applied in practice;
4. in *emergence* we identify which system-level phenomena truly emerge from individual traits;
5. in *interactions* we depict how the complexity of interactions is treated;
6. in *heterogeneity* we show how the diversity of the system elements is captured;
7. in *space and time* we describe the spatial and temporal dimensions, the process scheduling and the model initialization;
8. in *behavior* we focus on how the model deals with behavioral complexity;
9. in *verification and validation* we look at the strategies used to understand the model performance and the ability to represent the system under study;
10. finally, in *technical aspects* we identify the implemented programming languages and tools and other technical issues.

The main results of this classification effort are reported in Table 2.

Table 2. Comparative analysis of agent-based models of SES with climate change elements

Reference	Stream of research	System under study†	Climate issue‡	Agents§	Environment|	Emergence¶	Interactions#	Heterogeneity††	Space / Time‡‡	Behavior§§	Verification and Validation	Technical aspects
Janssen and de Vries (1998)	SOCES & AA	GL	CE	DM	Economy-energy-climate model	EO, CE	A-E	Agent's cultural perspectives	Aspatial; 100 years	GA	Absent	Mathematical equations
Dean et al. (1999)	SOCES & PE	LL Arizona (US)	R	HH	SCG and production model	PLUC	A-E, A-A	Agent's age, location and grain stocks; SA	CA, GIS based; 1000 years	HR	Statistical	Programmed in Object Pascal
Berman et al. (2004)	MOCCM	LL Canada	T, SP	I, HH	Environmental, economic and social indicators	EO and demographic change	A-E, A-A	Agent's age, HH type, education, wage-work and hunting-time capabilities	Aspatial; 40 years; complex scheduling	HR; CR	Statistical verification	Programmed in Visual Basic
Bharwani et al. (2005)	MOCCM & PE	LL South Africa	F, D	Farming HH	Planting fields and market place model	Crop yields and food security	A-E	Agent's wealth, crop type, location and timing	Aspatial; 100 years	Decision tree rules; LA; CR	Participatory	Repast
Werner and McNamara (2007)	SOCES	LL Georgia (US)	F, H	7 sets of economic agents	Economic model and landscape model	PLUC	A-E, A-A	Agent's types, prediction models and utility functions; SA	GIS re-sampled on a 100 x 100 grid; ~200 years	U functions	Absent	Programmed in Matlab
Barthel et al. (2008)	MOCCM	CRL Germany	T, R	HH, C, F	SCG	Water supply and consumption	A-E	Agents' type, location, level, behavior, preferences and plans; SA	1x1 km cells, GIS based; 100 years	U based decision rules and LA	Partial, Participatory	DeepActor programmed in Java
Entwisle et al. (2008)	DPNF	CRL Thailand	R, F, D	I, HH, C	SCG and social networks	Migration, social connections and PLUC	A-E, A-A	Agent's demography, wealth, social ties; SA	GIS based grid; time not specified	Probability rules	Under development	Repast
Hasselmann (2008)	SOCES	GL	T, CE	F, HH, Banks, DM	Three levels macroeconomic model	EO, CE	A-E	Environment levels, agent's objectives, physical units	Aspatial; 100 years	HR	Absent	Vensim
Beckenbach and Briegel (2009)	DPNF & AA	GL economy	CE	F	Sectoral demand model and inter-sectoral input/output tables	EO, CE	A-E, A-A	Agents' prevailing force among innovation imitation routine	Aspatial; 120 time steps equal to 30 years	Satisficing rules balancing different goals	Absent	Repast
Filatova (2009)	SOCES	LL Holland	F	HH, land owners	SCG and Land market model	Land prices and PLUC	A-E, A-A	Agents' location preferences , individual budget, risk perception; SA	CA, 35 x 63 cells; abstracts space and time	U maximization	Structural	NetLogo
Mandel et al. (2009)	SOCES & PE & P	CRL German economy	CE	HH, F, DM, Financial system	Economic process as schedule of events	EO, unemployment, wages.	A-E, A-A	Agents' type, economic activities, time steps	Aspatial; 40 years	HR, GA	Statistical	Lagom generiC programmed in Java

Notes to Table 2. † Global Level (GL), Country or Regional Level (CRL), Local Level (LL). ‡ Carbon Emissions (CE), Temperature (T), Rainfall (R), Snow Precipitations (SP), Floods (F), Droughts (D), Hurricanes (H). § Households (HH), Individuals (I), Decision Makers (DM), Communities (C), Firms (F). | Spatial Cellular Grid (SCG). ¶ Economic Output (EO), Patterns of Land Use and Cover (PLUC). # Agent-Environment (A-E), Agent-Agent (A-A). †† Spatial Attributes (SA). ‡‡ Cellular Automata (CA), Geographical Information Systems (GIS). §§ Heuristic Rules (HR), Utility (U), Learning Algorithm (LA), Genetic Algorithm (GA), Collective Response (CR)

3.1 Stream of research

This classification shows that the framework regarding the streams of research proposed in Table 1 remains valid in the climate change arena. However, at this early stage there seems to prevail one distinct research question. More than half of the studies we analysed are concerned about the self-organization and co-evolution of the system. Not surprisingly, this is the stream that paved the way to the application of ABM to social processes, meaning that the first examples of ABM dealing with climate change are following the most consolidated path of development.
Conversely, in Berman et al. (2004) the model purpose is to project how local institutions shape human adaptation to hypothetical futures. In Bharwani et al. (2005) the focus is on the emergence of strategies over time as a part of a cultural process. In Barthel et al. (2008) the focal point is on the implications for water management, given the system specific structure. These are all examples of the stream of research on modelling organizations, cooperation, and collective management.
Two very different studies are concerned about diffusion processes and networks formation. Entwisle et al. (2008) considers social influence at a local scale and at an empirical level , while Beckenbach and Briegel (2009) is about the diffusion of innovation at a global scale and in abstract terms.
Janssen and de Vries (1998) and Beckenbach and Briegel (2009) are models where the agent's architecture is a research question per se. Grothmann and Patt (2005) could be added to this subset even though it is not exactly an ABM model.
The programming phase is generally made to be case specific. Only in one case (Mandel et al. 2009) a generic software is produced, which can be applied to case studies other than the German economy.
Parallel experiments are not diffused but in three cases they are utilized to substantially improve the credibility of the model. In Dean et al. (1999) and Mandel et al. (2009) this is achieved a posteriori through statistical means. In Bharwani et al. (2005) this is an iterative process based on the participation of the stakeholders.

3.2 System under study and climate issue

ABM shows abilities to model local, regional and global systems both at a very abstract or more realistic level. We can distinguish between two typologies of ABM dealing with climate change: (a) the majority, that focus on adaptation, analysing regional and local systems and (b) few global models, that are concerned about mitigation (Janssen and de Vries 1998; Hasselmann 2008; Mandel et al. 2009; Beckenbach and Briegel 2009). In the first case the level of detail is at the community (or network of communities) level. In the second case there is much more aggregation even if a certain degree of heterogeneity is introduced by means of the agent-based thinking. Notwithstanding the novelty of the methodology this dichotomy appears quite conservative with respect to the climate change literature. In no case adaptation and mitigation are treated together.

3.3 Agents and Environment

Agents can represent various human actors at different decisional levels. Very surprisingly households emerge as the main category of agents in the climate change arena, as if it was the basic unit of reference, independently from the scope.
In general the number of agent's types is limited, in order to control complexity. Most of the model employ 1 to 3 agent's classes. Werner and McNamara (2007) is an exception with seven types of agents, which exponentially increase the level of details and the heterogeneity complexity of the

model.
The notion of environment is treated in a variety of ways. Very often these models rely on equations or indicators, which can be defined as sub-models describing theoretical spaces of interaction. Most of the models employ economic sub-models. In models dealing with land use and in Barthel et al. (2008) there is a significant correspondence between the landscape of the system under study and the environment of the ABM, however they also employ non-spatial sub models. The best example is Filatova (2009) in which the environment is constituted by the land market model where the price negotiation process and transactions take place and the by the cellular grid where the urban dynamics are represented.

3.4 Emergence

Emergence remains a central tenet of ABM dealing with climate change. Most of the models identify the economic outcome as an emergent property of the system. Other emergent properties are linked to demographic aspects and, where the spatial dimension is explicit, to land use patterns, which can be visualized on the grid. Those models that are concerned about mitigation look at carbon emissions as emerging from the system behavior. The studies belonging to the stream on modelling organizations, cooperation, and collective management see these outcomes as a consequence of emerging behaviors.

3.5 Interactions

In the climate change arena, ABM is consistently employed in order to capture the complexity of interactions. With the exceptions of Janssen and de Vries (1998), Bharwani et al. (2005), Barthel et al. (2008) and Hasselmann (2008) models investigate interactions both among agents and between the agents and their environment. Most of the studies show interdependencies across spatial and temporal scales. In Berman et al. (2004), Hasselmann (2008) and Mandel et al. (2009) interdependencies are particularly complex and can manifest with time lags and in form of feedback loops. In Entwisle et al. (2008) and Beckenbach and Briegel (2009) social influence is particularly crucial, given their main research question.

3.6 Heterogeneity

In contrast with the mainstream literature on climate change economics, with ABM the representative agent is avoided, as in those ground-breaking macroeconomic applications (Hasselmann 2008; Mandel et al. 2009). For instance, in Hasselmann (2008) the introduction of a higher degree of heterogeneity leads to quite important results. The actions of the real aggregate firm, defined as the aggregate sum of the actions of individual firms, will generally differ from the actions of the hypothetical single aggregate firm, which is concerned only with aggregate values. In his view, the discrepancy between the strategies of the hypothetical single aggregate actor and the strategies of the real aggregate actor is the origin of most macroeconomic instabilities, such as business cycles.
Agents can vary for demographic characteristics, location, own endowment, individual abilities, perception of the world, attitudes and behavior. Clearly, the level of diversity is linked to the level of detail of the model and therefore this ABM ability can be more effectively employed in the local dimension. However, some degree of aggregation is always necessary. Heterogeneity can also concern the spatial attributes in those cases in which the model is spatially explicit, as in Dean et al. (1999), Werner and McNamara (2007), Barthel et al. (2008), Entwisle et al. (2008) and Filatova

(2009).

3.7 Space and Time

Notwithstanding the suitability of the methodology, in the climate change arena the spatial representation of the environment is not the prevailing option. More than half of the model considered are not spatially explicit. Not only those models which are dealing with the global system are aspatial but also some dealing with local adaptation (Berman et al. 2004; Bharwani et al. 2005). Instead, Dean et al. (1999), Werner and McNamara (2007), Barthel et al. (2008), Entwisle et al. (2008) and Filatova (2009) are spatially explicit and make use of cellular grids. However, in Filatova (2009) the space represented by the grid remains abstract, while in the rest of these spatially explicit models the space is based on a GIS capturing the real geography of the system under analysis. Dean et al. (1999) and Filatova (2009) implement CA, given the emphasis on neighboring effects, as by definition of MAS/LUCC.

Most of the models are run for a time period of approximately 100 years, where every year is a time step. This is in average a time period of significance in order to capture climate change effects both in adaptation and mitigation terms. However, there can be exceptions in both directions. Dean et al. (1999) consider a 1000 years time period, given the archaeological value of their study. On the contrary Mandel et al. (2009) investigate a period of 40 years. In Beckenbach and Briegel (2009) time steps don't correspond to the years under consideration: a period of 30 years is simulated in 120 steps, in order to capture more details about the evolution of the system in the short to medium term. In Filatova (2009) time is abstract and follows market cycles.

Process scheduling can be programmed in a quite simple way, by executing the full repertoire of activities for all the agents each year (e.g. Dean et al. 1999), or in a more complex manner. For instance, in Berman et al. (2004) the sequence of decisions to be taken by agents follows different time clocks for different activities. Demographic change, household formation, seasonal wage employment, and migration follow a five-year cycle. On the other hand, the model recomputes hunting activities dynamically five times per year.

Given the fact that the methodology shows a certain path dependency, initialization is a prime object of testing. Initialization is strictly linked to the model purpose. For example, in Filatova (2009) all land is assumed to be under agricultural use and the city centre is exogenously set. Conversely, Dean et al. (1999) is initialized with the available archaeological data while Berman et al. (2004) with parameters obtained from field work and local experts.

3.8 Behavior

The prevailing options for modelling behavior are: (1) goal oriented heuristic rules drawn from field work expressed in form of statements and (2) utility functions based on economic theory expressed in form of equations. The first are preferred in the most empirical studies such as Berman et al. (2004) and Bharwani et al. (2005) but there can be exceptions mixing different options (e.g. Hasselmann 2008). The two studies that are more concerned about the agent's architecture, Janssen and de Vries (1998) and Beckenbach and Briegel (2009), employ respectively a genetic algorithm (Holland 1992) and a satisficing rule (Simon 2000). Janssen and de Vries (1998) simulated a learning process where agents may change their mind when they are surprised by observations, and make adjustments in their decisions according to their new perception of the problem. In Beckenbach and Briegel (2009) the multiple-self nature of the economic actor feeds different forces each of which is directed in favor of a possible mode of action.

Other models insert elements of learning (e.g. Bharwani et al. 2005; Barthel et al. 2008) and genetic

evolution (e.g. Mandel et al. 2009). In Bharwani et al. (2005) agents are endowed with the capacity of learning from previous experience so that they can modify their decision trees. In Barthel et al. (2008) each agent dispose of an history tracing successful and failed plan execution of previous time steps providing them with learning capabilities. In Mandel et al. (2009) agents update their belief according to information from the previous time step. On the long term, technologies and prices evolve genetically according to the profitability of firms. A genetic algorithm regulates any economic sector entry and exit, imitation and mutation.
On the behavioral side, it is worth noting that Berman et al. (2004) and Bharwani et al. (2005) also admit forms of collective adaptation in order to respond to harvest shortfalls.

3.9 Verification and Validation

ABM confirms its main pitfall in validation and verification even in the climate change arena. Almost half of the literature that we considered simply don't treat the argument. This is mainly justified by the models' level of abstraction, which impose a serious limitation to achieve any form of model testing. In contrast, those models that employed parallel experiments (see section 3.1) definitely overcame this problem. In Dean et al. (1999) verification and validation are extensively treated. Many iterations involving altered initial conditions, parameters, and random number generators have been performed in order to assess the model's robustness. Graphical output of the model includes a map for each year of simulated household residence and field locations, which runs simultaneously with a map of the corresponding archaeological and environmental data. These paired maps facilitate comparison of historical and simulated population dynamics and residence locations in statistical terms. In Mandel et al. (2009) input-output tables are used for validation, comparing real data and simulations results. In Bharwani et al. (2005) the model is driven by data collected from the field in a bottom-up process. Verification and validation, in accordance with the "French school", are achieved through the feedbacks deriving from the iterative inclusion of stakeholders by means of interviews, questionnaires and role games.
The remaining models are not fully satisfying from this point of view even if some have produced significant efforts. In Barthel et al. (2008) the means of verification and validation that have been applied are indirect and not of numerical type, including expert knowledge and consumer experiences. Filatova (2009) compare the model outcomes to the results deriving from other theories. In particular the land market model has been able to replicate qualitative properties of the standard equilibrium-based monocentric urban market model. Berman et al. (2004) achieve statistical verification by means of Monte Carlo simulations.

3.10 Technical aspects

Almost half of the models that we considered make use of an ABM platform. Three of them used Repast, one Netlogo and one Vensim, which is more appropriate for system dynamics but includes some agent-based features. Four models are programmed from scratch making use of a all set of different languages including Object Pascal, Visual Basic, UML and JAVA. As expected OOP turns out to be a real mainstream with regards to the implementation of ABM.
Quite surprisingly, Janssen and de Vries (1998) and Werner and McNamara (2007) only rely on mathematical equations. This proves the ability of ABM to be expressed in mathematical terms even if maths is not the ABM natural environment.

4. CONCLUSION

This paper reviewed the state of the art in ABM. We were interested in understanding how consolidated is this approach in dealing with the complexity of the coupled human-environment systems. More specifically, we wanted to investigate whether if ABM could be an innovative but sound methodology to model the dynamics of SES exposed to climate change and assess the related policies.

Our analysis suggests that ABM is today a quite consolidated interdisciplinary approach. In particular we showed that, at the theoretical level, the research questions are the same across social, economic and environmental applications. We were able to identify six main research purposes that we called the streams of research of ABM, as reported in section 2. The resulting framework can be used to categorize any ABM effort belonging to any sustainability dimension. This may support Boulanger and Bréchet (2005) who concluded that ABM is the most promising modelling approach for sustainability science. The intrinsic trans-disciplinarity of the methodology certainly justifies its application to the modelling of SES, where the human and the environmental systems co-evolve and a significant integration of the knowledge belonging to different domains is needed.

Past research often regarded ABM as a bottom-up methodology alternative to top-down equilibrium-based models but, to our knowledge, few publications have some relevancy in the climate change arena. Therefore, we reviewed those agent-based models of SES which included some kind of climate change related issue in order to clarify how the main ABM elements are applied, according to the systems under analysis. Our analysis, in section 3, described how the notions of agent, environment, emergence, interaction, heterogeneity, space and time, behavior and validation are treated in each study, including the computing languages, tools and platforms used for the simulations. The results support the idea that ABM is an appropriate bottom-up methodology for the exploration of climate policies.
ABM seems particularly well suited to the analysis of adaptation to climate change of local systems. Applications of this type spawn across all the streams of research of ABM composing the main body of work on agent-based models dealing with climate change. Households are the most crucial agents while the environment is the natural and economic landscape that can be expressed in spatially explicit terms and/or in form of sub-models describing theoretical spaces of interaction.
Surprisingly ABM also shows the possibility to be employed in more top-down orientations where the main issue is mitigation at a global level. Few ground-breaking studies are showing the way to insert agent-based thinking into macroeconomic models overcoming some unrealistic aggregative simplifications of traditional equilibrium models. One possible direction for further development of ABM research on climate change is the joint analysis of mitigation and adaptation.

In addition to the expected qualities of the methodology, i.e. the emergence of outcomes at the macro-level from micro-interactions, some specific strengths of ABM are particularly meaningful when dealing with climate change. The main advantages of ABM applied to climate change related issues are the abilities to take into account adaptive behavior at the individual or system level and to introduce a higher degree of heterogeneity resulting into a more natural representation of the system, compared to equilibrium-based models.
In the climate change arena adaptive behavior means the possibility to enable the SES to react, which is crucial in order to avoid unrealistic or meaningless results. At this early stage, behavioral architectures are mainly based on heuristic rules and on utility theory. More specific architectures exist but are not often employed.

Heterogeneity is another particularly relevant aspect, because people have different perceptions of the risk, environmental sensitivities, capacity to cope with change and so forth. Neglecting this diversity may lead to missing some crucial driver of change. ABM effectively shows the ability to overcome this problem.

The main disadvantage of ABM, as in other domains of application, stays in the challenges of testing the model which is not always very clear and often neglected. Where feasible participatory approaches seem the most suitable solution. For this reasons local applications may appear more robust. Further research is needed to consolidate ABM applications to the global system.

Two open issues should finally be highlighted and are related to programming and documenting agent-based models.
While there already exist various ABM packages and tools that can be employed in this field (e.g. Repast and NetLogo), it makes sense to think about a dedicated platform, for the future, which could simplify the modelling options into local and global systems and posses a library of household type agents and of specific socio-cognitive models of adaptation. This would certainly improve the accessibility of the methodology to those who cannot spend too much time in learning a programming language.
Finally, a communication barrier remains evident. While our specification effort in Table 2 may be more appropriate to explain the models to a public not trained on ABM, we also felt the need to find a common communication standard of the models we were analysing. We therefore recommend to the modellers to take into account a protocol such as in Parker et al. (2001) and/or Grimm et al. (2006) for their future publications.

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A SPATIAL AGENT-BASED MODEL TO EXPLORE SCENARIOS OF ADAPTATION TO CLIMATE CHANGE IN AN ALPINE TOURISM DESTINATION[1]

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Abstract

A vast body of literature suggests that the European Alpine Region may be one of the most sensitive to climate change impacts. Adaptation to climate change of alpine socio-ecosystems is increasingly becoming an issue of interest for the scientific community while the people of the Alps are often unaware of or simply ignore the problem. ClimAlpTour is a European research project of the Alpine Space Programme, bringing together institutions and scholars from all countries of the Alpine arch, in view of dealing with the expected decrease in snow and ice cover, which may lead to a rethinking of tourism development beyond the traditional vision of winter sports. The research reported herein analyses the municipality of Auronzo di Cadore (22,000 ha) in the Dolomites under the famous peaks of the "Tre Cime di Lavaredo". The local economy depends on tourism which is currently focused on the summer season, while the winter season is weak. As a whole, the destination receives approximately 65,000 guests per year with a resident population of 3,600 inhabitants. Since recently the Community Council is considering options on how to stimulate a further development of the winter tourism. This paper refers to a prototype agent-based model, called AuronzoWinSim, for the assessment of alternative scenarios of future local development strategies, taking into account complex spatial and social dynamics and interactions. Different typologies of winter tourists compose the set of human agents. Climate change scenarios are used to produce temperature and snow cover projections. The model is mainly informed by secondary sources, including demographic and economic time series, and biophysical data which feed-in its spatial dimension. Primary data from field surveys are used to calibrate the main parameters. AuronzoWinSim is planned for use in a participatory context with groups of local stakeholders.

Keywords

Alpine Winter Tourism; Spatial Agent-Based Model; Climate Change Adaptation

[1] A shorter version of this essay has been awarded as best student paper at the international conference of the Environmental Modelling & Software Society, in Ottawa, July 2010 (http://www.iemss.org/society/index.php?option=com_content&view=article&id=52&Itemid=63).
The paper is published in the related proceedings, in Session 7 (http://www.iemss.org/iemss2010/proceedings.html).

1. INTRODUCTION

The Alpine Region in Europe is among the areas that are most rapidly affected by climate change. In general, the mean temperature of this region has increased up to +2°C for some high altitude sites over the 1900-1990 period against +0.78°C in the last 100 years at a global level (IPCC 2007; ESFR ClimChAlp 2008). With a certain degree of local variability, glaciers have lost 50% of their volume since 1850 and snow cover is decreasing especially at the lowest altitudes and in fall and spring. A clear signal of climate change about precipitations is not detectable yet, but increasing risks of extreme events have been projected including floods, debris flows, avalanches, glacial hazards, and mountain mass movements (Castellari 2008). The main expected impacts on the Alps concern the hydrological conditions and water management, forests and biodiversity, agriculture, energy management, and eventually tourism, which is the focus of this paper. While summer tourism is most probably going to be favored by climate change (Bourdeau 2009), the World Tourism Organization started warning about the possible negative implications for winter tourism and sports since 2003 (UNWTO 2003). Nowadays already 57 of the main 666 ski resorts of the European Alps are considered to not be snow-reliable[2] (OECD 2007). However, climate change is also an opportunity for those resorts that are snow-reliable, as they will face less competition in the future (Simpson et al. 2008).

The alpine people are often unaware of or simply ignore the problem, which is a common problem of climate change adaptation. Perhaps, at a very local level, climate patterns are not evident enough to question the development model based on the "white dream" which has prevailed since the seventies. Indeed, a model of development based on snow, no matter if natural or artificial, is still somehow surviving notwithstanding the maturity of the traditional ski product and the stagnation of the market demand (Macchiavelli 2009). At this point very careful assessments should be carried on before any further snow-based development plan (WWF 2007).

ClimAlpTour is a European project of the Alpine Space Programme, bringing together institutions and scholars from all countries of the Alpine arch, in view of dealing with the expected decrease in snow and ice cover, which may lead to a rethinking of tourism development beyond the traditional vision of winter sports[3]. The project analyses 22 pilot areas with diverse environmental, social and economic conditions in order to provide a global perspective on the alpine tourism. Raising the awareness of the stakeholders including tourists, population and businesses on the impact of climate change on tourist economy of the Alps and on possible adaptation strategies is one of the goals of the whole project.

This paper explores the conceptualization phase of an agent-based model (ABM) capable of gathering the available heterogeneous information and of assessing different scenarios of future local development, and eventually tourist supply, taking into account complex spatial and social dynamics and interactions. We drew inspiration from previous ABM applications that have already proven to be successful in the field of natural resource management (i.e. Werner and McNamara 2007; Sax et al. 2007; Barthel 2008; Perez et al. 2009). To our knowledge, this is one of the first attempts to explore the interactions between climate change and winter mountain tourism by means of an agent-oriented approach[4]. Our work is still in progress and is meant to complement a decision

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[2] In general, a ski resort is considered to be snow-reliable if, in 7 out of 10 winters, a sufficient snow covering of at least 30 to 50 cm is available for ski sport on at least 100 days between December 1 and April 15 (Burki at al. 2007).

[3] The project website is www.climalptour.eu

[4] See also Sax et al. 2007.

support system (mDSS)[5], which will be implemented during a series of participatory workshops.

2. CASE STUDY

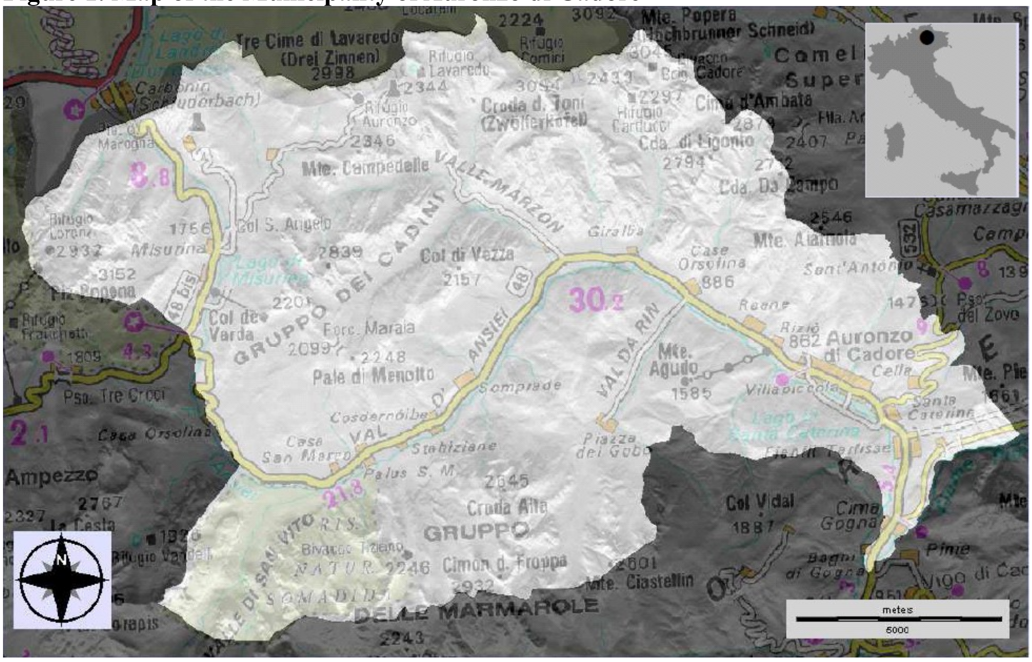
The research reported herein analyses the municipality of Auronzo di Cadore located in the province of Belluno, in the Veneto Region, in the north-east of Italy (see Figure 1). It covers a vast area (22.000 ha) which includes Misurina with its lake and the most famous mountain of the Dolomites, namely the "Tre Cime di Lavaredo", part of the UNESCO world heritage since 2009.
The village of Auronzo (866m on the sea level) hosts almost the entire population of the municipality of approximately 3,600 inhabitants. It is located in the middle of the valley of the Ansiei river, which forms the artificial Santa Caterina Lake, due to the presence of an old dam. The lake basin is 3 km long and is endowed with beach facilities that periodically host motor nautical and canoe competitions. Misurina is a small settlement at 25 km from the main village, placed at an altitude of 1,754 meters, just under the Tre Cime di Lavaredo peak, which is accessible both by means of several mountain paths and by a toll regulated carriageway.

The local economy depends on tourism which is currently focused on the summer season, while the winter season is weak, with only 25% of arrivals (Regione Veneto 2009). Indeed, hiking (200 km of signed mountain paths and 10 alpine refuges) and relax are the main elements of attraction. The total hosting capacity is of approximately 7,300 beds of which around 1,700 in the hotel sector and the remainder in the extra-hotel sector (B&Bs, lodgings, etc.). The 75% of the hotels' beds concern structures with 1 or 2 stars. In 2008 63,700 arrivals and 305,400 tourist nights were registered, showing a slight decrease from the previous year. The last 10 years have witnessed the increase of arrivals and the contraction of average stay.
Notwithstanding the presence of two small downhill ski-areas and two cross-country ski centers some hotels don't even open for the winter season. The four ski-lifts of Mount Agudo, which reach a maximum elevation of 1,600m, supply seven ski-trails covering 15 km. In the locality of Palus San Marco, just at halfway between Auronzo and Misurina, there is the Somadida Forest, one of the largest of the province, which becomes a cross-country ski centre (with nine loops of 52.5 km in total) during the winter season. The Marmarole sled-dog centre and an ice-kart circuit are also placed Palus. In addition, Misurina, which has an hosting capacity of approximately 500 beds is endowed with the two ski-lifts of Col de Varda (from 1,756m to 2,220m) that supply five ski-tracks, and 17km of cross-country ski loops.

Since recently the Community Council is considering options on how to stimulate a further development of the winter tourism. There exist several projects of ski-areas development. The most ambitious is located in Marzon valley, a few km from the main village, which would connect the valley to the ski-area of Misurina (with an average altitude over 2,000m). The main problem at stake is how to develop winter tourism in the next 40 years, in a context of climate change and market demand that is not favorable. In particular, the spatial heterogeneity given by the bipolarity of the case study, suggested the elaboration of a spatially explicit ABM.

[5] See Giupponi and Sgobbi (2008).

Figure 1. Map of the Municipality of Auronzo di Cadore



3. MODEL DEVELOPMENT

The development of a conceptual model has been carried out to support the design of the ABM by integrating three methods gravitating around different research groups of the heterogeneous ABM scientific community. The ARDI (Actor, Resources, Dynamics, and Interactions) method belongs to the companion modelling tradition, mainly applied to natural research management. It can be extremely efficient for jumpstarting the process of visual formalization of the domain model (Etienne 2006). The ODD (Overview, Design concepts, Details) protocol belongs to the individual-based modelling branch of ecology, but is gaining further diffusion in social science. Differently from the other methods, it consists of a narrative description of the various elements of an ABM, contributing to a more rigorous formulation phase (Grimm et al. 2006). Finally, the UML (Unified Modelling Language) belongs to the computer science tradition and is probably the most effective methods, preceding the coding phase, which can guarantee the full replicability of the model (Boch et al. 1999).

These methods have been firstly applied in the order in which are presented, subsequently leading to a more iterative approach. By means of ARDI we identified the tourist facilities as the main resources of the system, the winter tourists as the acting agents and the meta-economic agents as the economic units in charge of accounting the economic flows for each tourism sub-sector. The application of ODD led to the definition of the tourists' heterogeneous behavior and of the future scenarios. Finally, through UML, we were able to formalize in diagrams all the details. The clear advantage is that the modeler is endowed with a set of tools mutually checking the model internal consistency with regards to both its static and the dynamic aspects.

3.1 Representing Heterogeneous Market Behavior

Even though winter sports, and especially downhill skiing, are still the essence of winter mountain tourism the market has reached its maturity and is challenged by (a) loss of shares in the tourist market in the alpine countries throughout Europe, (b) competition from other tourist destinations,

(c) the growing economic and territorial divide between large and small resorts, (d) the need for huge new investments against the background of a reduction of public funding, (e) new recreational practices (free-style and free-ride), (f) the ageing of the tourist population, (g) demand for environmental quality, (h) the changed notion of resort[6], (i) the inclination toward shortened and repeated holidays, (j) behavioral unpredictability, due to wheatear forecasts, and finally (k) the search for new markets (Minghetti 2002; Daidola 2006; Bourdeau 2009; Macchiavelli 2009). However, according to Camanni (2002) and Daidola[7] (2007), a new light ski industry, with less investments and more flexibility with regard to climate conditions, is possible and the small resorts may thus be advantaged.

ABMs can be of great value in dealing with such dynamics because they are particularly well suited to incorporate heterogeneity of behavior. Drawing on the above cited literature and especially on secondary data from marketing surveys of the tourism statistical observatories of Trentino and Alto Adige[8] (Provincia Autonoma di Trento 2007, Provincia Autonoma di Bolzano 2009), we created a set of eight tourist profiles which is rich enough to take into account (1) the actual winter tourists of Auronzo, (2) the actual winter tourist visiting Auronzo's main competitors, and (3) the potential winter tourist of tomorrow (see Table 1).

In this first release we focus on the simulation of tourists' response (demand-side) to alternative and exogenously modelled strategies of development of tourism facilities of the destination (supply-side) in order to provide the local stakeholders (residents, entrepreneurs, local tourism organizations, community council), with quantitative indicators of possible futures which depend on their collective decisions. These strategies are infrastructure oriented and consider snow and non snow-related facilities.

[6] "The idea of the resort as a unity of place, time and action, can be circumvented or deviated by a new interpretation of the mountain playground. One example is the striking contrast that can be observed by the expansion and interconnection of large ski-areas, and the micro-scale of space in which the new sports are practiced by young snow surfers such as the snowparks" (Bourdeau 2009).

[7] Daidola's hypothesis is that artificial snow is less satisfying and more dangerous than natural snow. Because of artificial snow, the current skiing style has become repetitive, expensive and boring, and at the same time too easy to learn and too fast. On the contrary ski and snowboard magazines mainly propose powdery snow and exciting experiences. Moreover artificial snow is responsible for the vicious circle of huge investments of the last years.

[8] These are the two most important winter tourism regions of the Italian Alps.

Table 1. Narratives describing the tourist profiles

Traditional Ski-Intensive (TSI). Mainly motivated by the practice of downhill skiing (3/4) and snowboarding (1/4). Primarily interested about the ski-lifts and trails. Appreciate gastronomy. Not satisfied by the scarce presence of bars and pubs. Have a middle-low profile of expense (110 Euros/day). Have one or more winter holidays every year, often in the same destination. The booking process is often intermediated and the time unit of reference is 7 days. Book his holidays in February and March. Travel in company with one or more friends or with the family.

Ski Part-Time (SPT). Mainly motivated by the natural environment and by the practice of downhill skiing (2/3) and snowboarding (1/3), with a softer approach. The trend towards snowboard is more evident. Interested about ski-lifts and trails, but also about other winter sports. Dedicate to traditional skiing activities not more than half of the day. Often novices, mainly with family. Not interested in gastronomy. Not satisfied by the scarce presence of children facilities. Have a low profile of expense (100 Euros/day). Visit the same destination, often for the Christmas holidays. The time unit of reference is 7 days. Tend to book directly to the hospitality structure. Booking is less predictable and more subjected to weather conditions and forecasts.

Sporty Alternative. Mainly motivated by the natural environment and the practice of alternative winter sports. Often in group and on a day trip. Often adult or elder. Highly dependent on weather conditions and forecasts. Have the lowest profile of expense (under 100 Euros/day). This typology is composed of two profiles: the practitioners of cross-country skiing **(SAX)** and the practitioners of back-country skiing and ski-touring **(SAW)**.

Idle (ID). Mainly motivated by the natural environment. Scarcely interested by any intensive sport activities. Appreciate easy trekking in the snow, children facilities and wellness and spa services. Not satisfied by the scarce presence bars and pubs and other sport facilities. Often females, accompanying skiers. Often with family. Tend to book for the Christmas holidays. Have a middle-high profile of expense (130 Euros/day).

Eclectic (EC). Mainly motivated by the idea of having fun by means of a set diversified activities not related to traditional skiing. Interested in gastronomy, wellness and spa and shopping. Appreciates minor winter activities (i.e. ice skating, hockey, sled-dog…). The natural environment remains important. Have the highest profile of expense (over 150 Euros/day) but the shortest average stay. Not satisfied by the scarce presence of bars and pubs and other sport facilities.

Counter culture. Mainly motivated by the desire of having deep and authentic experiences, merging wilderness and playground, nature and adrenaline. Mainly sporty and expert in their discipline. Composed of two profiles: practitioners of free-style **(CCP)** and of free-ride **(CCW)**. Often travelling with friends practicing the same activity. Interested in natural snow, very dependent on weather conditions and forecasts. CCP tourists are interested in dedicated facilities as snowparks. CCW tourists appreciate the organization of the natural environment into off-piste trails and the presence of small ski-lifts and security services. Both are sensitive to environmental issues. Have a medium-high profile of expense according to the services that are offered.

3.2 Representing Alternative Futures

Every simulation run requires the users to make four choices: (1) the development strategy to be tested; (2) the societal scenario that sets the conditional context in terms of number of tourists that could be available to choose the destination; (3) the type of competition to which the destination is subjected by the neighboring destinations; and finally, (4) the climate projection, in terms of snow cover and temperature. The combination of these choices defines the future conditions, from 2011 to 2050, under which the tourists' response is simulated. The underlying idea that has inspired the model is to identify the most robust development strategy. In this regard, we have defined four spatially explicit alternative strategies which are able to take into account various orientation towards tourism and the perception of climate change from the local stakeholders' point of view.

The first strategy is the pursue of the traditional ski-intensive paradigm. Indeed, one of the most familiar measures in the struggle against snow-deficient winters is the construction of high cost artificial snowmaking facilities (Burki et al. 2007). However, in this strategy Auronzo not only maintains the ski-areas of Mount Agudo and Misurina, but also develops two new ski-areas with snowpark, on the basis of two projects about Marzon and Da Rin valleys, which have different spatial conditions. The overall hosting capacity remains untouched while a minor increase concerning restaurants and retailers supply is included.

The second strategy embraces the vision of Daidola (2006) and Burdeau (2009) of an alternative light ski oriented and post-modern development. It integrates the wilderness and the playground concepts increasing the supply of controlled off-piste tracks (Marzon and Da Rin valleys), cross-country itineraries (Palus) and snow parks (Mount Agudo). These are assisted by a very limited development of the existing ski-lifts and a more sober artificial snowmaking behavior.

The third is the beyond-snow strategy that is the well established, but often not self-sustaining, process of diversification and enlargement of tourist offer by means of higher quality hotels, shopping, gastronomy, pubs and bars, and, most of all, wellness and spa centers. This is mainly implemented in Auronzo, Misurina and Palus villages. The ski-areas remain in function without the support of artificial snow. Finally, the fatalistic strategy consists of no changes in the supply behavior, which could also be described as "business as usual".

The societal scenarios serve the purpose of considering the overall alpine winter tourism trend. We include scenarios that allow us to take into account two situations: where market demand is stable or slightly decreasing (conservative), possibly because of the ageing of the population of skiers, and where the demand for alpine winter tourism is increasing (optimistic), following the global trend of tourism sector.

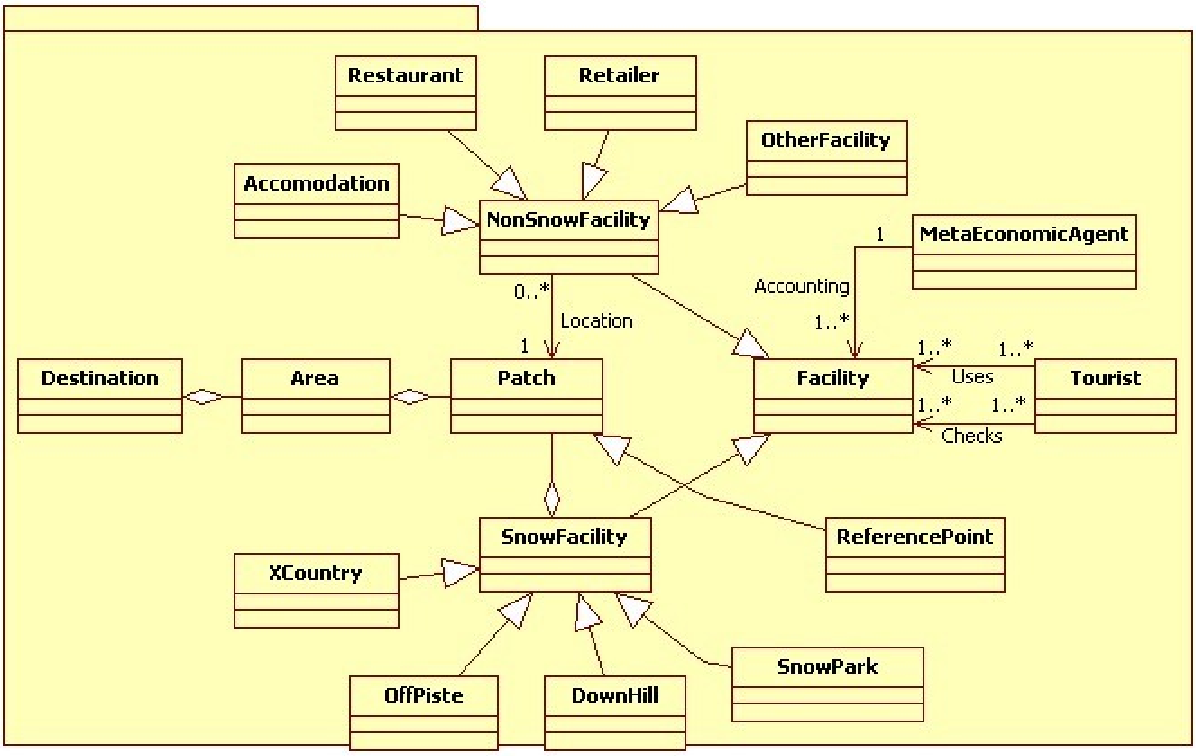
We also consider two types of competition with other neighboring winter destinations. With a generic competition all the tourist profiles are subjected to the same degree of attractiveness to other destinations. With a niche competition some tourist profile (i.e. TSI, EC) are more sensitive to this attitude, which could lead them to choose a competing destination rather than Auronzo di Cadore.

The climate projections are based on the SkiSim model (Steiger 2008) and represent two scenarios (A1B and B1) based on the regional climate model REMO UBA from the Max Planck Institute of Hamburg.

4. MODEL DESCRIPTION

This concise model description loosely follows the ODD protocol (Grimm et al. 2006). While a simplified class diagram is proposed in Figure 2, we also provide the complete UML class, sequence and activities diagrams in the appendices.

Figure 2. **AuronzoWinSim Simplified UML Class Diagram**



The model *purpose* is to analyze alternative winter development strategies for the case study simulating the tourists' response under different climate scenarios.

Entities and *state variables* are visually presented in the UML class diagram (Appendix A). The main entities are the tourists, the tourism facilities and the meta-economic agents. The tourists are divided in eight profiles: traditional ski-intensive (TSI), ski part-time (SPT), sporty alternative cross-country (SAX), sporty alternative wilderness (SAW), idle (ID), eclectic (EC), counter-culture wilderness (CCW) and counter-culture playground (CCP). According to the profile they belong to (variable "type"), tourist agents have different preferences and behavior with regards to the tourism facilities. The tourism facilities, which in turn compose the destination supply structure, are divided in eight types: four are snow-related (facilities dedicated to downhill skiing, snowparks, cross-country skiing and off-piste skiing) and four are non-snow-related (accommodations, restaurants, retailers, and other facilities including those for kids, wellness and spa, and other sports). The meta-economic agents are the accountants of the tourism facilities. One meta-economic agent is in charge of managing one type of tourism facility. They keep track of the investment required to put in place their facilities, defined by the development strategy to be analyzed, and of their money flow. The development strategies, which represent possible orientations of the local stakeholders, are set exogenously by the model.

Concerning the *scales,* both the snow and the non-snow-related facilities are located in a spatial grid of approximately 10.000 cells which represent the destination. Each cell represents a 150 x 150 meters square and contains the actual geographical information of the area. Twenty weather stations, named reference points, have been identified in order to represent the different snow conditions under alternative climate scenarios. A simulation is composed of 40 cycles, which are the winter seasons from 2011 to 2050. Each cycle consists of 126 days (time steps) that represent the 18 weeks from the 1st of December to the 6th of April. Summing up, every simulation takes into account 720 weeks and 5040 time steps.

Process overview and scheduling are captured in the UML sequence diagram (Appendix B), which shows the sequence of operations performed by each class. Every operation is then further described as activity diagram. Initially, the spatial units (patches) update their attributes and configure the tourism facilities presence as per selected development strategy. Each of the meta-economic agent is assigned with the investment needed to meet that configuration. The reference points read snow cover and temperature from the climate data which describe the selected climate projection. They also perform three kinds of forecasts concerning snow cover, at short and medium term, and snow security, at short term. Then, the snow facilities check those forecasts and store the information that they will subsequently pass to the tourists. Downhill and snowparks can decide to produce artificial snow. After that, the tourists, whose total amount is taken by the societal scenario, can check the destination in order to become visitors, if their requirements are met. According to their behavior, they can check the forecasts and go to the planning phase, in which they decide their day of arrival. If they are in the destination they enter into a loop of operations which describe the use of the tourism facilities. Then, every facility can check its own users and passes the information to the patches that can visually describe the tourists' density on the grid. The meta-economic agents calculate the return associated to the facilities use and update their balance sheet. Finally, the tourists in their last day of vacation calculate their overall satisfaction. If this is negative they exit from the simulation, if it is positive they remain among the potential visitors and can plan a further vacation. Those that eliminated are substituted by other tourist agents, but they are also accounted for in the statistics about dissatisfaction.

Input data is provided in various forms. The spatial units are georeferenced, based on GIS (geographical information system) layers concerning elevation, slope, aspect, land use and a thematic differentiation in areas of the destination. The reference points are provided with climate data in form of time series of snow cover and temperature, according to the selected climate projection. Finally, the demographic data provides the total number of tourist agents available for each of the 40 cycles during every simulation.
Most of the operations make use of *submodels* in form of simple algorithms and logical tests which are presented in detail in the activity diagrams. For instance, the calculation of return performed by the meta-economic agents is based on several parameters referred to the facility they are in charge of, including a tag price, the cost of labor and the cost of energy associated to the use by one tourist, and the seasonal investments requested by the development strategy. Most of the parameters used in the activity diagrams are calibrated on the case study, by means of field surveys. The rest are retrieved from the literature. The model *initialization* represents the destination winter tourism conditions in 2011 concerning the actual amount, type and spatial configuration of the tourism facilities.

4.2 ABM Design Concepts

Emergence. Once the boundary conditions of possible futures are set by the 3 choices on the scenarios for any model run, then the performance of the destination is a phenomenon that emerges from the tourists' behavior. This is numerically expressed in terms of tourist attracted and money flow produced by each facility type (see updateUsers and updateBalance activity diagrams in Appendix C) and visualized on the spatial grid at each time step in terms of tourists' density (see checkOccupation activity diagram).

Objectives. The tourists can choose whether to go or not to the destination, according to their preferences about the destination supply and to the weather forecasts. The objective function is expressed in form of sequential tests on certain conditions. During the operation named checkDestination every type of tourist compare the destination's dotation with their own desires. For instance a traditional ski-intensive tourist is looking for a minimum amount of groomed slopes. If the condition is satisfied the agent becomes a potential tourist (see checkDestination activity diagram). In order to effectively book the vacation every agent has to consider the weather forecasts, according to the agent's behavior (see initPlanning, checkForecast, and doPlanning activity diagrams).

Prediction. Tourists' expectations are based on the facilities available and their spatial configuration in the destination and on the snow cover and security forecasts. For long-term planners snow cover conditions are guessed on the basis of historic data (see doMidTermForecast activity diagram), while short-term planners are endowed with knowledge about next day projections with a certain error (see doShortTermForecast activity diagram).

Sensing. The tourists are fully aware of the destination's facilities and spatial attributes before the vacation, but they perceive the environmental conditions of the facilities they use only *in loco*.

Learning. Each day of their vacation the tourists calculate their satisfaction which depends on the effective environmental conditions encountered in terms of snow cover and tourists' density, so that their availability to a subsequent vacation depends on the memories of the previous one (see calcSatisfaction activity diagram).

Adaptation. The tourists adapt by not visiting Auronzo again once their satisfaction goes negative, in favor of other competing destinations (see updateSatisfaction activity diagram).

Interaction. The tourists directly receive stimuli, through sensing, from the destination's facilities and spatial attributes, which affect their eligibility to book their vacation. They also indirectly interact among each other with negative effects on their respective satisfaction, over certain density thresholds.

Stocasticity is used to reproduce variability in the various agents' decision processes, primarily by means of normal distributions, as showed in the activity diagrams.

Observation. The model collects data on the economic performance of the eight types of facilities and on the spatially distributed tourist fruition of the destination.

5. DISCUSSION AND CONCLUSION

Our work is still in progress but it can already provide some interesting insights on the modelling of climate change and tourism.
First of all, the scale of analysis and the level of detail represent a significant improvement in the climate change research, which is normally performed at a much higher level of spatial and temporal aggregation. This scale perfectly fits the crucial socio-economic dynamics of local adaptation that have to be investigated.
Second, to our knowledge this is one of the first attempts to formalize the supply structure of a winter tourism destination in classes by means of UML. The result is simple and clear but is able to represent complex interactions, for alternative development strategies, in a spatially explicit way. This conceptualization can eventually become a generic ontology, if it will be proved to fit the application to other case studies.
Third, the simulation focuses on the feed-backs of the demand side of tourism, which is often missing in the existing tourism models. However, the tourists are the ultimate judges of a destination adaptation strategy, because they will decide the winners and losers of the future. This is why we regarded as fundamental to focus on their agency in an heterogeneous way, drawing from disciplines such as customer behavior, which could only be done by means of an the agent-based approach.
Fourth, the model development itself is a novelty because we integrated some of the main practices of the ABM community which are never found together but can mutually benefit each other.

One main existing limitation of our approach is that it has proven to be quite demanding in terms of field work needed to retrieve some calibrated parameters.
The next steps of our work include the implementation of the UML model into software for computer simulation. We are also planning to test the model on historic data, and eventually explore the relationship between the climatic conditions and the economic performances of the system. AuronzoWinSim will then be used in a participatory context with groups of local stakeholders, in two ways. Initially, it will support the collective discussion on possible adaptation and development strategies, and the criteria to assess their robustness. Secondly, it will incorporate the strategic adjustments proposed by the stakeholders.

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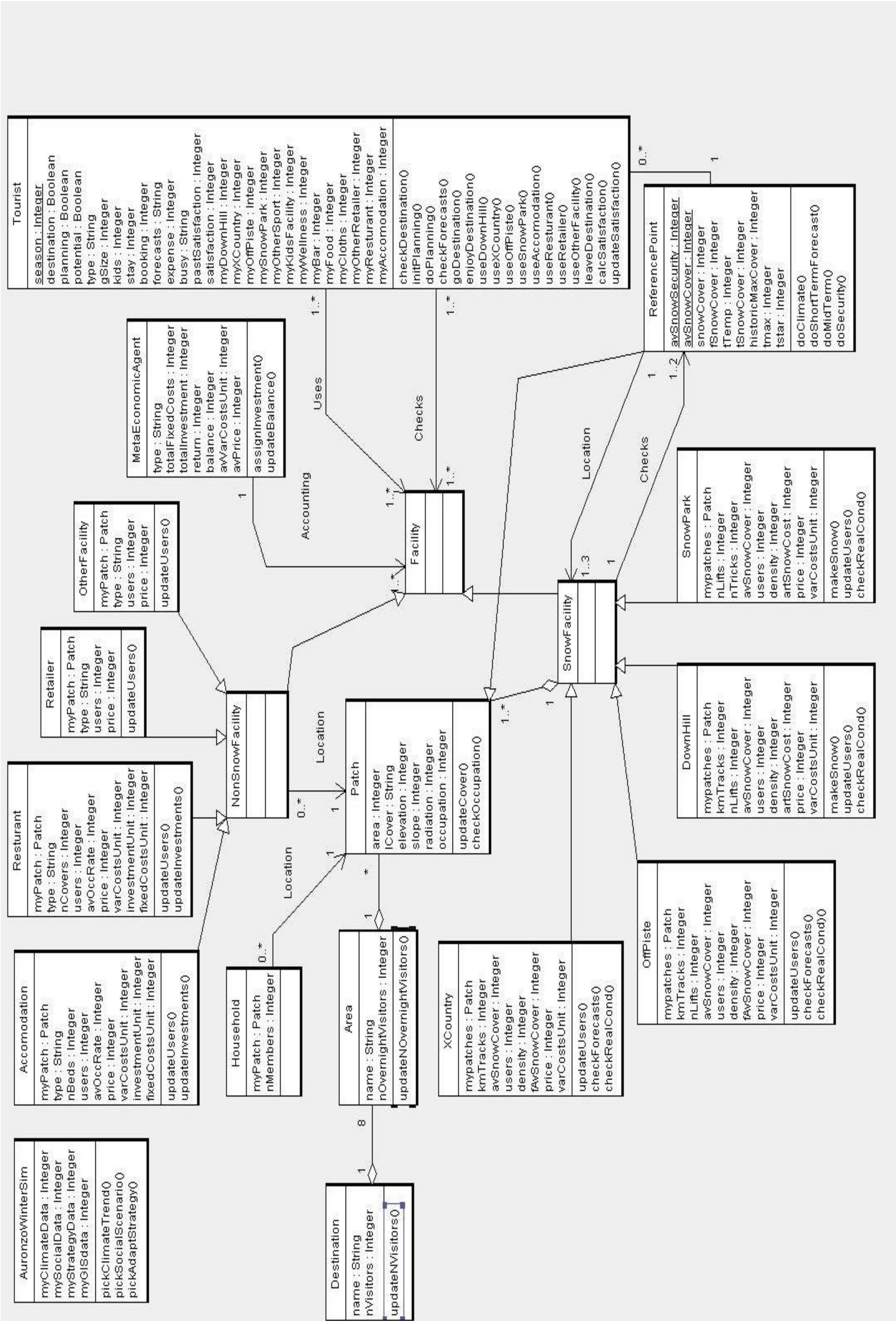
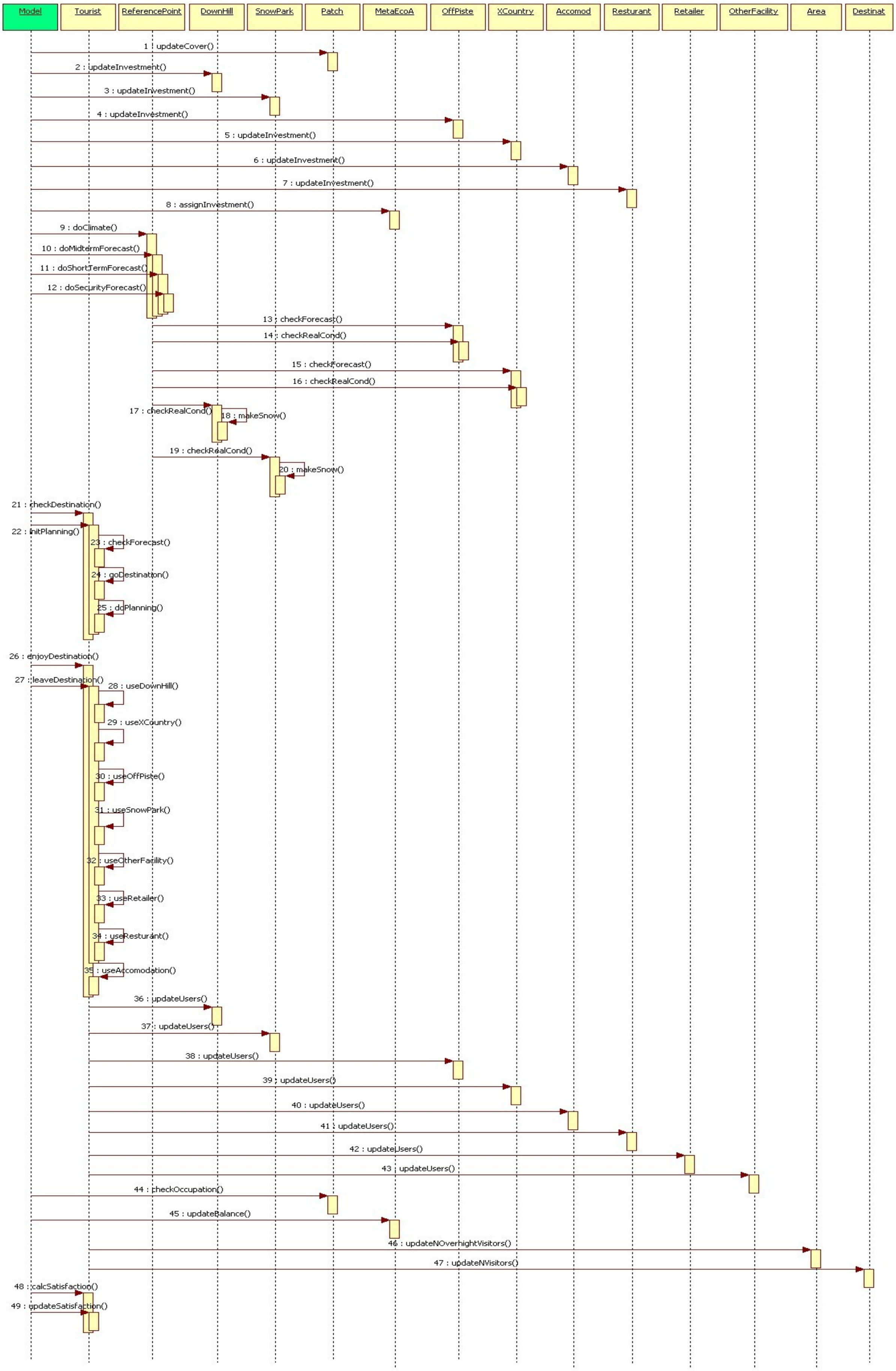
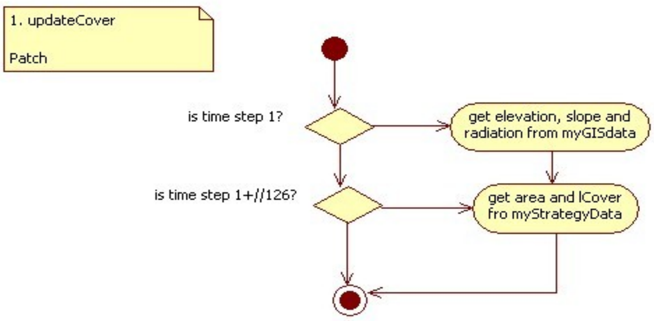
APPENDIX A. AuronzoWinSim Class Diagram

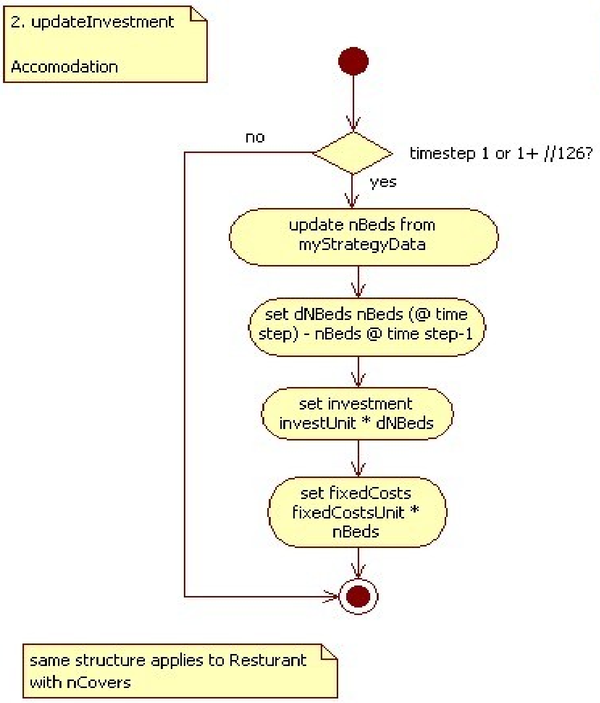


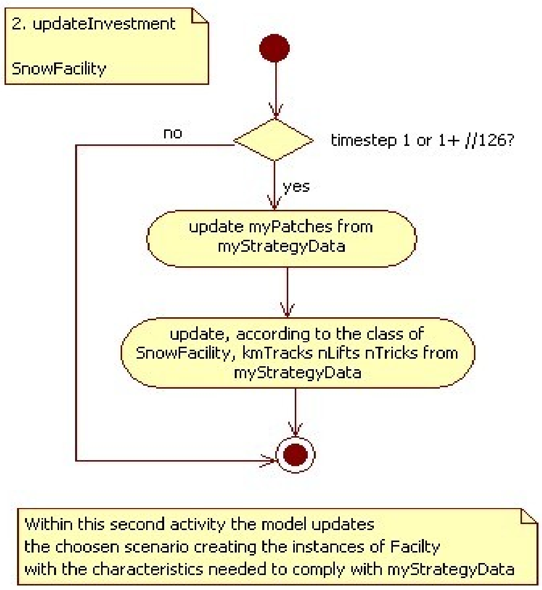
APPENDIX B. AuronzoWinSim Sequence Diagram

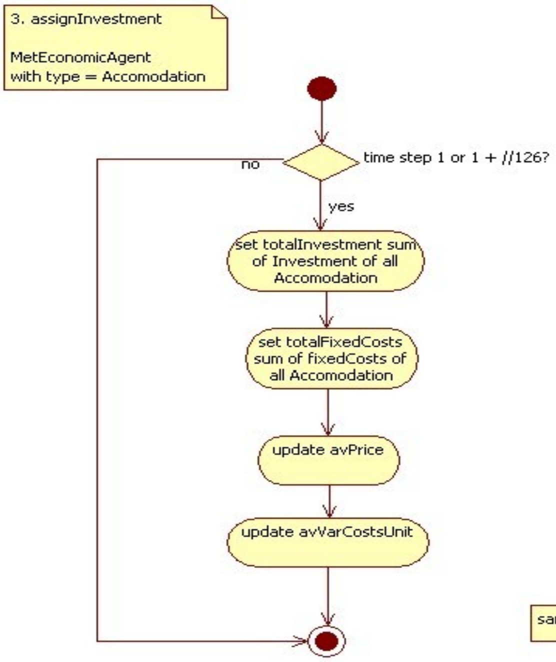


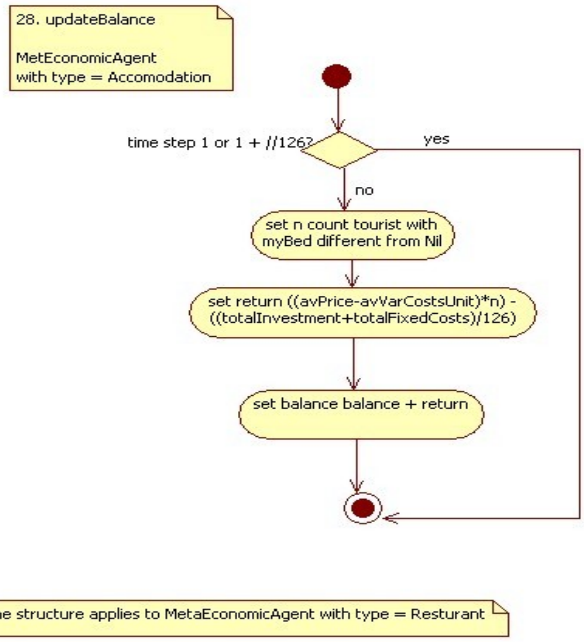
APPENDIX C. AuronzoWinSim Activities Diagrams

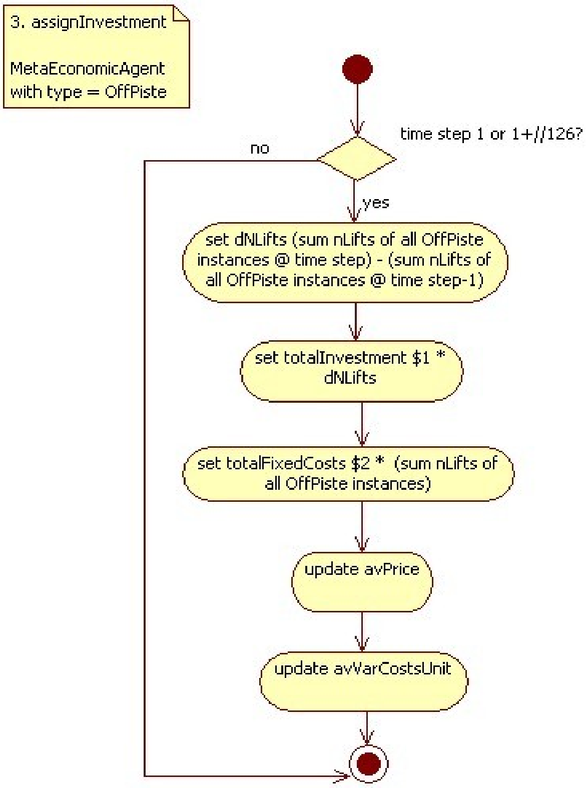


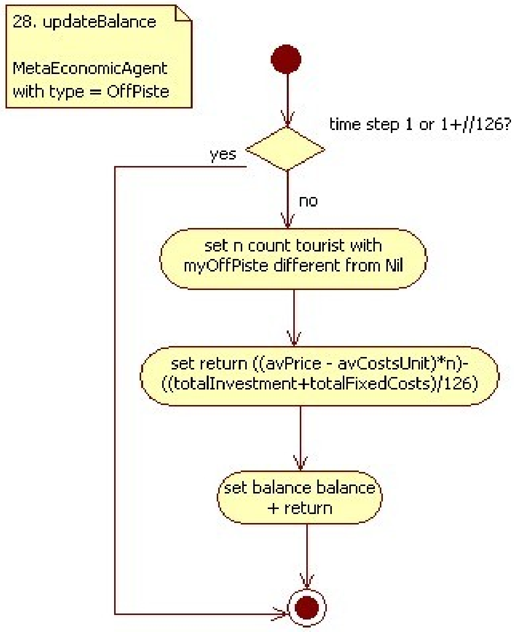


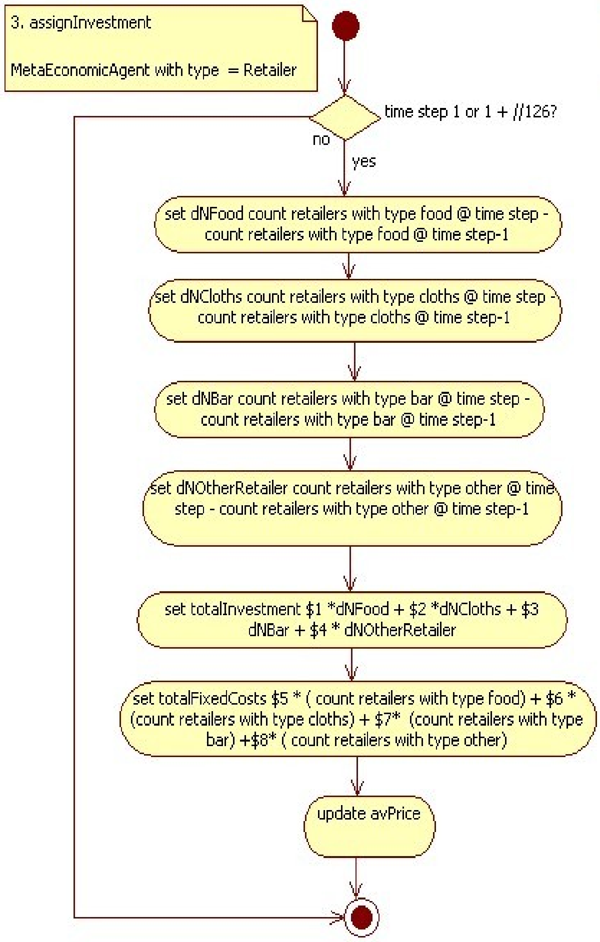


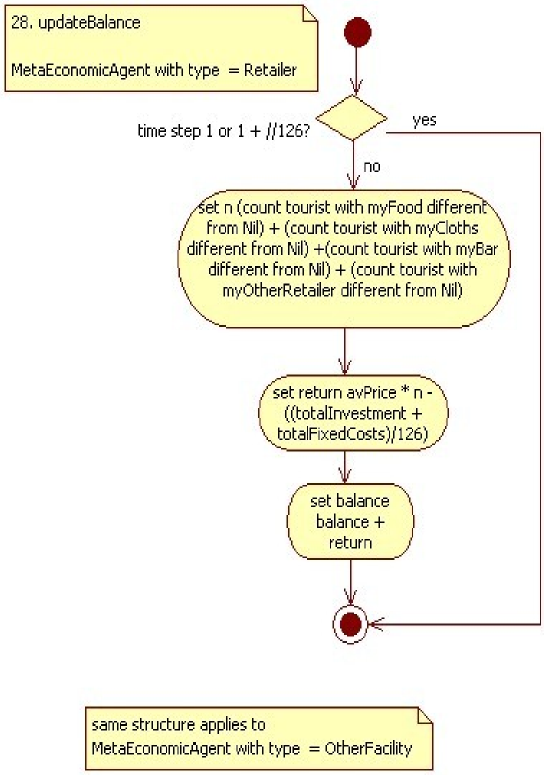


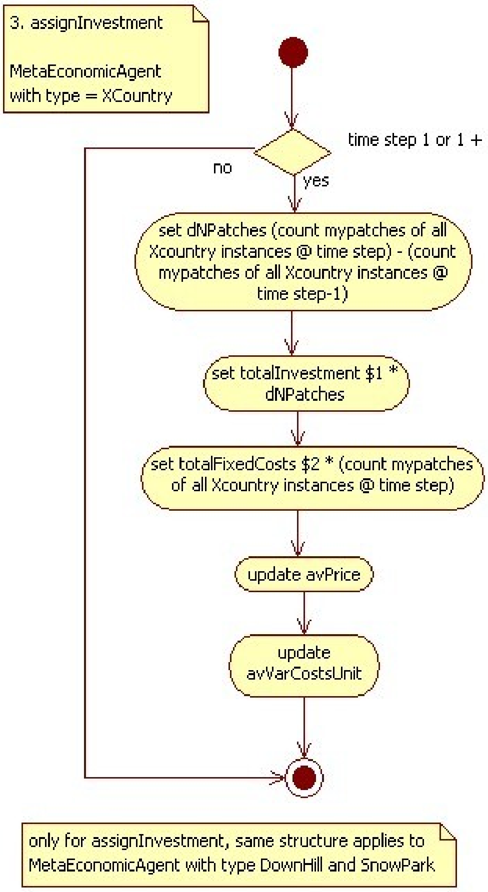


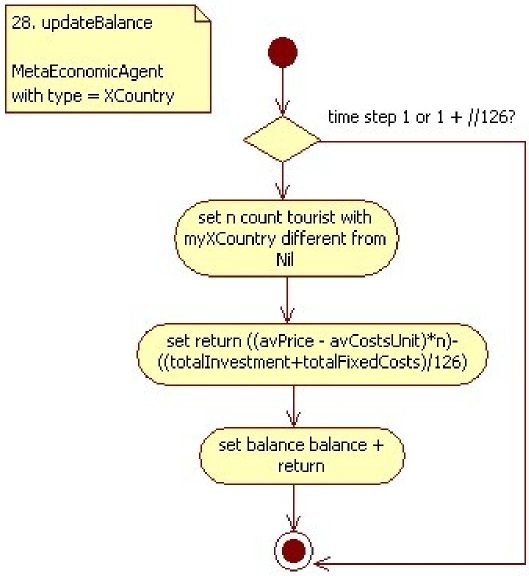

3. assignInvestment
MetaEconomicAgent with type = OffPiste
time step 1 or 1+//126?
no
yes
set dNLifts (sum nLifts of all OffPiste instances @ time step) - (sum nLifts of all OffPiste instances @ time step-1)
set totalInvestment $1 * dNLifts
set totalFixedCosts $2 * (sum nLifts of all OffPiste instances)
update avPrice
update avVarCostsUnit

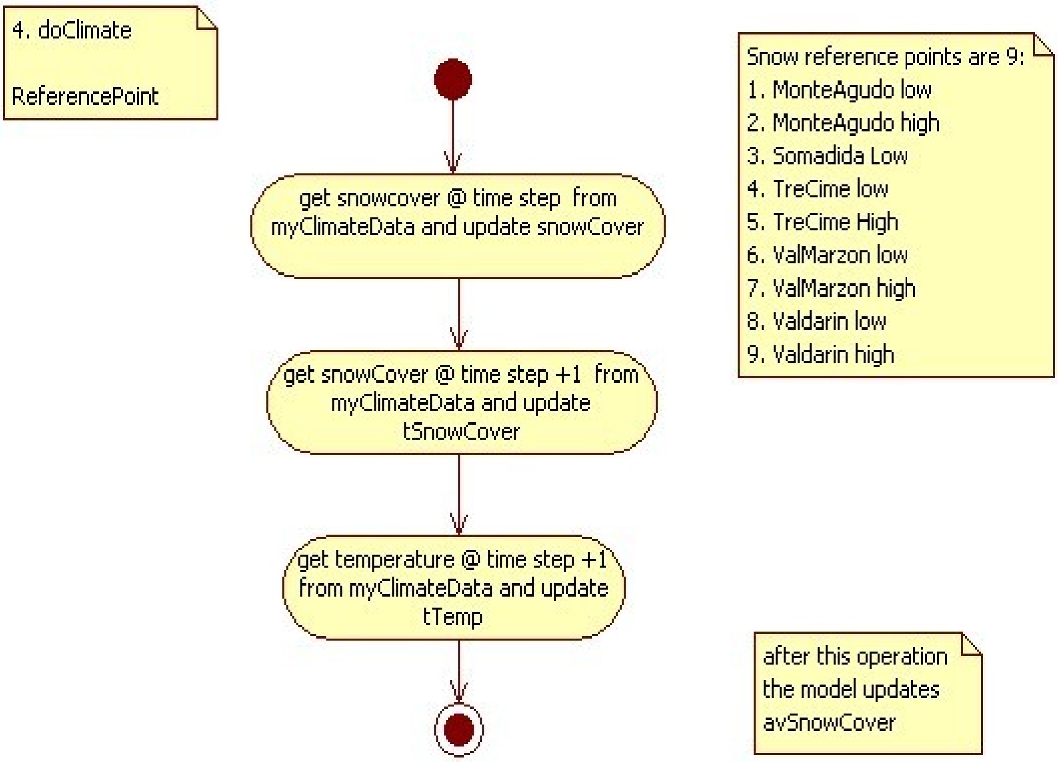

28. updateBalance
MetaEconomicAgent with type = OffPiste
time step 1 or 1+//126?
yes
no
set n count tourist with myOffPiste different from Nil
set return ((avPrice - avCostsUnit)*n)-((totalInvestment+totalFixedCosts)/126)
set balance balance + return

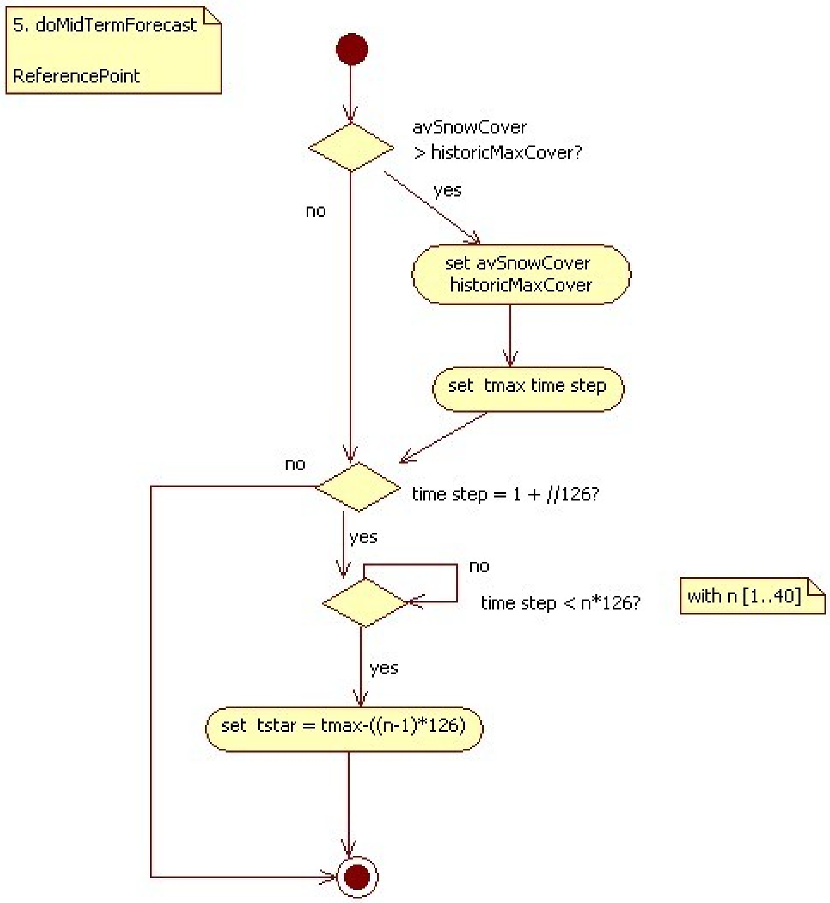

3. assignInvestment
MetaEconomicAgent with type = Retailer
time step 1 or 1 + //126?
no
yes
set dNFood count retailers with type food @ time step - count retailers with type food @ time step-1
set dNCloths count retailers with type cloths @ time step - count retailers with type cloths @ time step-1
set dNBar count retailers with type bar @ time step - count retailers with type bar @ time step-1
set dNOtherRetailer count retailers with type other @ time step - count retailers with type other @ time step-1
set totalInvestment $1 *dNFood + $2 *dNCloths + $3 dNBar + $4 * dNOtherRetailer
set totalFixedCosts $5 * (count retailers with type food) + $6 * (count retailers with type cloths) + $7* (count retailers with type bar) +$8* (count retailers with type other)
update avPrice

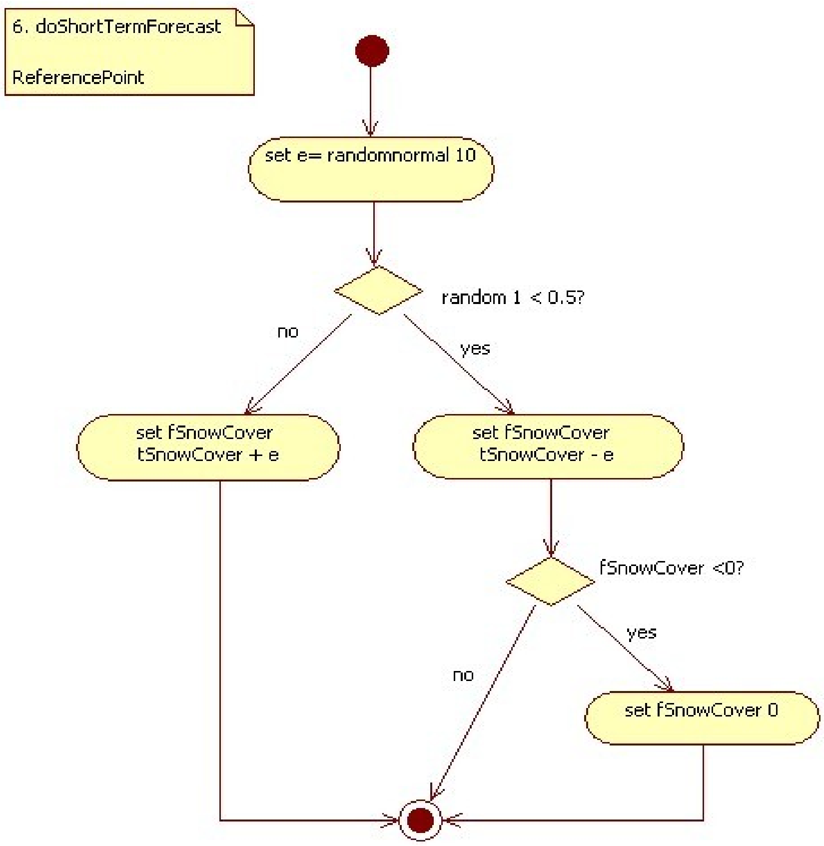

28. updateBalance
MetaEconomicAgent with type = Retailer
time step 1 or 1 + //126?
yes
no
set n (count tourist with myFood different from Nil) + (count tourist with myCloths different from Nil) +(count tourist with myBar different from Nil) + (count tourist with myOtherRetailer different from Nil)
set return avPrice * n - ((totalInvestment + totalFixedCosts)/126)
set balance balance + return
same structure applies to MetaEconomicAgent with type = OtherFacility

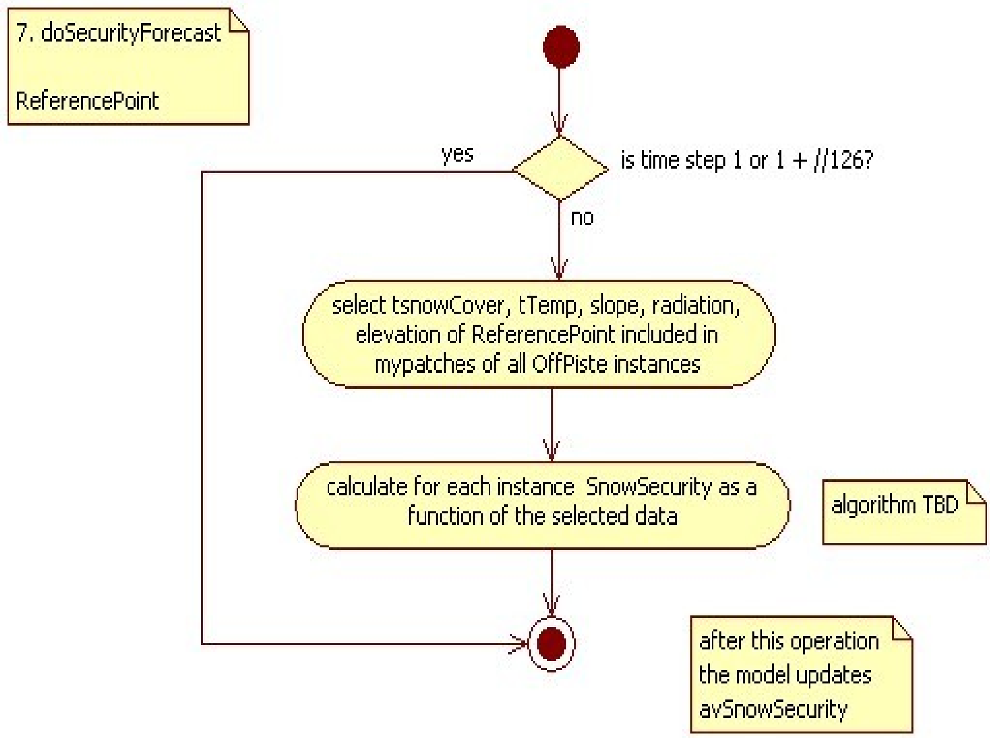

3. assignInvestment
MetaEconomicAgent
with type = XCountry
time step 1 or 1 + //126?
no
yes
set dNPatches (count mypatches of all Xcountry instances @ time step) - (count mypatches of all Xcountry instances @ time step-1)
set totalInvestment $1 * dNPatches
set totalFixedCosts $2 * (count mypatches of all Xcountry instances @ time step)
update avPrice
update avVarCostsUnit
only for assignInvestment, same structure applies to MetaEconomicAgent with type DownHill and SnowPark

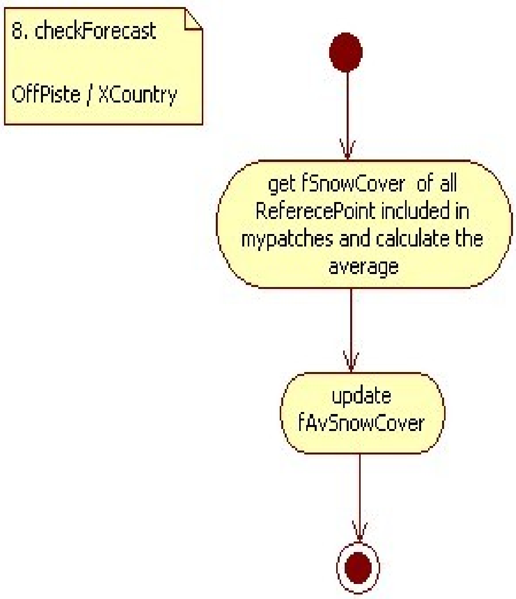

28. updateBalance
MetaEconomicAgent
with type = XCountry
time step 1 or 1 + //126?
set n count tourist with myXCountry different from Nil
set return ((avPrice - avCostsUnit)*n)-((totalInvestment+totalFixedCosts)/126)
set balance balance + return

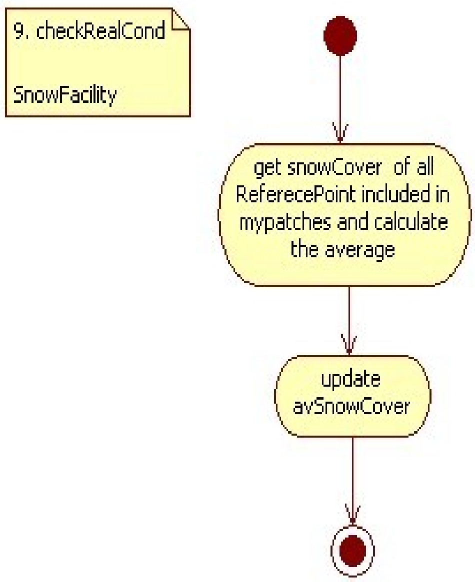

4. doClimate
ReferencePoint
get snowcover @ time step from myClimateData and update snowCover
get snowCover @ time step +1 from myClimateData and update tSnowCover
get temperature @ time step +1 from myClimateData and update tTemp
Snow reference points are 9:
1. MonteAgudo low
2. MonteAgudo high
3. Somadida Low
4. TreCime low
5. TreCime High
6. ValMarzon low
7. ValMarzon high
8. Valdarin low
9. Valdarin high
after this operation the model updates avSnowCover

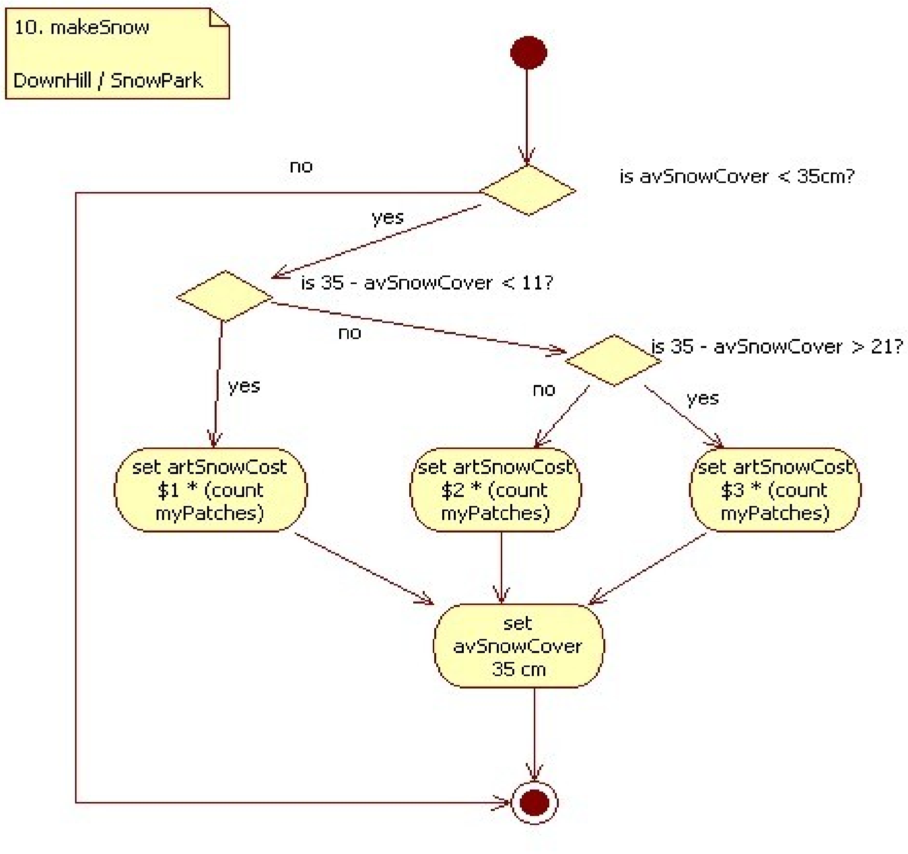

5. doMidTermForecast
ReferencePoint
avSnowCover
> historicMaxCover?
yes
no
set avSnowCover
historicMaxCover
set tmax time step
no
time step = 1 + //126?
yes
no
time step < n*126?
with n [1..40]
yes
set tstar = tmax-((n-1)*126)


6. doShortTermForecast
ReferencePoint
set e= randomnormal 10
random 1 < 0.5?
no
yes
set fSnowCover
tSnowCover + e
set fSnowCover
tSnowCover - e
fSnowCover <0?
yes
no
set fSnowCover 0

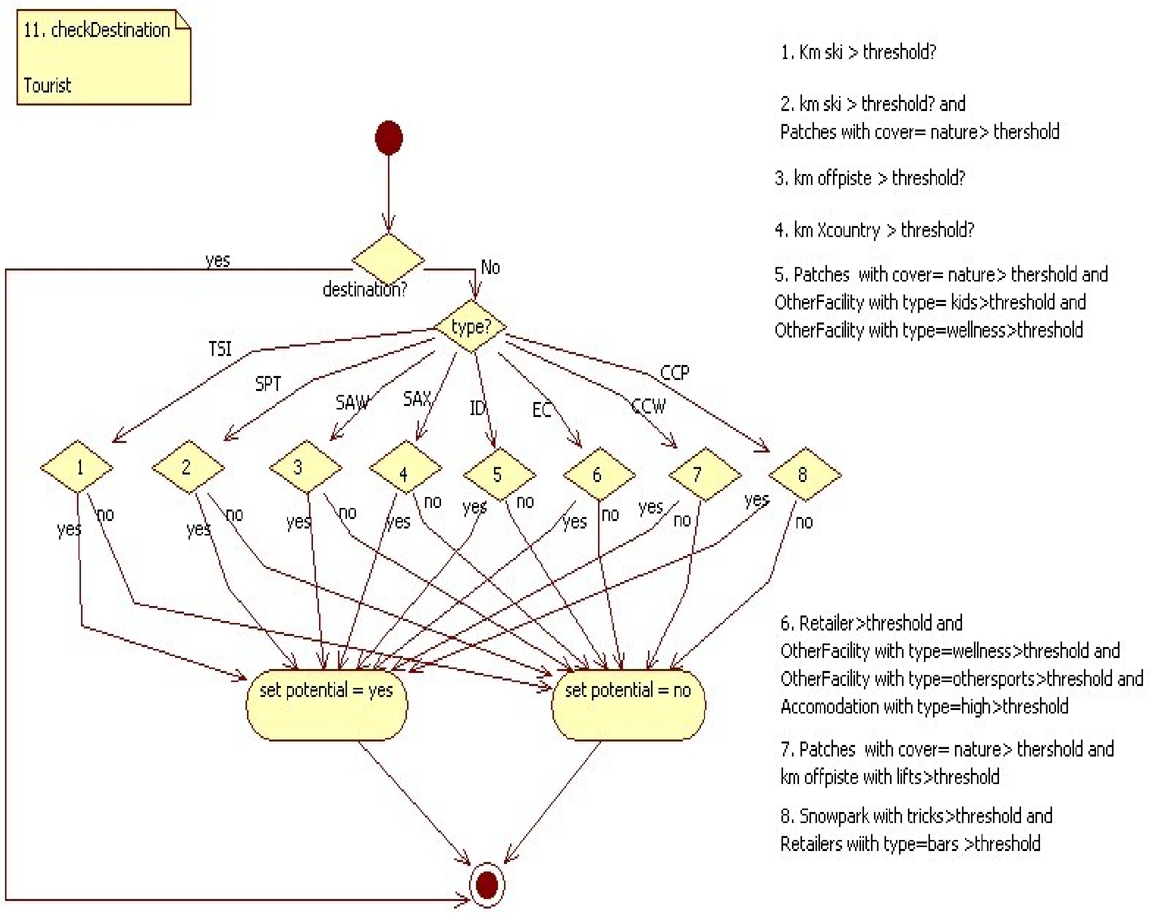

7. doSecurityForecast
ReferencePoint
yes
is time step 1 or 1 + //126?
no
select tsnowCover, tTemp, slope, radiation, elevation of ReferencePoint included in mypatches of all OffPiste instances
calculate for each instance SnowSecurity as a function of the selected data
algorithm TBD
after this operation the model updates avSnowSecurity


8. checkForecast
OffPiste / XCountry
get fSnowCover of all RefercePoint included in mypatches and calculate the average
update fAvSnowCover

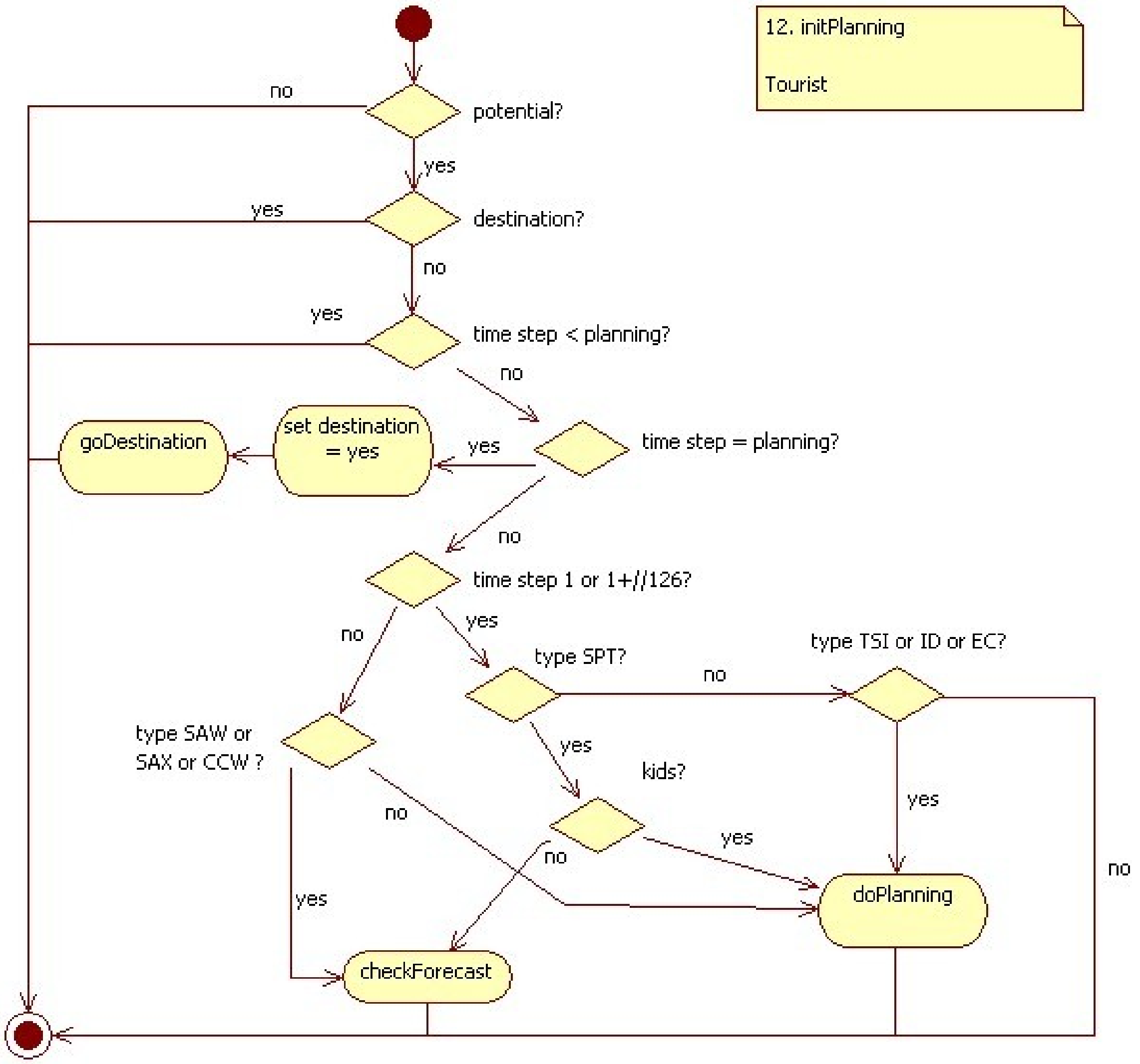

9. checkRealCond
SnowFacility
get snowCover of all RefercePoint included in mypatches and calculate the average
update avSnowCover



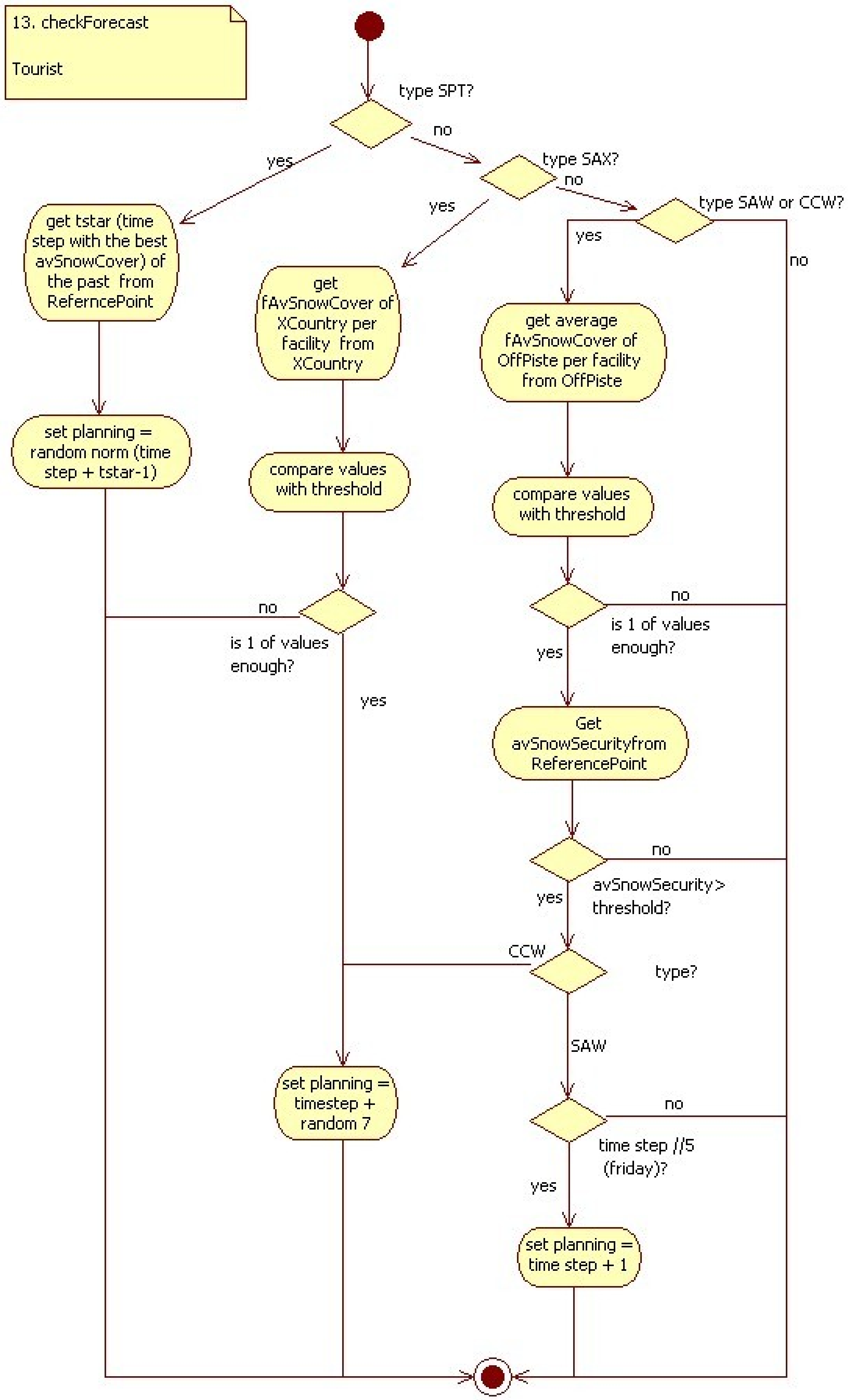
10. makeSnow
DownHill / SnowPark
is avSnowCover < 35cm?
no
yes
is 35 - avSnowCover < 11?
no
yes
is 35 - avSnowCover > 21?
no
yes
set artSnowCost $1 * (count myPatches)
set artSnowCost $2 * (count myPatches)
set artSnowCost $3 * (count myPatches)
set avSnowCover 35 cm

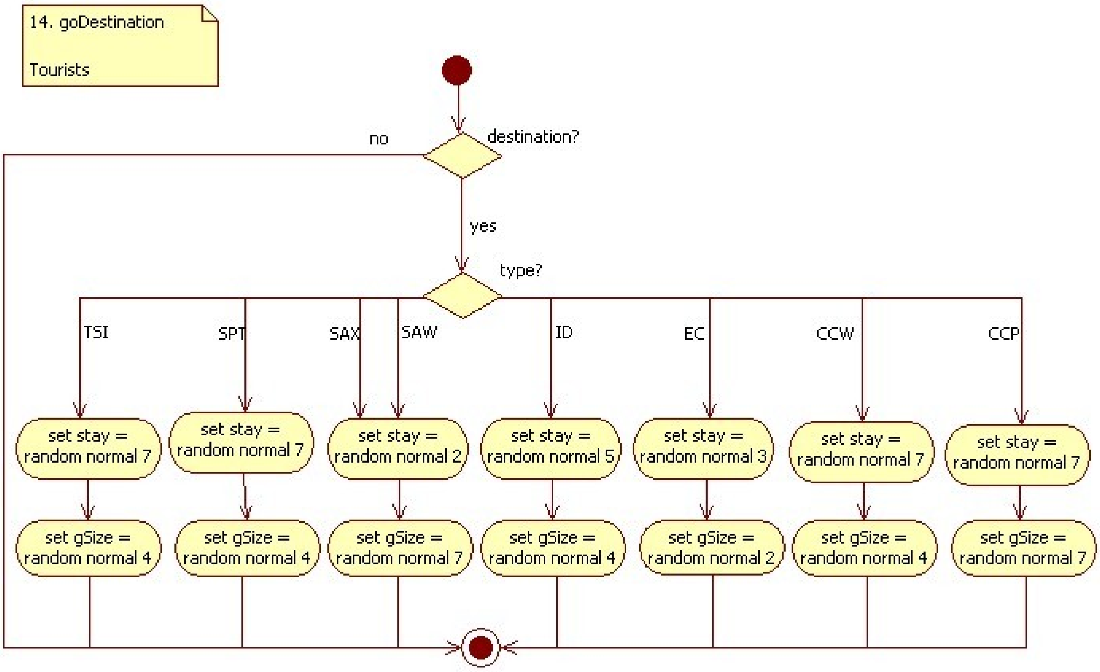


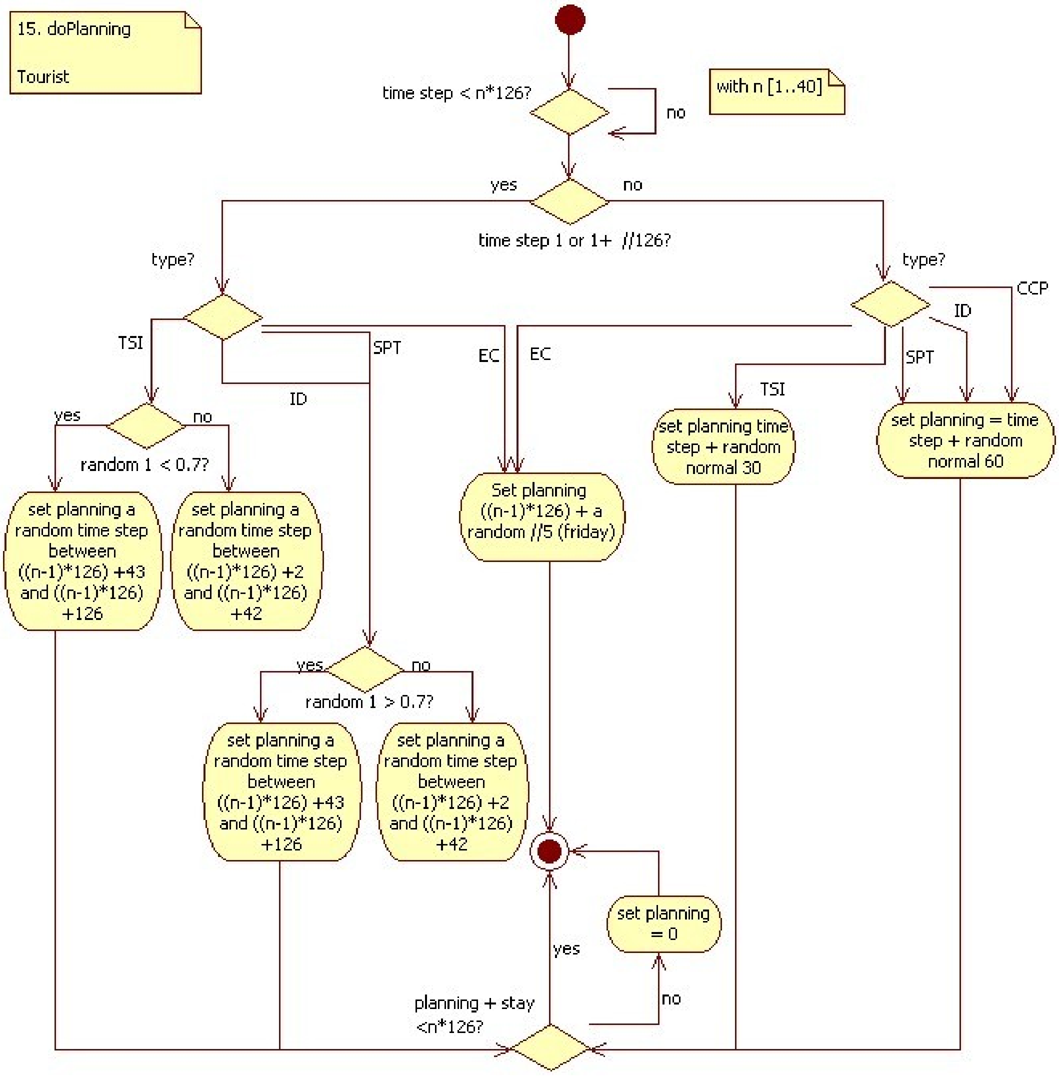
11. checkDestination
Tourist
destination?
yes
No
type?
TSI
SPT
SAW
SAX
ID
EC
CCW
CCP
1
2
3
4
5
6
7
8
yes
no
set potential = yes
set potential = no
1. Km ski > threshold?
2. km ski > threshold? and
Patches with cover= nature> thershold
3. km offpiste > threshold?
4. km Xcountry > threshold?
5. Patches with cover= nature> thershold and
OtherFacility with type= kids>threshold and
OtherFacility with type=wellness>threshold
6. Retailer>threshold and
OtherFacility with type=wellness>threshold and
OtherFacility with type=othersports>threshold and
Accomodation with type=high>threshold
7. Patches with cover= nature> thershold and
km offpiste with lifts>threshold
8. Snowpark with tricks>threshold and
Retailers wiith type=bars >threshold

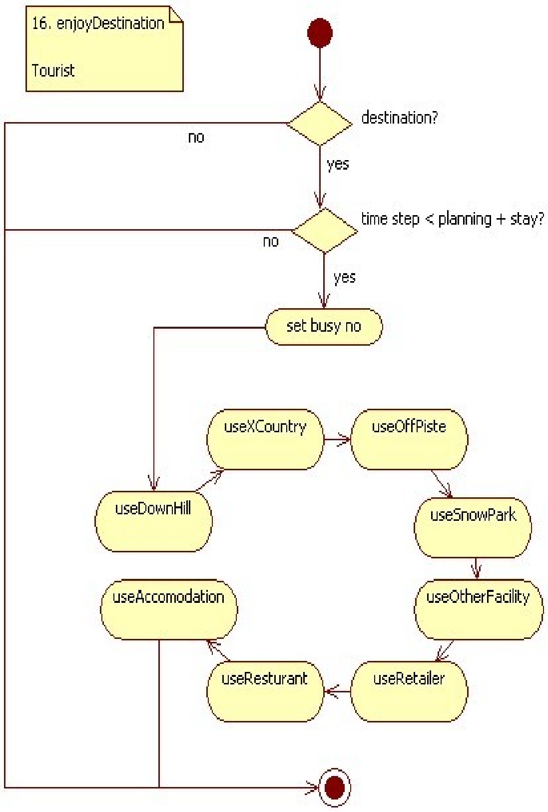


12. initPlanning
Tourist
no
potential?
yes
yes
destination?
no
yes
time step < planning?
no
goDestination
set destination = yes
yes
time step = planning?
no
time step 1 or 1+//126?
no
yes
type SPT?
no
type TSI or ID or EC?
type SAW or SAX or CCW ?
yes
kids?
yes
no
yes
no
no
yes
doPlanning
checkForecast

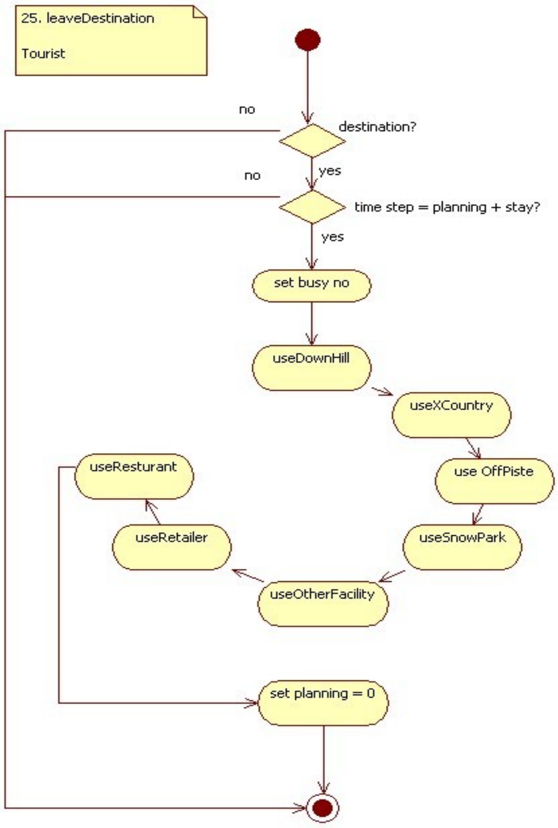

13. checkForecast
Tourist
type SPT?
no
yes
type SAX?
no
yes
type SAW or CCW?
yes
no
get tstar (time step with the best avSnowCover) of the past from ReferncePoint
get fAvSnowCover of XCountry per facility from XCountry
get average fAvSnowCover of OffPiste per facility from OffPiste
set planning = random norm (time step + tstar-1)
compare values with threshold
compare values with threshold
no
is 1 of values enough?
yes
no
is 1 of values enough?
yes
Get avSnowSecurityfrom ReferencePoint
no
avSnowSecurity> threshold?
yes
CCW
type?
SAW
set planning = timestep + random 7
no
time step //5 (friday)?
yes
set planning = time step + 1


14. goDestination
Tourists
destination?
no
yes
type?
TSI
SPT
SAX
SAW
ID
EC
CCW
CCP
set stay = random normal 7
set stay = random normal 7
set stay = random normal 2
set stay = random normal 5
set stay = random normal 3
set stay = random normal 7
set stay = random normal 7
set gSize = random normal 4
set gSize = random normal 4
set gSize = random normal 7
set gSize = random normal 4
set gSize = random normal 2
set gSize = random normal 4
set gSize = random normal 7

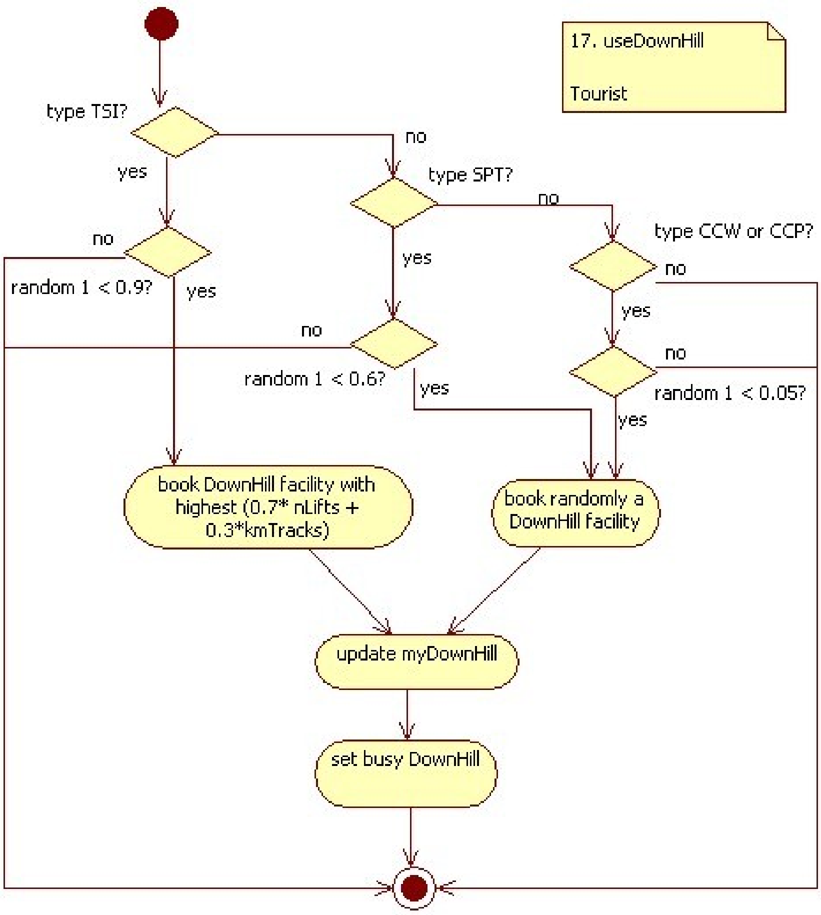

15. doPlanning
Tourist
time step < n*126?
no
with n [1..40]
yes
no
time step 1 or 1+ //126?
type?
type?
TSI
SPT
ID
EC
EC
CCP
ID
SPT
TSI
yes
no
random 1 < 0.7?
set planning a random time step between ((n-1)*126) +43 and ((n-1)*126) +126
set planning a random time step between ((n-1)*126) +2 and ((n-1)*126) +42
Set planning ((n-1)*126) + a random //5 (friday)
set planning time step + random normal 30
set planning = time step + random normal 60
yes
no
random 1 > 0.7?
set planning a random time step between ((n-1)*126) +43 and ((n-1)*126) +126
set planning a random time step between ((n-1)*126) +2 and ((n-1)*126) +42
set planning = 0
yes
no
planning + stay <n*126?



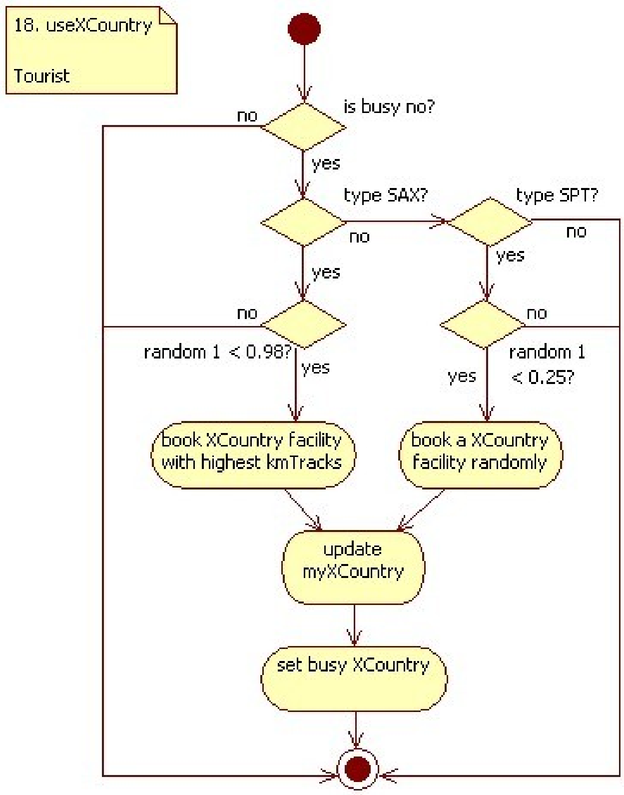
16. enjoyDestination
Tourist
destination?
no
yes
time step < planning + stay?
no
yes
set busy no
useXCountry
useOffPiste
useDownHill
useSnowPark
useAccomodation
useOtherFacility
useResturant
useRetailer



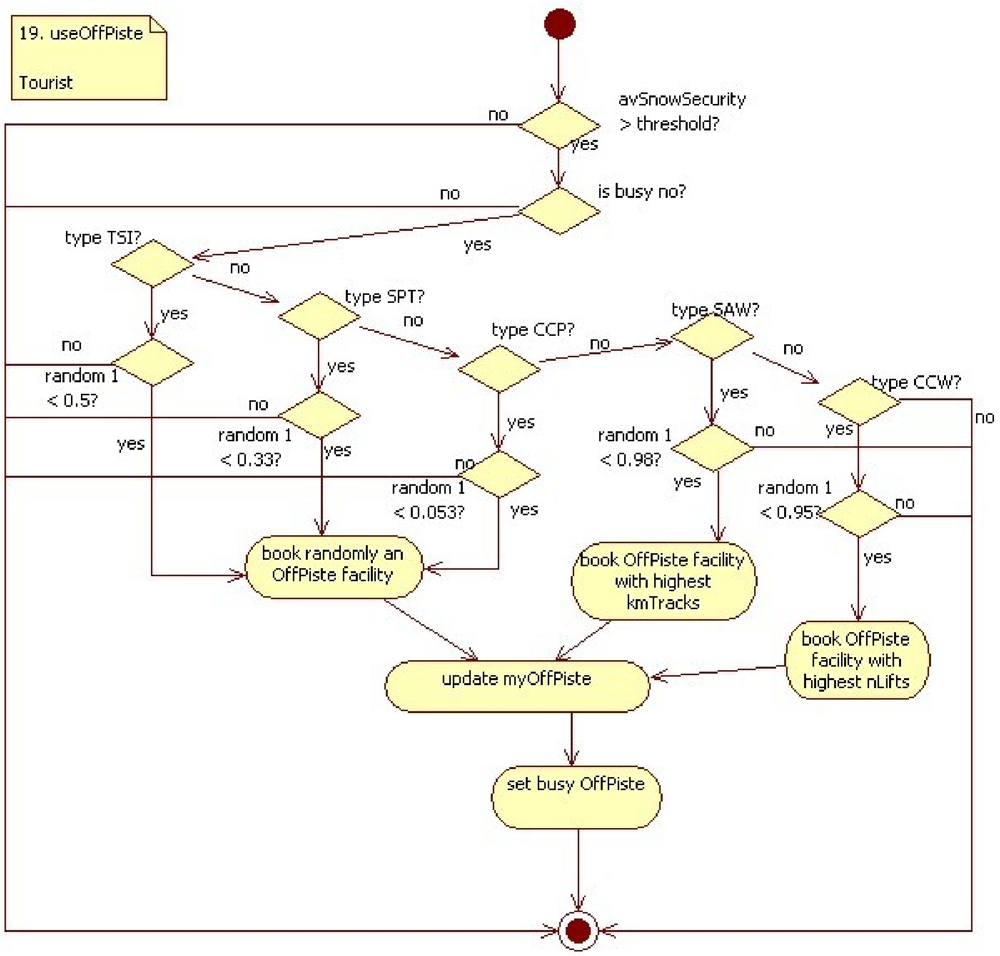
25. leaveDestination
Tourist
no
destination?
no
yes
time step = planning + stay?
yes
set busy no
useDownHill
useXCountry
useResturant
use OffPiste
useRetailer
useSnowPark
useOtherFacility
set planning = 0



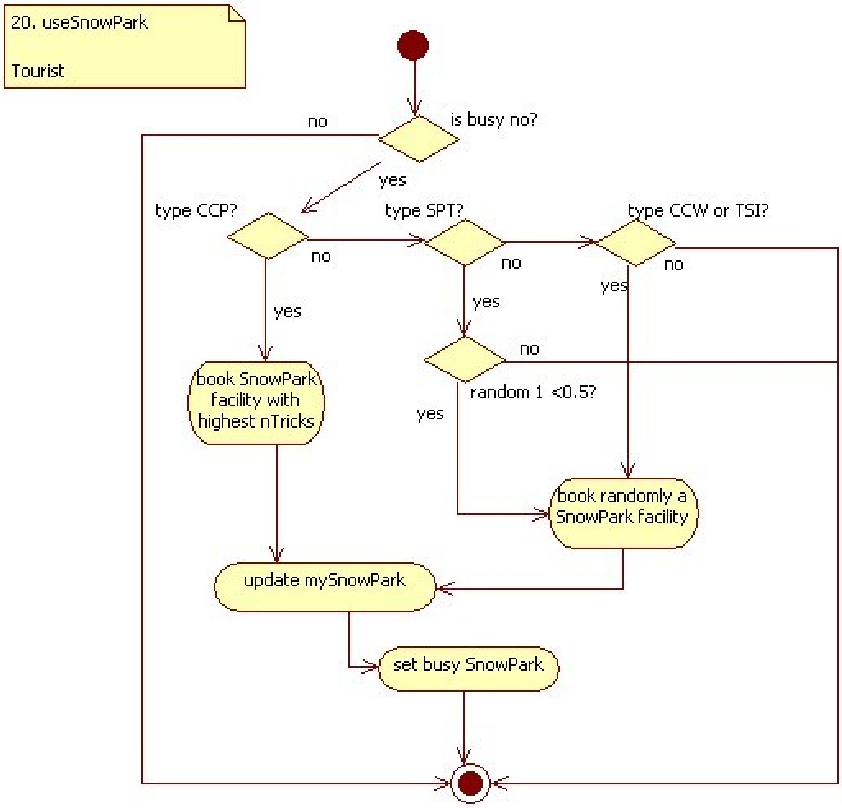
17. useDownHill
Tourist
type TSI?
no
yes
type SPT?
no
type CCW or CCP?
no
random 1 < 0.9?
yes
yes
no
yes
no
random 1 < 0.6?
yes
no
random 1 < 0.05?
yes
book DownHill facility with highest (0.7* nLifts + 0.3*kmTracks)
book randomly a DownHill facility
update myDownHill
set busy DownHill

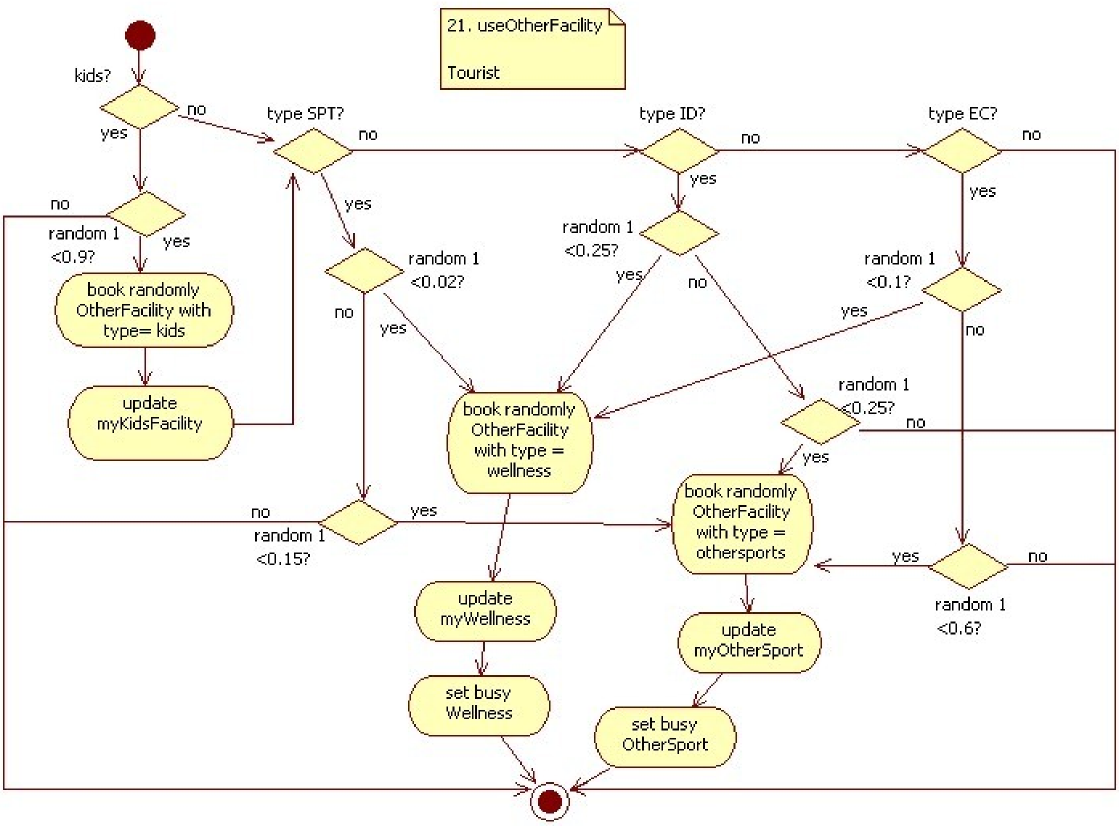


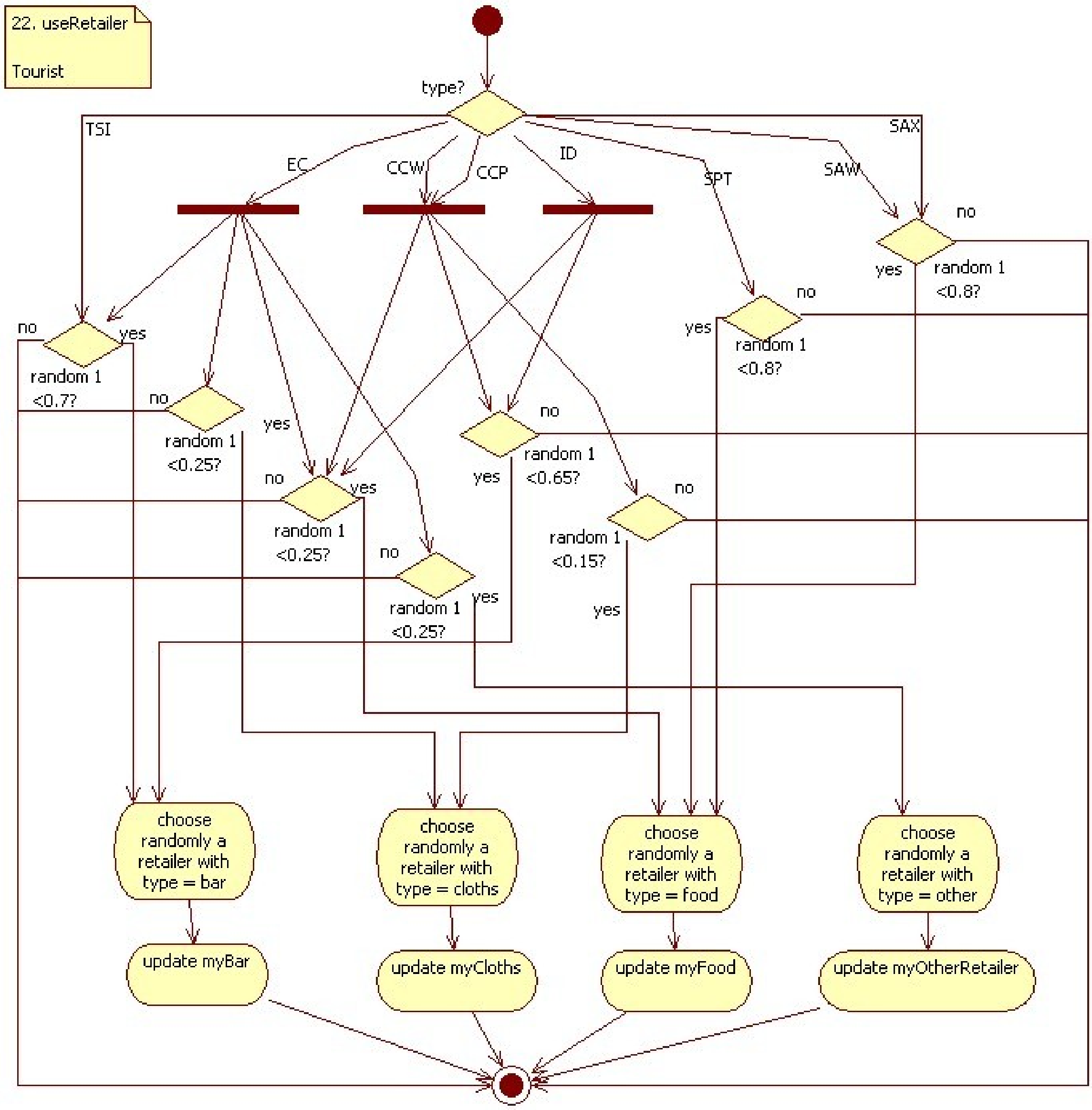
18. useXCountry
Tourist
is busy no?
no
yes
type SAX?
type SPT?
no
no
yes
yes
no
no
random 1 < 0.98?
yes
random 1
< 0.25?
yes
book XCountry facility with highest kmTracks
book a XCountry facility randomly
update myXCountry
set busy XCountry

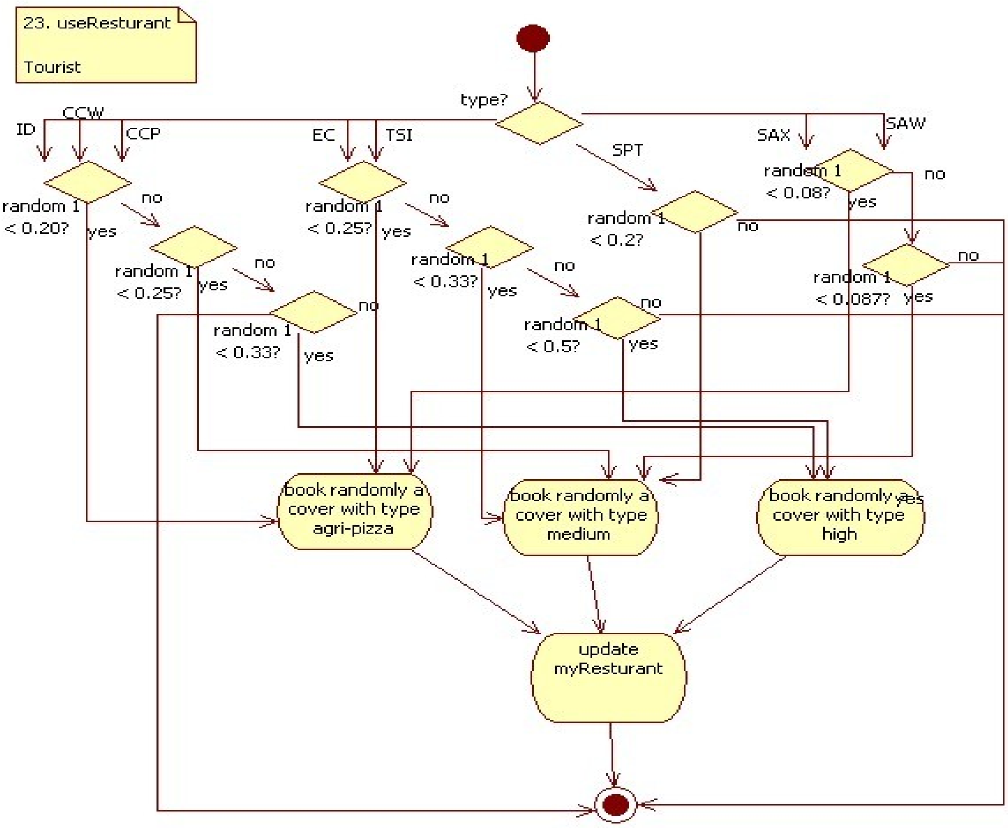


19. useOffPiste
Tourist
avSnowSecurity
> threshold?
no
yes
is busy no?
no
yes
type TSI?
no
yes
type SPT?
no
type CCP?
no
type SAW?
no
type CCW?
no
random 1
< 0.5?
yes
random 1
< 0.33?
random 1
< 0.053?
random 1
< 0.98?
random 1
< 0.95?
yes
book randomly an OffPiste facility
book OffPiste facility with highest kmTracks
book OffPiste facility with highest nLifts
update myOffPiste
set busy OffPiste

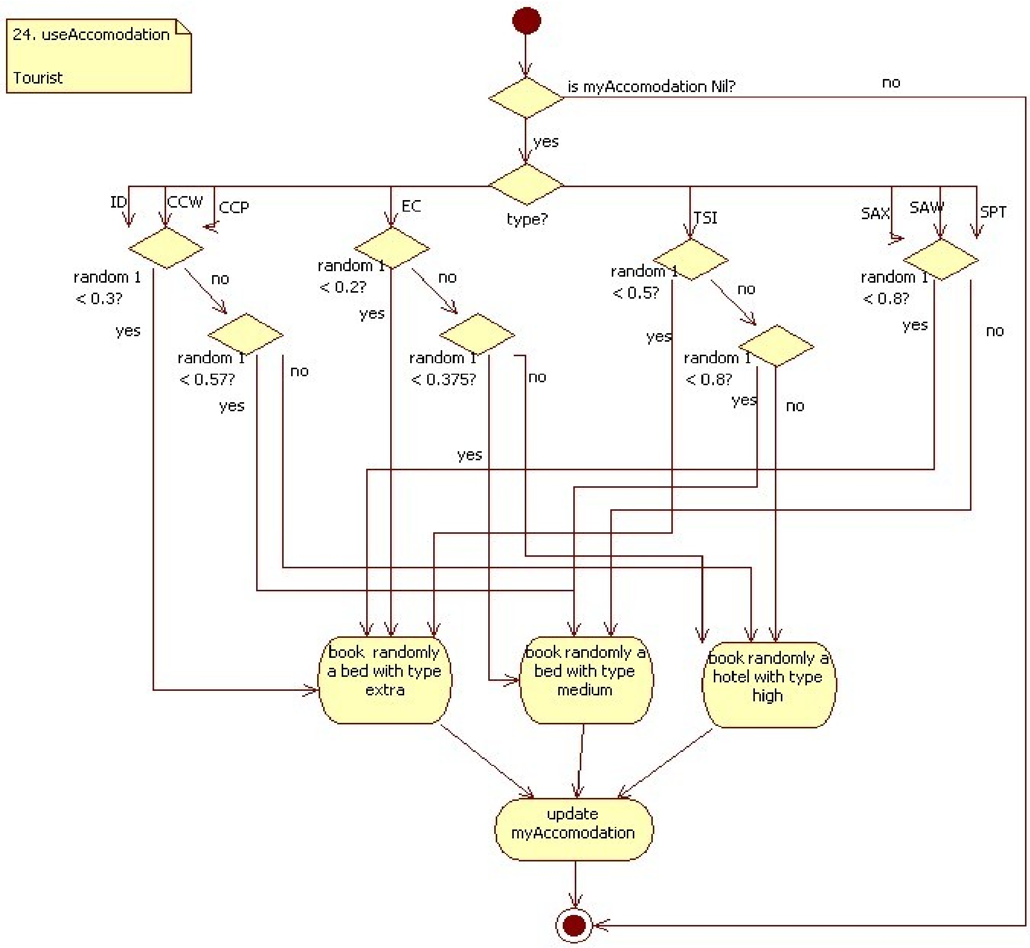

20. useSnowPark
Tourist
is busy no?
no
yes
type CCP?
type SPT?
type CCW or TSI?
no
no
no
yes
yes
yes
no
book SnowPark facility with highest nTricks
random 1 <0.5?
yes
book randomly a SnowPark facility
update mySnowPark
set busy SnowPark


21. useOtherFacility
Tourist
kids?
no
yes
type SPT?
no
type ID?
no
type EC?
no
no
random 1 <0.9?
yes
yes
yes
yes
book randomly OtherFacility with type= kids
random 1 <0.02?
random 1 <0.25?
yes
no
random 1 <0.1?
yes
no
no
yes
update myKidsFacility
book randomly OtherFacility with type = wellness
random 1 <0.25?
no
yes
no
random 1 <0.15?
yes
book randomly OtherFacility with type = othersports
yes
no
random 1 <0.6?
update myWellness
update myOtherSport
set busy Wellness
set busy OtherSport

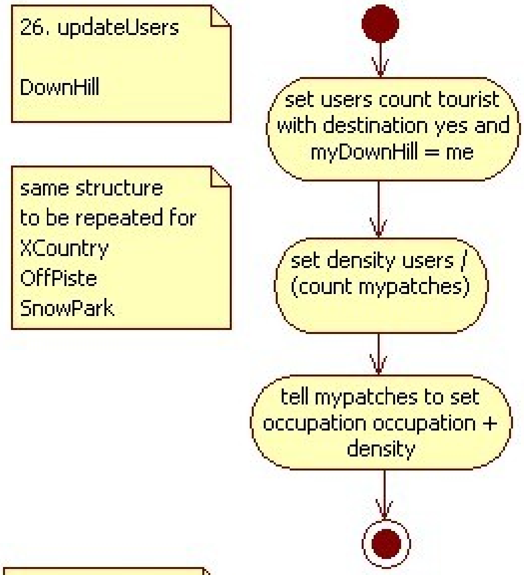

22. useRetailer
Tourist
type?
TSI
EC
CCW
CCP
ID
SPT
SAW
SAX
no
yes
random 1
<0.8?
no
yes
random 1
<0.8?
no
yes
random 1
<0.7?
no
random 1
<0.25?
yes
no
yes
random 1
<0.25?
no
yes
random 1
<0.65?
no
random 1
<0.15?
yes
no
yes
random 1
<0.25?
choose randomly a retailer with type = bar
choose randomly a retailer with type = cloths
choose randomly a retailer with type = food
choose randomly a retailer with type = other
update myBar
update myCloths
update myFood
update myOtherRetailer

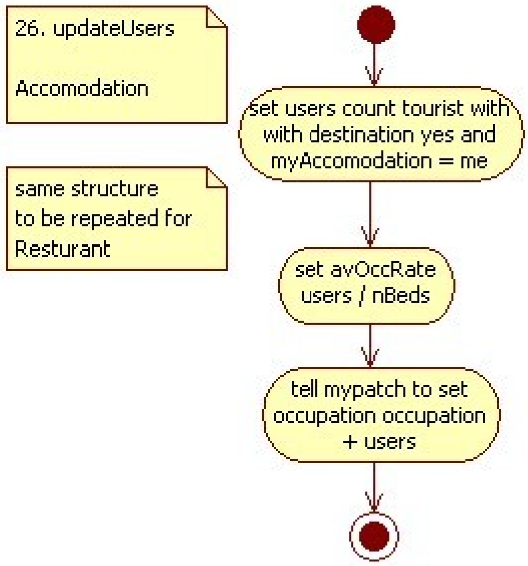


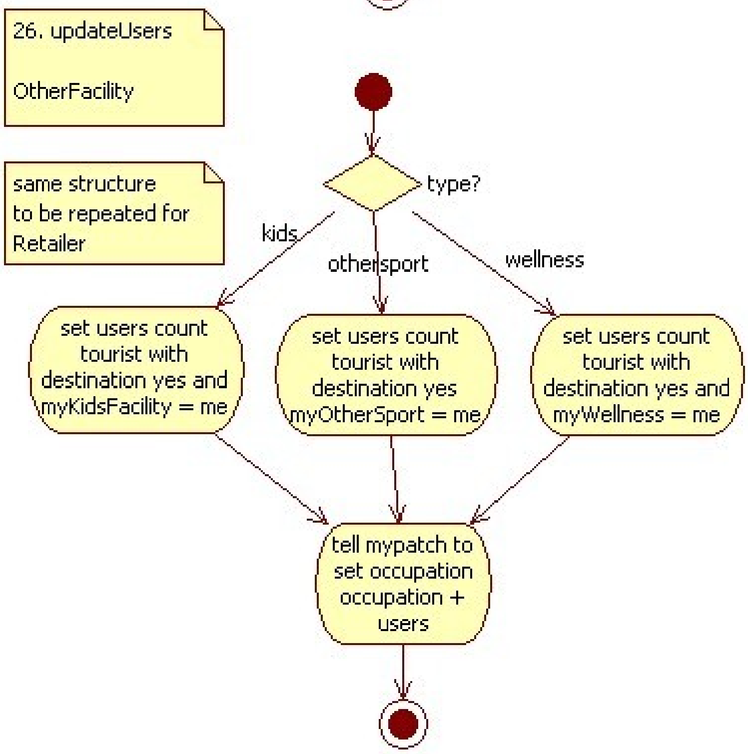
23. useResturant
Tourist
type?
ID
CCW
CCP
EC
TSI
SPT
SAX
SAW
random 1 < 0.20?
random 1 < 0.25?
random 1 < 0.33?
random 1 < 0.2?
random 1 < 0.08?
random 1 < 0.087?
random 1 < 0.5?
yes
no
book randomly a cover with type agri-pizza
book randomly a cover with type medium
book randomly a cover with type high
update myResturant

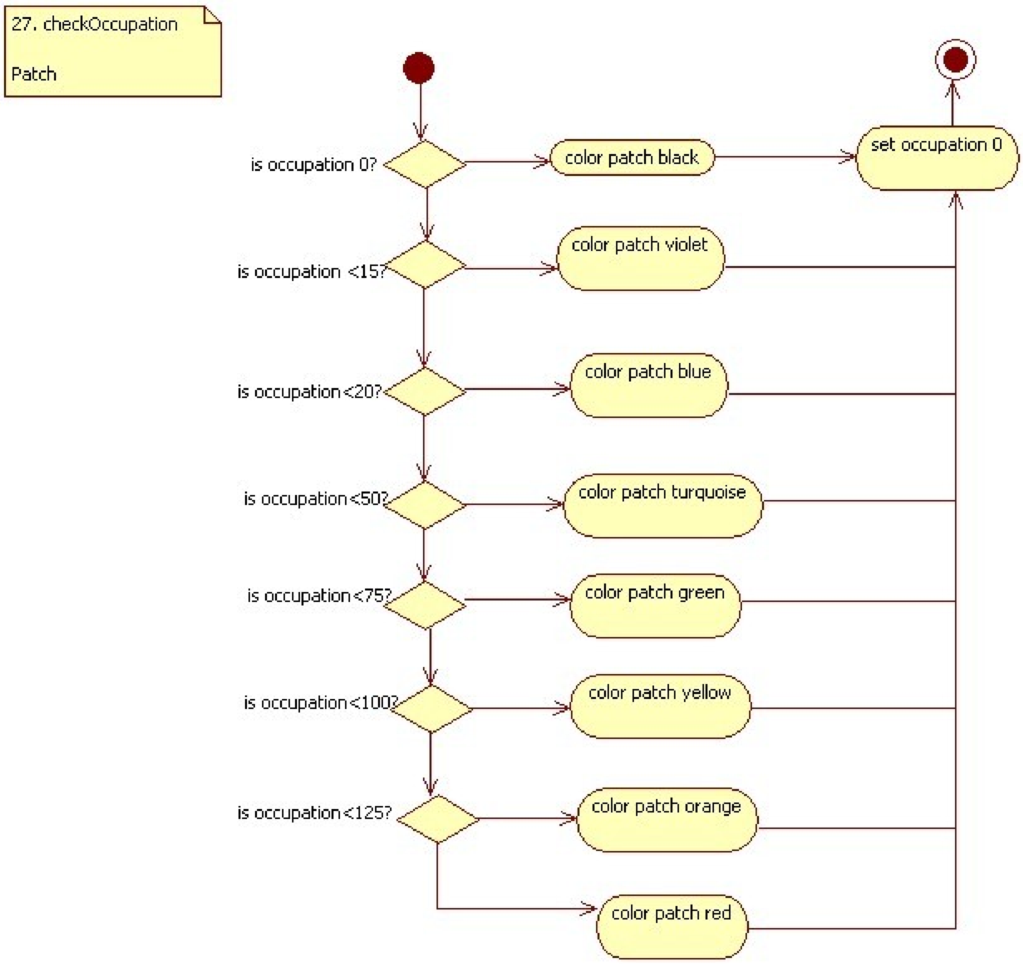


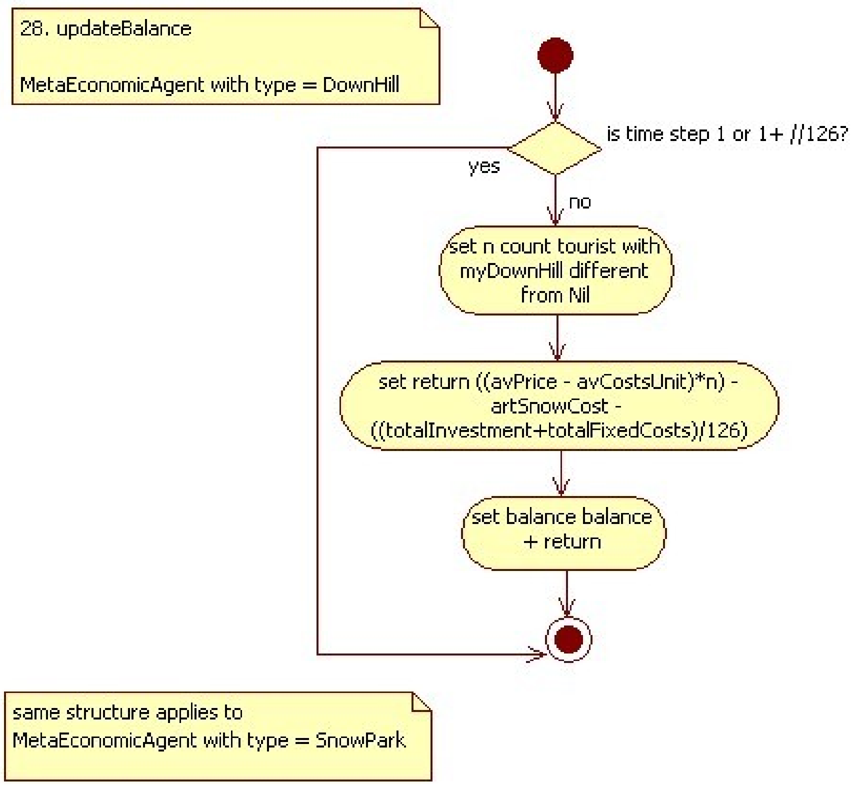
24. useAccomodation
Tourist
is myAccomodation Nil?
no
yes
type?
ID
CCW
CCP
EC
TSI
SAX
SAW
SPT
random 1 < 0.3?
random 1 < 0.57?
random 1 < 0.2?
random 1 < 0.375?
random 1 < 0.5?
random 1 < 0.8?
book randomly a bed with type extra
book randomly a bed with type medium
book randomly a hotel with type high
update myAccomodation

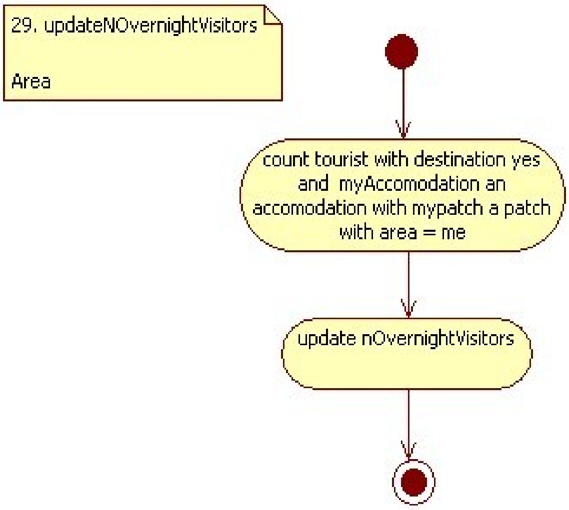

26. updateUsers
DownHill
same structure to be repeated for XCountry OffPiste SnowPark
set users count tourist with destination yes and myDownHill = me
set density users / (count mypatches)
tell mypatches to set occupation occupation + density

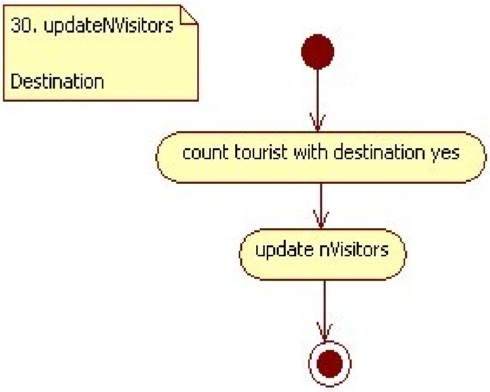

26. updateUsers
Accomodation
same structure to be repeated for Resturant
set users count tourist with with destination yes and myAccomodation = me
set avOccRate users / nBeds
tell mypatch to set occupation occupation + users

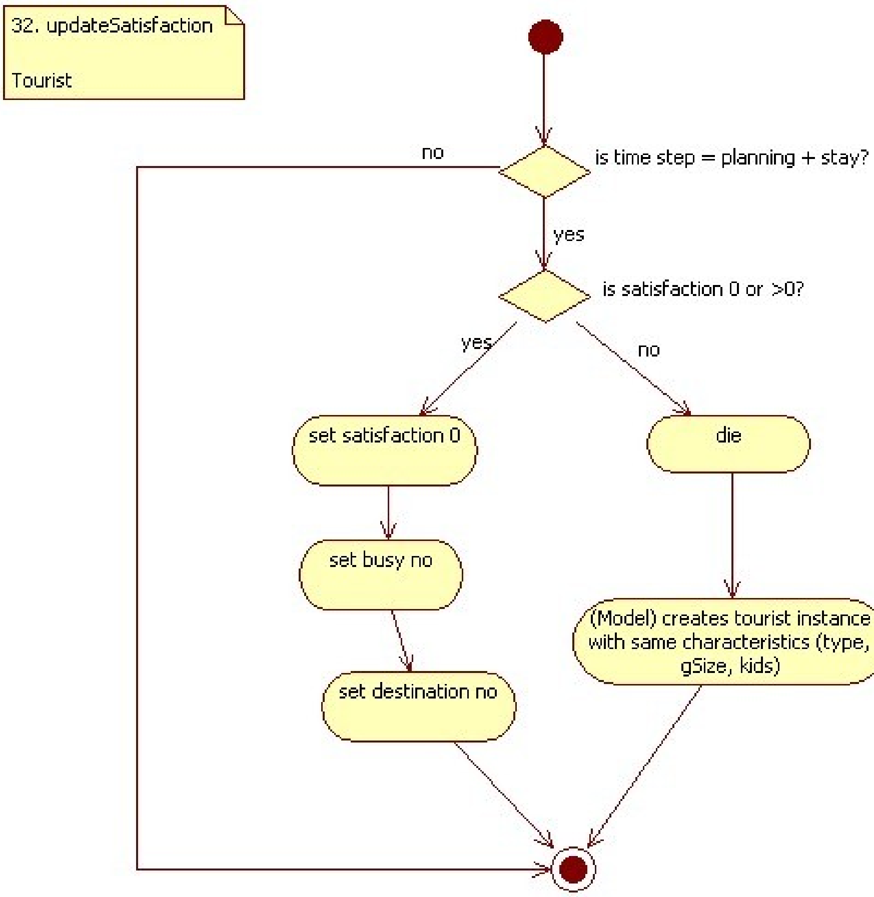

26. updateUsers
OtherFacility
same structure to be repeated for Retailer
type?
kids
othersport
wellness
set users count tourist with destination yes and myKidsFacility = me
set users count tourist with destination yes myOtherSport = me
set users count tourist with destination yes and myWellness = me
tell mypatch to set occupation occupation + users

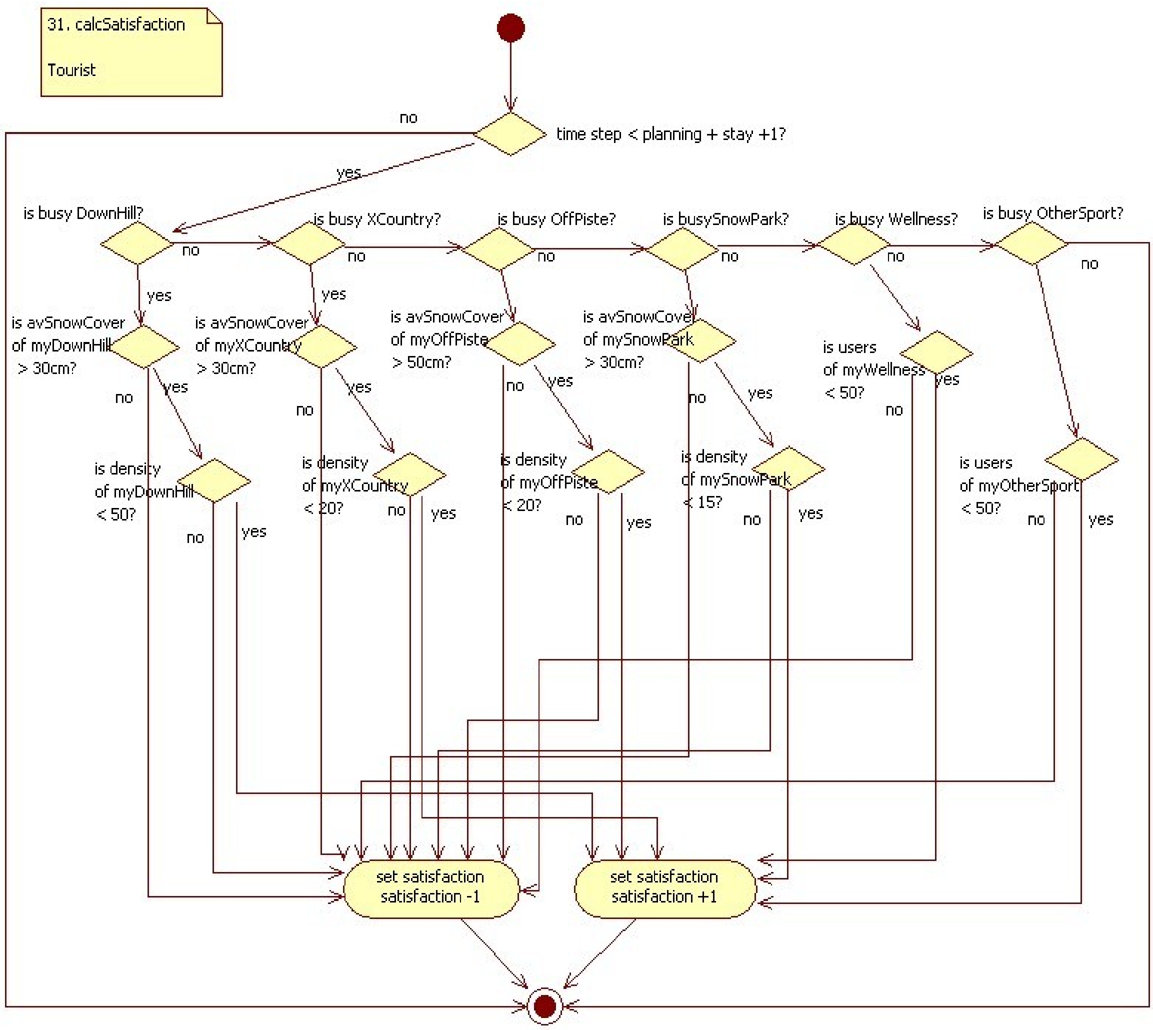

27. checkOccupation
Patch
is occupation 0?
color patch black
set occupation 0
is occupation <15?
color patch violet
is occupation<20?
color patch blue
is occupation<50?
color patch turquoise
is occupation<75?
color patch green
is occupation<100?
color patch yellow
is occupation<125?
color patch orange
color patch red


28. updateBalance
MetaEconomicAgent with type = DownHill
is time step 1 or 1+ //126?
yes
no
set n count tourist with myDownHill different from Nil
set return ((avPrice - avCostsUnit)*n) - artSnowCost - ((totalInvestment+totalFixedCosts)/126)
set balance balance + return
same structure applies to
MetaEconomicAgent with type = SnowPark


29. updateNOvernightVisitors
Area
count tourist with destination yes and myAccomodation an accomodation with mypatch a patch with area = me
update nOvernightVisitors


30. updateNVisitors
Destination
count tourist with destination yes
update nVisitors


32. updateSatisfaction
Tourist
is time step = planning + stay?
no
yes
is satisfaction 0 or >0?
yes
no
set satisfaction 0
set busy no
set destination no
die
(Model) creates tourist instance with same characteristics (type, gSize, kids)


31. calcSatisfaction
Tourist
time step < planning + stay +1?
no
yes
is busy DownHill?
is busy XCountry?
is busy OffPiste?
is busySnowPark?
is busy Wellness?
is busy OtherSport?
is avSnowCover of myDownHill > 30cm?
is avSnowCover of myXCountry > 30cm?
is avSnowCover of myOffPiste > 50cm?
is avSnowCover of mySnowPark > 30cm?
is users of myWellness < 50?
is density of myDownHill < 50?
is density of myXCountry < 20?
is density of myOffPiste < 20?
is density of mySnowPark < 15?
is users of myOtherSport < 50?
set satisfaction satisfaction -1
set satisfaction satisfaction +1

AN AGENT-BASED INTEGRATED ASSESSMENT OF WINTER TOURISM DEVELOPMENT IN THE EUROPEAN ALPINE REGION[1]

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Abstract

This paper concerns the implementation of the conceptual agent-based model AuronzoWinSim, which has ultimately been programmed within the NetLogo 4.1 modelling environment. The model represents the winter tourism system of Auronzo di Cadore, a quite extended municipality located in the Dolomites, including a very diverse set of environmental and climatic conditions. The main acting agents are the winter tourists divided in eight heterogeneous profiles, according to their tourist fruition behavior. Sensitivity analysis is performed on the tourists' behavioral parameters. Validation is carried out both empirically and through stakeholders' inclusion. We use the model for assessing three hypothetical, divergent and infrastructure oriented development strategies of winter tourism supply, which have been discussed with the local stakeholders, as alternatives to the business as usual situation. These strategies are tested against multiple future scenarios, which project (a) the weather conditions in terms of snow cover and temperature, (b) the composition and the total number of tourist agents and (c) the type of market competition. We take into consideration a set of socio-economic indicators that are strongly coupled with relevant environmental implications. Conclusions are drawn on the robustness of the ranking of alternatives.

Keywords

Integrative Social Simulation, Multi-Agent Approach, Climate Change Adaptation, Winter Tourism Development

[1] A shorter version of this essay is planned to be published in mid 2011in the thematic issue on spatial agent-based models of the Environmental Modelling & Software journal.

1. INTRODUCTION

AuronzoWinSim (Balbi et al. 2010) is a conceptual model included in a European research effort that considers the possible impacts of climate change on tourism in the Alps. The ClimAlpTour project, which is under the EC Alpine Space Programme, brings together institutions and scholars from the Alpine arch to analyze multiple pilot sites and to produce a framework of joint recommendations in view of comprehensively dealing with this crucial issue[2]. As a matter of fact, climate change is already significantly affecting the European Alpine Region beyond the average temperature signals that have been registered at a global level (IPCC 2007). Everybody, even the climate skeptics, must face the evidence of a 50% decrease of glaciers' volume since 1850 (Castellari 2008). Establishing whether this change is human-induced or not is not relevant to this study, we are rather interested in exploring what this change, that cannot be ignored anymore by the people of the mountains, may imply for the winter tourism in the Alps and how local development can be driven to take it into account.

The AuronzoWinSim concept has been conceived as an exploratory and case-specific application of a spatially explicit agent-based model (ABM), capable of gathering heterogeneous but incomplete information, to produce computer simulations about possible futures, and discuss them with local stakeholders.

The model is an original concept in the sense that, to our knowledge, this is the very first application of agent-based modelling to investigate adaptation to climate change of winter tourism at a local level, integrating socio-economic and environmental components, and adopting a complexity science approach. The model, which has been firstly developed in Unified Modelling Language (UML) (Bock et al 1999), is meant to be fully tailored on the case study, the municipality of Auronzo di Cadore, located in the Dolomites. However, it has the potential to be generalized and eventually become an ontology of a generic winter tourism destination, especially for what concerns its conceptual structure in classes.

The spatial representation is particularly relevant given the characteristics of the system to be modelled that shows an extended geographical area with an evident bipolarity emerging from the presence of two main villages, Auronzo and Misurina, which stand at very different climatic and environmental conditions, and consequentially possess different elements of tourism attraction.

One further distinctive element that heavily influenced the model's design, and justifies *per se* the agent-based approach, is that we were interested in representing the supply-demand structure of the local winter tourism system capturing the multifaceted behavior of its active components. In particular, we opted for simulating the decision-making process of different typologies of winter tourists, including those that are currently preferring other destinations or that are emerging since recently as a post-modern social *phenomenon* of tourism fruition (i.e. free-style and free-ride).

The tourist's composition and their attitude towards the competing destinations contribute to the societal dimension of the model, which together with the climatic projections and the development strategies to be tested, allow for the constitution of multiple integrated scenarios. These are to be considered as a set of composed glimpses into reasonable futures[3]. Such a kind of formulation is also well suited for our case's participatory context, in which we could involve the public and

[2] For more information please visit the official project's website www.climalptour.eu

[3] "The formal purpose of validation therefore, can only be for purposes of calibration and not for forecasting. The purpose of the models themselves is to introduce precision into policy and strategy discussion. The validation exercise integrates the models into the discussions of longer term processes […]. The models are no more likely to be in any sense true than are narrative scenarios and they lack the richness of the narratives. By integrating the modelling process into the development of narrative scenarios, policy and strategy analysts obtain the benefits of formal precision and the benefits of the rich expressiveness of storylines and scenarios" (Moss 2008).

private actors constituting the supply side of the market, but we couldn't rely on the tourists' participation, especially with regard to the prospective ones.

Scientifically supporting discussions about the future conditions of the system is fundamental in order to take into account the entire spectrum of sustainability issues and climate change is certainly one of the most imperative of those, as the ClimAlpTour project suggests. However, in dealing with the stakeholders, we decided not to isolate climate change and treat it as self-standing issue for two main reasons: first, it is particularly ineffective at the local level, when the negationist attitude of certain actors could eventually turn the entire set of stakeholders into an hostile crowd, second, as a matter of fact, the winter alpine tourism is threatened by the maturity of the market demand (Bourdeau 2009) as much as, or even more than, by climate change. Indeed, we preferred to adopt a mainstreaming approach, meaning that we put emphasis on widening the stakeholders' perspectives about local development in order to include possible climatic threats. In this sense we interpret adaptation as a thoughtful and concerted process of tourism development planning.
The bottom line of the study is discussing about the future of Auronzo with its people (more precisely, a representative set of them), and more specifically about the prospects for revitalizing the winter tourism performances in a sustainable way. These are represented by some general development strategies (i.e. “ski-intensive”, “alternative-ski” and “beyond-snow”) that have been further elaborated to fit the local conditions and are hereby assessed according to a selected set of relevant socio-economic indicators. Further environmental implications are taken into account by means of a decision support system (Giupponi 2007) that our model is meant to complement. However, its description and application to the evaluation phase is beyond the scope of this paper.
For more details about the AuronzoWinSim conceptual model, please refer to Balbi et al. (2010)[4].

This paper is about the implementation and the analysis of AuronzoWinSim 1.0 (AWS1.0)[5] that is the software application deriving from the conceptual model.
In the materials and methods section we present the case study focusing on the different types of information available and the knowledge gaps that we tried to fill. One type of input to the model that deserves particular attention is the data on projected climate conditions. We hereby describe how this type of data was produced with SkiSim 2.0 (Steiger 2011). We then proceed with a model description carefully based on the software application divided in thematic blocks: (a) interface, (b) initialization and space cover updating, (c) economics of the tourism supply, (d) climate, (e) tourists' behavior, (f) closing procedures, (g) monitoring and plotting.
In the discussion and results section we talk about the analysis of the model and we comment on its outcomes in assessing the development strategies. In the analysis sub-section, we firstly explore what might happen with different parameters values. We perform a sensitivity analysis for the most relevant tourist's behavioral parameters. This leads us to calibrate our initial set of selected parameters' values. We show that the parameterized model lead to statistics on the initial population that are consistent with the most recent empirical data. Then, we approach the model's validity issue in a combined way. Given the empirical problems with data collection, and the explicit inclusion of cognitive and social processes, achieving good statistical performance is not sufficient in ABMs (Janssen and Ostrom 2006). Even though we show that with more detailed statistical data a validation of the model could be feasible in empirical terms, and we highlight the model capacity of

[4] We acknowledge that there are minor changes between the UML description and the implementation into code that are not reported herewith. UML diagrams should be understood as a very effective and structured set of guidelines that have been used for coding the software application.
[5] The package can be downloaded from http://www.dse.unive.it/clim/climalptour.htm

reproducing observed patterns, we decided to focus on the model validity from the final users' perspective. We therefore went back into the field in order to answer two questions: (1) does the behavior of the model coincide with the understanding of the relevant stakeholders about the system? and (2) is the model a legitimate and useful tool for action from their point of view? The results of this authentication process (Becu et al. 2003) are presented and discussed. We conclude this section with a robustness analysis of the ranking of the development strategies, which allow us to describe in details the model's outcome of interest.
In the conclusions we summarize some pros and cons about the implementation of our conceptual model and we propose further elements that could be added to the implemented version. Ultimately, we build on the model's results suggesting some main recommendations to the final beneficiaries.

2. MATHERIALS AND METHODS

In this section we firstly present the used data, explaining how information is heterogeneous and incomplete. The various types of available and relevant information concerning the case study were given by secondary sources including economic, demographic and biophysical time series. This is the information that led to the problem identification and consequentially to the model conceptualization.
Further information was retrieved from primary sources by means of *ad-hoc* on the field investigations and local workshops. The results of an external model are also used as input to the climate block of AuronWinSim 1.0. In this part it was the model conceptual structure that suggested the remaining information needs. Moreover, there exists the information on the ethnography of the tourists that led to the creation of the tourist profiles. This information is for obvious reasons incomplete, because we cannot comprehensively know the decision making process of the winter tourists, especially with regards to the potential ones. This is a knowledge gap that we try to cover with the simulation and that stands at the base of our theory formulation.
Then, we describe the implemented model.

2.1 Data

2.1.1 Case Study

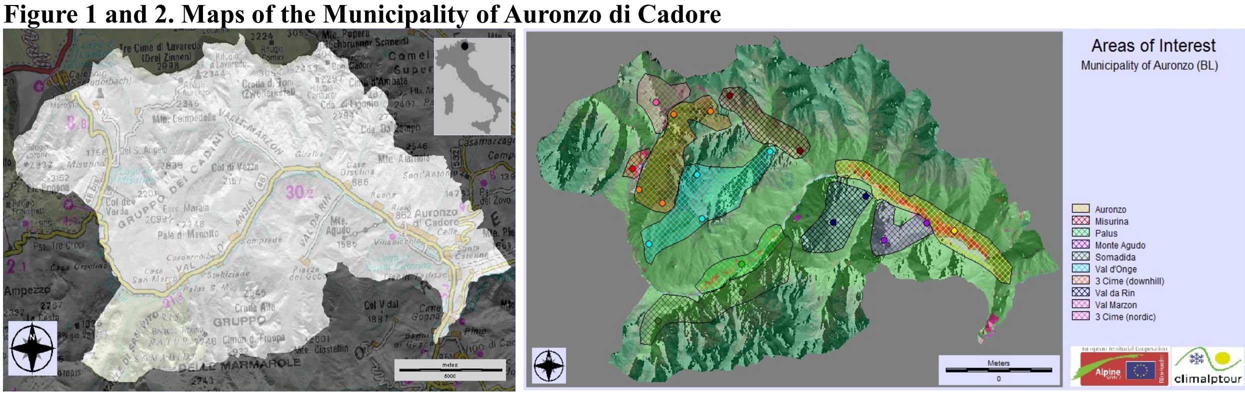
The ClimAlpTour project led to a first data survey, common to all the pilot sites, concerning three impact fields:

1. climate change (i.e. local geography, precipitations, snow cover, energy consumption, etc…);
2. destination (i.e. demography , tourism supply , tourism demand);
3. economics (i.e. growth, labor, etc…).

Our pilot is the municipality of Auronzo di Cadore, located in the province of Belluno, in the Veneto Region, in the north-east of Italy. It covers a vast area (22,000 ha), which includes Misurina and the most famous peaks of the Dolomites, namely the “Tre Cime di Lavaredo” (see Fig.1). The village of Auronzo (866m above the sea level) hosts almost the entire population of the municipality of approximately 3,600 inhabitants. The migration balance is stable. Misurina is a small settlement at 25 km from the main village, placed at an altitude of 1,754 meters.
The local economy depends on tourism which is currently focused on the summer season, while the winter season is weak, with only 25% of arrivals (Regione Veneto 2009). The total hosting capacity is of approximately 6,000 beds of which 25% are in the hotel sector and the remainder in the extra-hotel sector (i.e. B&Bs, lodgings, etc.). In 2008, 63,700 arrivals and 305,400 tourist nights were

registered, showing a slight decrease from the previous year. The last 10 years have witnessed the increase of arrivals and the contraction of average stay.
Notwithstanding the presence of two small downhill ski-areas and two cross-country ski centers some hotels don't even open for the winter season. The four ski-lifts of Mount Agudo, which reach a maximum elevation of 1,600m, supply seven ski-trails covering 15 km. In the locality of Palus San Marco, just at halfway between Auronzo and Misurina, there is the Somadida forest, one of the largest of the province, which becomes a cross-country ski centre (with nine loops of 52.5 km in total) during the winter season. Misurina, which has a hosting capacity of approximately 500 beds is endowed with the two ski-lifts of Col de Varda (from 1,754m to 2,220m) that supply five ski-tracks, and 17 km of cross-country ski loops. In addition, the area around the Cadini peaks, at the east of Misurina, is regarded as one of most beautiful spot for back-country skiing in the Dolomites.
Snow precipitation and cover are significantly more consistent around Misurina, compared to Monte Agudo. However, the latter is equipped with a superior artificial snow production system.
Since recently the Community Council is considering options on how to stimulate a further development of the winter tourism. There exist several projects of ski-areas development. The most ambitious is located in the Marzon valley, a few km from the main village, which would connect the valley to the ski-area of Misurina (with an average elevation over 2,000m). After a preliminary consultation with the local public administration we decided to focus our study on how to develop winter tourism in the next 40 years, in a context of climate change and market demand that is not favorable, given by the expected warming effect and by the ageing of the population of skiers.

Figure 1 and 2. Maps of the Municipality of Auronzo di Cadore



The underlying idea that has inspired the model is to identify the most robust among three active adaptation strategies that are presented, in general terms, in Burki et al. (2007):

1. the pursue of the traditional downhill ski-intensive paradigm (SKINT),
2. an alternative light ski-oriented post-modern development (ALTSKI),
3. the process of diversification and enlargement of tourist offer beyond-snow (BYDSNW).

We also included a passive "business as usual" scenario (BAU). In this regard, we have defined four case-specific and spatially explicit alternative strategies which are able to take into account various orientation towards tourism and the perception of climate change from the local stakeholders' point of view. In the map generated with a geographical information system (GIS), Fig. 2, the heterogeneous areas of interest in which the strategies and the simulation take place are shown. The same information is passed to the cellular grid of AWS1.0, including land use. The bullet points represent the weather stations (i.e. reference points) provided with information about elevation, snow cover and temperature, as it is described below.

2.1.2 Retrieved strategic parameters

In the first local workshop the three alternative strategies were presented and further tailored to the participants' suggestions. Each strategy consists of a defined set of non snow-related facilities (i.e. accommodations, restaurants, retailers and others) and snow-related facilities (i.e. downhill skiing areas, cross-country skiing areas, off-piste skiing areas and snowparks) located on the areas of interests.

Each non-snow facility type is further divided into categories according to the tag-price associated to their fruition. For instance accommodations can be of three types: lodgings, one to two stars hotels and three to four stars hotels. They are composed of bed units on which a tag price applies (i.e. 20, 30, 43 €), which is the price paid by one tourist for one night. These values consider average prices across a winter season. According to its category every bed is also characterized by: (a) a fixed seasonal energy consumption cost (i.e. 1, 2, 3 €), (b) a variable human labor cost that applies at each utilization (i.e. 3, 4, 5 €), (c) a cost relative to the investment required to build a new one (i.e. 15, 25, 45 thousand €).

The same structure applies to restaurants which have three levels of price and whose unit is one cover. Retailers can be of four categories (i.e. bars, souvenirs, food and clothes & rentals). The energy costs are based on the squared meters of extension of each shop. The other facilities are of three types: indoor sports, wellness and kindergarten. Their energy costs are based on their carrying capacity.

Snow-related facilities also have an individual tag-price based on their type. The geographical unit of reference is the squared km of skiing area. The required investments are related to the extension of the ski-area and to the number of ski-lifts, while the seasonal energy costs are based on the number of ski-lifts and on the production of artificial snow. The variable part of human labor cost is associated to the number of skiers. In general, all the labor related parameters are thought to capture the creation of seasonal labor and not the fixed costs. This is for the model to be able to generate information about how the tourism demand, rather then the existence of new infrastructures, could influence the creation of job opportunities.

Artificial snow production varies with the temperature and snow cover conditions within each downhill, cross-country and snowpark facility that is endowed with a production system. It is calculated on the basis of the centimeters of snow produced (to meet the 30 cm minimum threshold) per km of pistes covered. We assume that the cost of producing the bottom layers of snow are more expensive and therefore the parameters' values are not proportional. Assuming that the artificial snow cost is divided in 40% water and 60% energy[6], we are able to use it as a proxy of water and energy consumption. These parameters, which are presented in Table 1, were calculated on the basis of the data retrieved from the primary sources, by means of individual direct interviews, compared with sectoral average values (i.e. from real estate agents, external ski-areas consultants, etc.).

In this first implementation of the model we don't test these parameters in the sensitivity analysis section, we rather use them as a way to restrict the set of possible worlds that we are considering (Grimm and Railsback 2005). This simplification is consistent with choice of analyzing hard-wired strategies that do not evolve with time.

[6] According to the CIPRA-International the seasonal production of artificial snow covering one ha of ski-pistes requires 4,000 m^3 of water and 25,000 kWh of electricity (Hahn, 2004). Further we assume water cost 1 € /m^3 and electricity cost 0.2 € /kWh. The parameters on artificial snow were calibrated on this information and only include the costs of water and energy.

Table 1. Strategic parameters

Facility type	Unit	Parameter Description				
			lodgings	**1-2 stars**	**3-4 stars**	
Accommodations	bed	tag price	€ 22	€ 30	€ 43	
		seasonal energy per bed	€ 1	€ 2	€ 3	
		labor per use of one bed	€ 3	€ 4	€ 5	
		investment for a new bed	€ 15,000	€ 25,000	€ 45,000	
			low-price	**medium**	**high price**	
Restaurants	cover	tag price	€ 15	€ 23	€ 30	
		seasonal energy per cover	€ 0.25	€ 0.50	€ 0.75	
		labor per use of one cover	€ 0.50	€ 1.00	€ 1.50	
		investment for a new cover	€ 3,500	€ 6,000	€ 9,000	
			bar-pub	**others**	**food**	**clothes &.**
Retailers	m^2 of shop area	tag price	€ 5	€ 8	€ 15	€ 30
		seasonal energy per m^2	€ 40	€ 30	€ 50	€ 30
		labor per client	€ 0.50	€ 0.50	€ 0.50	€ 0.50
		investment for a new m^2	€ 4,000	€ 3,000	€ 4,000	€ 3,000
			indoor sports	**wellness**	**kindergarten**	
Other Facilities	unit of carrying capacity	tag price	€ 10	€ 14	€ 20	
		seasonal energy per unit	€ 80	€ 100	€ 60	
		labor per client	€ 0.50	€ 3	€ 5	
		investment for a new unit	€ 4,000	€ 4,000	€ 2,500	
				n-lifts	**km^2**	
DownHill Areas	n-lifts and km^2 of ski-area	tag price	€ 27 (€ 25 for free-ride)			
		seasonal energy per unit		€ 25,000	€ 50,000	
		labor per client	€ 5 (€ 7 for free-ride)			
		investment for a new unit		€ 2,000,000	€ 3,000,000	
				n-lifts	**km^2**	
SnowParks	n-lifts and km^2 of ski-area	tag price	€ 10			
		seasonal energy per unit		€ 10,000		
		labor per client	€ 1			
		investment for a new unit		€ 500,000	€ 1,000,000	
XCountry Tracks	km	tag price	€ 5			
		seasonal energy per unit	€ 0.00			
		labor per client	€ 0.50			
		investment for a new unit	€ 2,000			
			10cm	**20cm**	**30cm**	
Artificial Snow	km	cost of producing artificial snow per km of piste/track	€ 200	€ 500	€ 1,000	

2.1.3 Climate Projections

Data about projected weather conditions, concerning temperature and snow cover were produced with the SkiSim 2.0 model (Steiger 2011), consisting of two main components: the snow model and the snowmaking module. We made use of the first module, in which the natural snow accumulation and melt are simulated.

SkiSim 2.0 required as input data:

1. daily data of Auronzo's climate stations in form of long time series recording precipitation, temperature (min, max) and snow depth and/or fresh snow;
2. monthly change signals of climate scenarios for temperature (Δt) and precipitation (Δp) (see Table 2). This data, downscaled to each climate station, was provided by the CLISP EU project, also included in the Alpine Space Programme (CLISP 2009).

In the CLISP project all the parameters were calculated in terms of an absolute change from the reference period (1961-1990) to the 20 year mean of two future periods (2011-2030 and 2031-2050). In Table 2 we present the absolute changes for temperature and the relative changes for precipitation.

Table 2. Monthly change signals for temperature and precipitation

REMO UBA M 2006 A1B	2011-2030		2031-2050	
	abs. Δt mean (°C)	% Δp mean (mm)	abs. Δt mean (°C)	% Δp mean (mm)
Dec	0.5604	-0.1704	1.5290	30.6705
Jan	0.5700	-1.1547	1.4498	-8.4651
Feb	1.8636	2.8748	2.1743	12.9410
Mar	-0.1687	16.8779	1.1765	4.9881
Apr	-0.0681	10.5628	1.5542	-0.4037
Seasonal over the 20 year period	**0.5°C**	**5.8%**	**1.6°C**	**7.9%**
REMO UBA M 2006 B1	2011-2030		2031-2050	
	abs. Δt mean (°C)	% Δp mean (mm)	abs. Δt mean (°C)	% Δp mean (mm)
Dec	1.8063	-31.5573	1.4465	-14.2580
Jan	1.9778	-21.7396	1.9986	20.6313
Feb	1.8259	21.2355	2.0756	0.0719
Mar	-0.4535	7.5838	0.1064	9.5005
Apr	0.7770	-5.9416	0.4011	25.8071
Seasonal over the 20 year period	**1.2°C**	**-6%**	**1.2°C**	**8.3%**

We decided to focus on the climate signals from the regional climate model REMO UBA M 2006[7], because among the available regional climate model included in the CLISP project: (a) it has the highest geographical resolution (10 km) and (b) both A1B and B1 SRES scenarios of IPCC were presented.

SkiSim 2.0 is able to create the requested daily data for each altitudinal band (100m) of the ski-area in form of time series of 40 years. This serves as an input to AWS1.0, which reads the time series at the initialization phase, according to the selected climate scenario. Then, it passes the information to the simulated areas' weather stations (i.e. reference points), according to their elevation.

We shall acknowledge that SkiSim 2.0 produces good statistical results for multi-year averages. However, in AWS1.0 daily data are used for the purpose of creating a scenario of local snow and temperature conditions without any presumption to be considered as a statistically meaningful forecast.

2.1.4 Simulating Tourists' Behavior

[7] The global driving model of REMO UBA M 2006 is ECHAM5.

While the development strategies are set exogenously as a result of the discussion with the stakeholders, the focus of the simulation is on the endogenous tourists' response.
There is no doubt that the tourists will be tomorrow's ultimate judges of any adaptation strategy. Indeed, we eventually want to know how they might react to future conditions. However, the tourism demand is not a homogeneous mass that only takes into account price signals. On the contrary, as it's shown by a great body of marketing surveys, they seem to have a very heterogeneous behavior and different profiles of expense according to the tourism experience they are looking for (Provincia Autonoma di Trento 2007; Provincia Autonoma di Bolzano 2009; Dolnicar and Leisch 2003). Moreover they are constantly evolving: new typologies of tourism fruition emerge as a result of the evolution of the society (Bourdeu 2009). Drawing on the above cited literature we created a set of eight tourist profiles (i.e. Traditional Ski-Intensive (TSI), Ski Part-Time (SPT), Idle (ID), Eclectic (EC), Sporty Alternative Wilderness (SAW), Sporty Alternative X-Country (SAX), Counter Culture Wilderness (CCW), Counter Culture Playground (CCP)), which is rich enough to take into account (1) the actual winter tourists of Auronzo, (2) the actual winter tourists visiting Auronzo's main competitors, and (3) the potential winter tourists of tomorrow.
Indeed, social simulation is a unique tool that allows the inclusion of heterogeneous actors and even those that wouldn't be accessible for any direct interview, explicitly taking into consideration their decision-making process. However, in this sense information is incomplete, because we are capturing a very small portion of details about how tourists really behave, especially with regard to the potential prospective ones. Our simple representation of their decision making process is therefore a substantial part of the theory that we formulated with AuronzoWinSim[8].

2.2 Model Description

The model is implemented in NetLogo 4.1 (Wilensky 1999). This software platform has become very popular in recent years. Originally being more designed for teaching, it is increasingly used for research. It is easy to learn, provides powerful concepts for implementing ABMs, and it has continuously been supported by its developers and a large and growing user community for more than ten years (Thiele and Grimm 2010).

2.2.1 Interface

Once AWS1.0 is opened, every simulation run requires the user to make four main choices, which are located into the chooser buttons at the upper left side of the interface:
(1) the climate projection,
(2) the development strategy to be tested,
(3) the societal scenario,
(4) the type of competition.

Among the climate projections we also included the base-line data representing the period 1981-2000, which has been used in the validation phase.
The societal scenarios set the number of tourist agents (i.e. the catchment area) and the proportions among the tourist profiles (i.e. prop-factor). The conservative scenario creates a lower number of agents and divides them among the tourist profiles giving a strong preference to the consolidated

[8] Please refer to Balbi et al. (2010) for a closer look to the narratives describing the tourist profiles. In this paper we go through their decision rules, in the model description, and we test the sensitivity of the model results to their behavioral parameters.

categories (TSI, SPT, ID). For this scenario the number of agent is calibrated to produce simulated data on arrivals and tourist nights consistent with the latest empirical data, as shown in section 3.1.2. The optimistic scenario creates a higher number of agents with a certain increase of the alternative categories (EC, SAW, SAX, CCW, CCP). They are both static throughout the simulation, assuming zero demographic and market growth.

The competition scenario sets the percentage of tourists that are potentially attracted by Auronzo but prefer to choose other destinations (i.e. comp-factor). When competition is generic it is assumed that this percentage is equal to all the tourist profiles, while in the case of niche competition it is assumed that some categories are more exposed to the attraction of the competitors (i.e. TSI, EC).

The combination of these choices defines the future conditions, from 2011 to 2050, under which the tourists' response is simulated. The setup button launches the initialization while the go button launches the entire simulation, which automatically stops at the 5040th time step (40 winter seasons of 126 days/time steps each).

An additional button is used to choose the tourists' behavioral parameters setting, which are presented in the sensitivity analysis section. The model results were produced with the "base" setting. Another chooser called "layer" simply selects the GIS layer to be visualized on the spatial grid, on the upper right side, among land use and the thematic differentiation in areas of interest.

The rest of the interface is occupied by the monitors, in the upper part, which keep track of the destination main characteristics and the tourists' inflow, and by the plots in the lower part, which register the main output of the model, as it is shown in the results section. In Appendix 1 we included a screenshot of the interface of AWS1.0.

2.2.2 Initialization and Space Cover Updating

Initialization and space cover updating are two similar early phases of each simulation in which the characteristics of the system are hard-wired in order to represent the scenarios to be tested. Every simulation starts with a "business as usual" (BAU) configuration which lasts until the end of the first season. Than, a different configuration, according to the selected strategy can come into play, from the beginning of the second season (i.e. at time step 127).

The initialization firstly loads the geographical and climatic data and the tourists' behavioral parameters, and secondly creates the tourist agents and the tourism facilities. Within the BAU configuration snow and non-snow-related facilities are created with the characteristics and the location that fit the current situation of Auronzo di Cadore.

The space cover updating can take place in three different ways, according to the selected development strategy. The "ski-intensive" (SKINT) strategy develops new ski-areas both in the lower and in the upper part of the municipality. It includes the large project in Val Marzon area, a 40 millions € cableway connecting the lower part of the municipality to the "Tre Cime di Lavaredo". Further ski-lifts and pistes are located around Misurina and in Val d'Onge creating a fully connected ski-area devoted to the tour of the Cadini peaks. At the same time the Monte Agudo area is doubled in size extending into Val da Rin. Two snowparks become available: one in Auronzo and one in Misurina. The use of artificial snow is significantly increased covering 50% of the ski-pistes and even some cross-country tracks. Other limited non-snow facilities are created, mainly restaurants and bars and two new kindergartens.

With the "alternative-ski" (ALTSKI) strategy the same Val Marzon installation is used to create the free-ski/back-country tour of Cadini supported by few ski-lifts but no artificial snow and pistes preparation, apart from what already exists. One bigger snowpark becomes available in Misurina. Cross-country ski-tracks are further extended including itineraries dedicated to the snow shoes

practitioners. Other limited non-snow facilities are created, mainly restaurants, bars, rentals and a new kindergarten. Comprehensively investments are inferior to the previous strategy and more flexible with regard to snow conditions.
According to the “beyond-snow” (BYDSNW) strategy, artificial snow is abolished and the qualification of the receptive facilities is enhanced moving the supply structure to higher standards and creating several new facilities for wellness, kids and other indoor sports (i.e. a big pool-spa center in Auronzo). Further shops are created to stimulate holidays’ shopping. All the investments concern the non-snow-related facilities in order to move out from a snow dependent tourism system.
Each strategy modifies the land use configuration in a different way, so that new geographical data are loaded.

2.2.3 Economics of the tourism supply

This block is divided in two stages and is performed by a class called meta-economic agents: firstly the investments related to the strategies are calculated and secondly the daily inflow and outflow of money are updated. The meta-economic agents are eight, one for each tourism facility class, and represent the local administrators of the eight compartments, in which we divided the tourism sector.
For instance, the total investment in new accommodations is the sum of the investments in new beds in lodgings, in one or two stars hotels, and in three or four stars hotel. The compartment average energy cost, labor cost and price are calculated as the weighted average of the accommodations parameters on the number of beds. Then, once the number of tourist nights is registered, the Equation 1 (extrapolated from the code) applies in order to calculate the daily cumulative return of all accommodations:

(Eq. 1) *return = (((avPrice - avVarCostUnit) * n) - (avFixedCostUnit * newTotNBeds) - (totalInvestment / 4914))*

where *avPrice* is the price for a single bed, *avVarCostUnit* is the human labor cost associated to the use of one bed, *n* is the number of tourist nights for the current time step, *avFixedCostUnit* is the daily portion of the seasonal energy cost associated to one bed, *newTotNBeds* is the total number of beds as updated by development strategy, and *totalInvestment* is the investment in accommodations that the strategy required. The latter is allocated to each of the remaining time steps of the simulation (4914 at the end of the first season) as a sort of mortgage installment. In this version we simplified the model to the basics, by assuming the rate of interest and inflation equal to zero. In the BAU scenario the total investment is equal to zero.
The same structure applies to each of the eight compartments with minor changes and different units of reference, as shown in Table 1. For instance in the case of downhill ski-areas Equation 2 applies:

(Eq. 2) *return = (((avPrice - avVarCostUnit) * n) - totArtSnowCostDH -
((avFixedCostUnit * newTotKm2DH) / 126) - (totalInvestment / 4914))*

where *totArtSnowCostDH* is the cost of the daily production of artificial snow in all the downhill ski-areas, *avFixedCostUnit* is the seasonal cost of energy for a portion of one squared km of ski-area. It is assumed that such a portion fits two ski-lifts costing 25,000 € of energy each season.
At each time step every compartment balance is updated by a positive or negative return and plotted in the interface.

2.2.4 Climate

This block passes the data on the snow cover and temperature conditions to the reference points according to their elevation. These data were saved by the model at the initialization phase in form of array. Now the model assigns the values of the previous and present time step. Than, the reference points perform the weather forecast and the snow facilities check the real conditions. Some of them can decide to produce artificial snow.

In total, there are fifteen reference points on the map representing ten altitudinal bands (800, 1000, 1100, 1200, 1400, 1500, 1600, 1700, 1800, 2600 m above the sea level). This number is the result of the selection of the highest and the lowest point for each of the ten areas of interests excluding double counting within each area.

In calculating the short term forecast values of snow cover an error is applied to the real condition data. Mid term forecasts simply register the period of the season with maximum snow cover. A third kind of forecast is related to the snow stability conditions: if the snow cover is superior to 30 cm and there has been temperature increase of more than 5ºC from the previous time step a security index number is assigned. On the basis of this index averaged among the reference points tourists can be not allowed to go off-piste.

The snow facilities that are endowed with a production system can produce artificial snow if the maximum temperature of the ski-area is inferior to zero and the average snow cover is inferior to 30 cm. They just produce the amount that is necessary to satisfy this minimum threshold and it is regarded as a daily solution. In this version of the model we ignore the cumulative effect of artificial and natural snow. This simplification can be justified by the factual evidence that nowadays artificial snow is produced constantly during the season, every time that the conditions allow.

2.2.5 Tourists' behavior

In order to become potential tourists all the tourist agents perform a potentiality test comparing the destination's features to their individual thresholds at the beginning of each season (i.e. *checkDestination* procedure). At this stage the competition parameter applies, so that even if the condition is met they don't become potential tourists with a certain probability, given by the competition factor (see comp-factor in Table 3).

For the sake of maintaining the computing process as simple as possible, in the potentiality test, we focused on the one threshold that mostly characterize each category (a part from ID and EC that have more diversified interests)[9].

For instance, TSI tourists look at the km of downhill ski-tracks. SPT tourists look at the km of downhill ski-tracks and at the nature ratio, which is given by number of spatial units with land use “nature” for each spatial unit with land use “facility”. SAX tourists look at km of cross-country ski-tracks. SAW tourists look at the km of off-piste tracks. CCW tourists look at km of free-ride tracks[10]. SAX, SAW and CCW tourists also look at the nature ratio. The thresholds based on the km of winter sport activity, being those that are defining the potentiality of 5 over 8 tourist profiles, have been included in the sensitivity analysis (see km-threshold in Table 3).

CCP look at the dimension of the snowparks in terms of number of features included. ID tourists

[9] A further development of the model could implement a multi-criteria function considering the entire destination’s features assigned with different weights, according to the tourist profile.

[10] Free-ride differs from off-piste because while free-ride tracks are served by cable-ways or ski-lifts, off-piste tracks are not.

look at the number of places in kindergartens, at the number of wellness centers, and at the nature-ratio. EC tourists look at number of high standard hotels, wellness centers and at the boutique ratio, which is the share of retailers with higher prices.
The individual threshold is calculated by means of a stochastic process on the basis of a normal distribution with mean and standard deviation that are shared among the tourists with the same profile (i.e. *init-tourist* procedure). Data about mean and standard deviation are given as input to the model according to the chosen parameters setting.
For most of the behavioral parameters, we assume that the normal distribution is appropriate because the aim is to capture a typology of behavior that is distributed around a certain value, but allowing for exceptions. For instance, a TSI tourist in the base parameters setting (see Table 3) has a km of desired downhill ski-tracks threshold (km-threshold) that results from a normal distribution with mean 25 and standard deviation 5. So, most of the TSI tourists will have a km-threshold of around 25 but some even over 30 or below 20. On the other side a SPT tourist is less demanding and it's individual km-threshold results from a normal distribution with mean 10 and standard deviation 3.

Potential tourists can enter into the planning phase that sets the day of arrival. SAX, SAW and CCW are short-term planners, so on Friday they look at the snow cover forecast and if there is compliance with their individual snow cover threshold they can leave within the next two days. A further check on snow security is also done for those who are keen to go off-piste. The remaining categories can be both long and short term planners so that they decide when to book at the beginning of the season but they can repeat the vacation in the same season within certain conditions. In the planning phase the proportional factor applies, meaning that some tourists are excluded from deciding the day of arrival at the current time step but they can repeat the process at the next one. In the case of a TSI tourist the following equations describe this multifaceted behavior:

(Eq. 3) If [category = "TSI" and (ticks = (126 * (season - 1)) + 1) and ((dest-counter + (10 * creation)) / season) < 10 and random-float 1 < prop-factor]
Then [set planning = round ((126 * (season - 1)) + random-normal 30 20)]

(Eq. 4) If [category = "TSI" and (ticks != (126 * (season - 1)) + 1) and ((dest-counter + (10 * creation)) / season) < 10 and random-float 1 < prop-factor]
Then [set planning round = (ticks + random-normal 20 10)]

Equation 3 applies at the beginning of the season, when *(ticks = (126 * (season - 1)) + 1): ticks* is the current time step, *season* is the current winter season [1...40]. *dest-counter* is the number of times that the individual tourist is gone to the destination, creation is the season in which that agent was created (an agent that is not satisfied at the end of its vacation dies and is replaced by another of the same category). A TSI tourist is allowed to go skiing up to a maximum of 10 times per season including day trips. *random-float* 1 picks randomly a non integer number between 0 and 1, *prop-factor* is the proportional factor, *planning* is the day of arrival, random-normal 30 20, picks a number from a normal distribution with mean 30 and standard deviation 20. Equation 4 applies during the entire season.

Once the day of arrival is set the tourist agents acquire their individual information about the duration of stay, the number of units (single tourists) composing their own group, and the presence of kids. In fact, a tourist agent does not represent a single person, but a group of tourist behaving homogeneously among them. During the *goDestination* procedure, the duration of stay, the group size, and the probability of the presence of kids are also defined by means of a stochastic process based on a normal distribution with mean and standard deviation that are diversified among the tourist profiles (see Table 3). Further, a tourist agent can choose a day trip (i.e. *stay = 0*), with a certain probability attached to its category. As in the case of the potentiality thresholds, this information is based on our theory about the eight tourist profiles and is further detailed and tested in the sensitivity analysis.

Once the tourists are in the destination they enter into the *enjoyDestination* loop, according to which they have the possibility to access all the snow and non-snow facilities. These possibilities are regulated by probability rules differentiated per tourist profiles. Snow facilities are mutually exclusive within each time step while non snow facilities are not. Tourists also tend to choose the facilities that better suit their characteristics so for instance a TSI tourist would choose, among the ski-areas, the one with the greater km of ski-pistes. When they choose a facility a relation is established between the tourist and the facility.
Accommodations are excluded from the set of fruition possibilities for day trippers and tourists in their last day of vacation.

Table 3. Behavioral parameters and values per tourist profile for base setting

Parameter name	TSI	SPT	ID	EC	SAX	SAW	CCW	CCP
group-size μ	4	5	5	2	5	5	4	5
group-size σ	1	1	2	1	2	2	1	2
stay μ	5	5	5	3	3	3	5	5
stay σ	1	1	1	1	1	1	1	1
prob-of-stay=0	0.5	0.2	0.2	0.5	0.8	0.8	0.5	0.5
km-threshold μ	25	10			10	3	5	
km-threshold σ	5	3			3	0.5	2	
nature-ratio-threshold μ		3	3		3	3	3	
nature-ratio-threshold σ		1	1		1	1	1	
snow-threshold μ	35	35	10	10	35	50	50	35
snow-threshold σ	3	3	3	3	3	5	5	3
kids-prob μ	0.3	0.4	0.6	0.3	0.2	0.2	0.2	0.2
kids-prob σ	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
s-shoes-prob μ	0.05	0.2	0.3	0.2	0.05	0.05	0.05	0.05
s-shoes-prob σ	0.01	0.05	0.05	0.05	0.01	0.01	0.01	0.01
n-wellness-threshold μ			3	5				
n-wellness-threshold σ			0.5	2				
n-sports-threshold σ				7				
n-sports-threshold σ				2				
n-qualityhotels-threshold μ				10				
n-qualityhotels-threshold σ				2				
boutiques-ratio-threshold μ				0.25				
boutiques-ratio-threshold σ				0.01				
n-tricks-threshold μ								12
n-tricks-threshold σ								2
cc-kiderg-threshold μ			50					
cc-kinderg-threshold σ			10					
prop-factor (conservative)	0.5	0.22	0.14	0.08	0.02	0.01	0.02	0.01
prop-factor (optimistic)	0.25	0.2	0.2	0.15	0.05	0.05	0.05	0.05
comp-factor (generic)	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
comp-factor (niche)	0.3	0.9	0.9	0.3	0.9	0.9	0.9	0.9

Note to Table 3. In bold are those parameters that have been tested in the sensitivity analysis (see Table 4).

2.2.6 Closing Procedures

In the closing procedures both the tourists and the tourism facilities are involved. The tourism facilities calculate their own daily customers. This data is also aggregated per compartment. Arrivals and tourist nights are updated in this phase.
The tourists calculate their daily expense and satisfaction. Individual satisfaction is built over the entire holiday on a daily basis, depending on the activity that has occupied the tourist agent's day among downhill skiing, cross-country skiing and snowshoes, off-piste skiing, snowpark, indoor sports and wellness.
Satisfaction is based on the snow conditions (only for the snow facilities) and on the density of users of the facility that has been used (for both snow and non snow facilities). The density is calculated for each facility on the basis of its daily users and its comfortable carrying capacity, which is a given parameter of the facility.
So density is the only type of interaction among different tourist agents within the model. In this first implemented version it is assumed that an idle day, without any of these activities, is regarded as satisfying and that restaurants and accommodations do not contribute to the satisfaction building process.
If the cumulative satisfaction at the end of the vacation is negative than the tourist agent is eliminated from the simulation and it is substituted by one of the same category/profile. One could argue that in this way only the intra-vacation memory is preserved and rest is lost. On the contrary this mechanism generates a very powerful dynamic for which, on average, tourist categories with a high rate of dissatisfaction become more selective and tend to not choose the destination[11]. At the same time, satisfied tourist agents are eligible for a second vacation (or multiple day trips) within the same winter season. So in this sense even long-term memory is preserved.

2.2.7 Monitoring and Plotting

Monitors and plots represent the model's observation capacity during the simulation cycles, which is included in the interface of the software application (see Appendix 1).
On the one hand, by means of the monitors, we can observe the current information regarding the tourist supply, which is exogenous and more static, and demand, which is endogenous and more dynamic, and the weather conditions. It's possible to stop the simulation at any day of the 40 winter seasons and have a comprehensive snapshot of the status of the system.
On the other hand, plots are registering the flow of information that is the final output of the model, on which we performed the analysis of results. Indeed, AWS1.0 is able to gather data about tourists' inflow and expenses, divided per tourist profiles, on a daily basis and on a cumulative seasonal basis. It also gathers data about the economic performance of each tourism supply compartment with special focus on the creation of labor and the consumption of energy. Other information regards the rate of occupation of the facilities averaged within each compartment and the number of dissatisfied tourists. Then, the climate related plots simply represent the information acquired by SkisSim 2.0 with the additional value of considering the production of artificial snow and the distribution of risky days, according to our simple snow stability sub-model.

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[11] This is because the eliminated tourists, which satisfied the potentiality test, are substituted by new tourists which might not satisfy the same test. This dynamic is linked to the stochastic process of assignment of the behavioral parameters (e.g. km-threshold). In this way the non potential tourist are never eliminated because they are never dissatisfied (i.e. they simply don't go to the destination). The result is that the catchment area of potential tourists gradually shrinks for the categories with a high rate of dissatisfaction.

3. DISCUSSION AND RESULTS

In the previous section we went through a description of the data used and of the model's structure[12]. In this section we firstly analyze the model focusing on some of the main parameters and outputs, both at an individual and at the system level. Secondly, we present the results emerging from the simulations also considering their robustness in relation to the variation of the most sensitive parameters.

3.1 Model's Analysis

We envisioned the analysis process of AWS1.0 as a combination of three steps. First, we checked the model's sensitivity to some of the parameters, which are at the base of our theory formulation. Second, we used the results to calibrate some parameters' values. Third, we built the case to establish whether if the model is appropriate for its intended application or not in two ways. In the validation section, we made use of the available empirical data, observed patterns and results from other models (i.e. SkiSim 2.0). In the authentication[13] section we made use of the opinions of the stakeholders involved in the project.

3.1.1 Sensitivity Analysis

Notwithstanding the "keep it simple" mantra has been constantly kept in mind, AWS1.0 results to be to be very rich in content and makes use of numerous parameters, which is a common characteristic of many ABMs with heterogeneous agents. As a result, to perform a comprehensive sensitivity analysis may become unfeasible, not only for the number of parameters but also for the many levels of outcomes that emerge. Therefore, we had to constrain the object of the sensitivity analysis on the basis of our understanding of the model.
All the simulations of the sensitivity analysis were run with the A1B climate scenario, conservative social scenario and generic competition.
The sensitivity analysis was run on the main behavioral parameters of the tourist profiles because they represent the foundation of the individual traits of each acting agent, which lead to the emergence of system level outcomes. In other words we were interested in exploring how aggregated macro results vary with changes at a micro level.

The entire set of behavioral parameters considered in the sensitivity analysis is described in Table 4. They define:

1. the agent's group size,
2. the agent's duration of stay,
3. the agent's probability of day trip (i.e. duration of stay equal to 0),
4. the agent's minimum threshold of desired km of tracks for own discipline,
5. the agent's minimum threshold of desired snow cover,
6. the agent's probability of having kids,
7. the agent's probability of practicing snow-shoeing, and
8. the competition factor.

Given our approach that is very much case-study oriented and the results from field surveys, we

[12] For more information on the models' details that we couldn't include in this paper we suggest to download the entire code from the website http://www.dse.unive.it/clim/climalptour.htm.
[13] We used the term authentication as in Becu et al. (2003) to define validation from the final users' perspective.

regarded the remaining parameters, which are not considered hereby, consolidated enough to help us restrain the set of possible worlds.

The final values of these eight variables (excluding the probability of day trip and the competition factor), which are attached to each individual agent, depend on a stochastic process of assignment based on a normal distribution given by two parameters defining mean and standard deviation. These parameters are shared among each tourist profile but every agent is endowed with a stochastic individual value. In addition, we included the probability of day trip and the competition factor (for the generic scenario), which are described by a point value for each category. The competition factor sets the probability of a tourist of being potentially attracted by Auronzo but preferring to choose other destinations.

Table 4. Parameters considered in the sensitivity analysis with base values

Parameter Name	TSI	SPT	ID	EC	SAX	SAW	CCW	CCP
group-size μ	4	5	5	2	5	5	4	5
group-size σ	1	1	2	1	2	2	1	2
stay μ	5	5	5	3	3	3	5	5
stay σ	1	1	1	1	1	1	1	1
prob-of-stay=0	0.5	0.2	0.2	0.5	0.8	0.8	0.5	0.5
km-threshold μ	25	10			10	3	5	
km-threshold σ	5	3			3	0.5	2	
snow-threshold μ	35	35	10	10	35	50	50	35
snow-threshold σ	3	3	3	3	3	5	5	3
kids-prob μ	0.3	0.4	0.6	0.3	0.2	0.2	0.2	0.2
kids-prob σ	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
s-shoes-prob μ	0.05	0.2	0.3	0.2	0.05	0.05	0.05	0.05
s-shoes-prob σ	0.01	0.05	0.05	0.05	0.01	0.01	0.01	0.01
comp-factor	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7

As the tourist profiles are described in relative terms among each other we further simplified the set of parameters values to be tested by identifying a base, a minimum and a maximum value for the mean and standard deviation of each of the eight variables and a fixed set of multipliers of these values for each of the tourist profiles (both for the mean and for the standard deviation), which renders the final parameter values implemented in the sensitivity analysis. The multipliers and the base, the minimum and the maximum values, which are shared among the profiles, are reported in Table 5.

Table 5. Multipliers of the base, minimum and maximum shared values tested in the sensitivity analysis

Parameter Name	TSI	SPT	ID	EC	SAX	SAW	CCW	CCP	Base	Min	Max
group-size μ	8	10	10	4	10	10	8	10	**0.5**	**0.3**	**0.7**
group-size σ	2	2	4	2	4	4	2	4			
stay μ	10	10	10	6	6	6	10	10	**0.5**	**0.2**	**0.7**
stay σ	2	2	2	2	2	2	2	2			
prob-of-stay=0	10	4	4	10	16	16	10	10	**0.05**	**0.01**	**0.09**
km-threshold μ	25	10			10	3	5		**1**	**0.5**	**1.5**
km-threshold σ	5	3			3	0.5	2				
snow-threshold μ	7	7	2	2	7	10	10	7	**5**	**3**	**7**
snow-threshold σ	0.6	0.6	0.6	0.6	0.6	1	1	0.6			
kids-prob μ	6	8	12	6	4	4	4	4	**0.05**	**0.03**	**0.08**
kids-prob σ	1	1	1	1	1	1	1	1			
s-shoes-prob μ	1	4	6	4	1	1	1	1	**0.05**	**0.01**	**0.1**
s-shoes-prob σ	0.2	1	1	1	0.2	0.2	0.2	0.2			
comp-factor	8	10	10	4	10	10	8	10	**0.5**	**0.06**	**0.14**

For instance, with base values, a general TSI tourist's group size mean is $\mu TSI = 8 * 0.5 = 4$ and the standard deviation is $\sigma TSI = 2 * 0.5 = 1$. With minimum values $\mu TSI = 8 * 0.3 = 2.4$ and $\sigma TSI = 2*0.3 = 0.6$. With maximum values $\mu TSI = 8 * 0.7 = 5.6$ and $\sigma TSI = 2*0.7 = 1.4$. These linear relations are based on our subjective translation, in analytical terms, of the narratives describing the eight tourist profiles.

As a result the sensitivity analysis was performed on eight parameters for each of whom an upper and lower range value has been identified. We tested each parameter separately for ten simulations for each development strategy (40 simulations per parameter in total), five with the minimum value and five with the maximum value. On these ten simulations we calculated the mean and standard deviation regarding eight indicators that constitute the main set of output of the model and that we use as currencies for contrasting versions of the model[14]. These currencies were calculated as average values resulting from each of the 40 winters simulations:

1. seasonal arrivals (n),
2. seasonal average expense of tourists (€),
3. seasonal tourist nights (n),
4. seasonal cost of energy (€),
5. seasonal variable cost of human labor (€),
6. seasonal production of artificial snow (€),
7. seasonal internal transfers of tourist agents (km),
8. Gini index of the number of daily visitors.

In Table 5 the data resulting from the sensitivity analysis are reported. For the base parameter setting we included the values on standard deviation, while for the eight settings with one varying parameter we kept only the mean values, as the standard deviation values are, similarly to the base setting, not significant.

Table 5. Sensitivity Analysis Data

base setting	**BAU**		**SKINT**		**ALTSKI**		**BYDSNW**	
	μ	σ	μ	σ	μ	σ	μ	σ
Arrivals	17,388.71	94.08	15,787.52	100.61	19,279.79	74.94	22,837.78	79.98
Av. Expense	37.56	0.08	50.85	0.08	40.56	0.04	41.53	0.07
Tourist Nights	85,953.56	472.82	78,650.36	509.80	95,660.71	380.44	109,051.44	395.34
Cost of Energy	2,024,070.74	17,242.86	3,086,270.05	27,352.37	2,080,902.55	12,807.76	2,350,485.69	18,073.84
Human Labor	503,439.77	2,522.76	676,965.43	2,919.95	553,927.87	2,329.58	661,544.32	2,521.16
Artificial Snow	154,024.39	0.00	636,193.90	0.00	158,200.00	0.00	6,439.02	0.00
Transfers	235,243.44	1,041.14	291,690.28	741.12	266,454.23	1,479.09	373,542.49	594.28
Gini nVisitors	0.30	0.00	0.21	0.00	0.29	0.00	0.26	0.00
group-size	**BAU**		**SKINT**		**ALTSKI**		**BYDSNW**	
(μ)	Min	Max	Min	Max	Min	Max	Min	Max
Arrivals	11,364.06	22,827.10	10,289.85	20,363.24	12,407.43	25,674.46	14,082.78	31,059.76
Av. Expense	33.69	33.33	48.48	49.45	36.51	37.06	39.89	39.55
Tourist Nights	56,229.65	112,689.90	51,265.26	101,411.88	61,574.03	127,350.09	66,955.58	148,970.52
Cost of Energy	2,020,991.39	2,027,137.10	3,074,094.75	3,079,840.37	2,077,685.63	2,085,708.57	2,347,378.82	2,350,150.54
Human Labor	329,267.28	661,361.40	432,045.84	894,276.87	357,780.03	736,559.89	409,097.33	900,002.35
Artificial Snow	154,024.39	154,024.39	636,193.90	636,193.90	158,200.00	158,200.00	6,439.02	6,439.02
Transfers	247,390.87	226,455.87	303,049.03	276,310.41	280,050.74	258,115.56	381,707.00	360,541.18
Gini nVisitors	0.28	0.31	0.21	0.21	0.28	0.30	0.26	0.27
stay	**BAU**		**SKINT**		**ALTSKI**		**BYDSNW**	

[14] We used the term currency as in Grimm and Railsback (2005) to define a standard, which provide a summary description of the state of the system, that allows us to compare contrasting versions of the model.

(μ)	Min	Max	Min	Max	Min	Max	Min	Max
Arrivals	18,680.86	16,876.90	16,898.78	14,978.31	20,376.66	18,787.10	23,479.91	22,235.15
Av. Expense	33.37	33.41	48.53	48.75	37.35	36.78	39.99	39.30
Tourist Nights	37,008.56	116,640.67	33,695.77	104,404.50	40,490.49	130,397.22	44,624.79	149,138.71
Cost of Energy	2,031,565.21	2,015,406.25	3,084,738.42	3,083,580.28	2,081,475.89	2,067,726.82	2,351,484.08	2,344,375.89
Human Labor	243,573.77	667,340.71	356,869.34	860,556.87	263,854.55	736,965.25	308,664.54	880,913.61
Artificial Snow	154,024.39	154,024.39	636,193.90	636,193.90	158,200.00	158,200.00	6,439.02	6,439.02
Transfers	132,440.73	299,789.68	167,549.63	357,831.65	145,055.95	339,901.50	197,392.20	475,578.70
Gini nVisitors	0.30	0.29	0.21	0.21	0.30	0.29	0.27	0.26
prob-of-stay=0	**BAU**		**SKINT**		**ALTSKI**		**BYDSNW**	
(μ)	Min	Max	Min	Max	Min	Max	Min	Max
Arrivals	22,539.74	13,445.07	24,913.74	7,587.38	24,846.37	14,581.42	29,766.20	16,940.22
Av. Expense	32.83	33.48	50.02	47.52	36.11	36.39	40.11	38.51
Tourist Nights	108,573.77	67,195.71	123,498.10	37,941.04	121,305.28	72,850.42	137,623.42	83,823.15
Cost of Energy	2,019,834.80	2,021,740.73	3,087,053.48	3,083,220.27	2,080,035.30	2,079,778.64	2,340,010.49	2,336,726.64
Human Labor	619,442.40	404,335.72	1,043,870.02	337,152.01	686,482.89	433,824.66	815,830.35	522,414.15
Artificial Snow	154,024.39	154,024.39	636,193.90	636,193.90	158,200.00	158,200.00	6,439.02	6,439.02
Transfers	298,515.05	191,713.38	442,958.68	146,309.20	333,160.73	207,057.43	487,532.18	269,355.53
Gini nVisitors	0.28	0.30	0.18	0.24	0.28	0.30	0.25	0.27
km-threshold	**BAU**		**SKINT**		**ALTSKI**		**BYDSNW**	
(μ)	Min	Max	Min	Max	Min	Max	Min	Max
Arrivals	23,395.48	12,352.07	15,935.96	12,860.86	24,856.26	14,122.07	29,259.56	17,436.65
Av. Expense	42.70	33.56	49.04	46.13	44.21	37.35	44.65	40.79
Tourist Nights	115,970.58	60,728.05	79,402.52	63,972.38	123,538.60	69,881.65	141,257.98	81,812.59
Cost of Energy	2,033,683.87	2,036,789.92	3,071,860.50	3,078,807.03	2,065,378.19	2,084,991.46	2,346,328.60	2,334,246.03
Human Labor	858,633.97	337,308.26	685,277.64	500,036.52	883,112.02	384,663.31	1,045,699.00	481,470.26
Artificial Snow	154,024.39	154,024.39	636,193.90	636,193.90	158,200.00	158,200.00	6,439.02	6,439.02
Transfers	422,576.10	127,034.13	290,948.15	205,978.64	415,757.79	148,849.03	577,304.79	248,442.10
Gini nVisitors	0.27	0.29	0.21	0.25	0.27	0.28	0.24	0.25
snow-threshold	**BAU**		**SKINT**		**ALTSKI**		**BYDSNW**	
(μ)	Min	Max	Min	Max	Min	Max	Min	Max
Arrivals	17,720.22	16,858.84	16,207.90	15,230.07	19,907.92	18,469.86	23,226.59	22,284.15
Av. Expense	32.09	33.13	48.77	48.57	36.84	35.85	39.08	40.31
Tourist Nights	87,341.80	83,547.49	80,670.05	75,929.63	98,488.98	91,798.76	110,750.24	106,469.73
Cost of Energy	2,038,901.83	2,030,324.41	3,093,907.28	3,098,402.88	2,067,393.56	2,078,191.49	2,335,923.06	2,350,762.20
Human Labor	512,423.99	488,817.56	693,548.41	653,906.38	571,427.88	530,340.81	672,168.56	645,582.87
Artificial Snow	154,024.39	154,024.39	636,193.90	636,193.90	158,200.00	158,200.00	6,439.02	6,439.02
Transfers	245,297.79	224,494.62	299,922.90	279,069.03	281,173.64	248,230.67	383,890.67	362,467.44
Gini nVisitors	0.29	0.20	0.20	0.21	0.29	0.30	0.26	0.26
kids-prob	**BAU**		**SKINT**		**ALTSKI**		**BYDSNW**	
(μ)	Min	Max	Min	Max	Min	Max	Min	Max
Arrivals	17,357.58	17,409.24	15,805.53	15,748.05	19,213.06	19,211.57	22,878.14	22,843.52
Av. Expense	35.71	40.23	49.35	52.96	38.71	43.26	39.76	44.16
Tourist Nights	85,802.28	86,033.39	78,765.78	78,418.18	95,353.76	95,367.94	109,238.90	109,074.67
Cost of Energy	2,031,788.89	2,021,251.19	3,090,715.37	3,097,249.29	2,068,107.84	2,084,482.56	2,343,418.76	2,341,411.09
Human Labor	501,149.44	506,229.37	676,013.66	677,711.95	550,187.72	554,899.61	660,755.92	664,892.47
Artificial Snow	154,024.39	154,024.39	636,193.90	636,193.90	158,200.00	158,200.00	6,439.02	6,439.02
Transfers	236,401.49	235,574.05	291,360.90	290,632.41	266,000.97	266,229.77	373,114.64	374,853.90
Gini nVisitors	0.29	0.30	0.21	0.21	0.29	0.29	0.26	0.26
s-shoes-prob	**BAU**		**SKINT**		**ALTSKI**		**BYDSNW**	

(μ)	Min	Max	Min	Max	Min	Max	Min	Max
Arrivals	17,394.71	17,386.75	15,863.24	15,843.49	19,621.53	18,406.51	22,872.27	22,780.80
Av. Expense	37.55	37.50	50.80	50.82	40.61	40.50	41.54	41.52
Tourist Nights	85,914.36	85,919.87	79,028.21	78,947.00	97,332.82	91,304.59	109,236.12	108,774.11
Cost of Energy	2,010,999.24	2,026,673.79	3,077,216.53	3,086,683.93	2,080,998.84	2,061,601.81	2,326,659.38	2,348,739.48
Human Labor	503,024.80	502,909.12	679,239.56	678,588.23	561,388.44	533,192.21	662,771.27	660,067.70
Artificial Snow	154,024.39	154,024.39	636,193.90	636,193.90	158,200.00	158,200.00	6,439.02	6,439.02
Transfers	235,454.26	235,603.82	289,196.54	291,695.64	254,451.97	290,201.87	373,908.87	374,098.74
Gini nVisitors	0.29	0.30	0.21	0.21	0.29	0.30	0.26	0.26
comp-factor	**BAU**		**SKINT**		**ALTSKI**		**BYDSNW**	
(μ)	Min	Max	Min	Max	Min	Max	Min	Max
Arrivals	18,504.24	13,317.53	18,464.56	11,496.44	21,479.39	14,283.57	25,273.99	16,348.90
Av. Expense	36.44	37.85	52.93	49.17	41.30	40.46	43.00	41.20
Tourist Nights	91,181.72	65,930.05	91,982.08	57,253.79	106,444.81	70,945.49	120,023.61	78,436.03
Cost of Energy	2,016,375.61	2,025,736.25	3,088,204.07	3,081,284.34	2,084,142.82	2,078,770.53	2,353,345.49	2,345,472.75
Human Labor	538,104.49	385,270.20	843,218.78	467,729.13	618,536.33	411,256.89	729,766.86	476,541.48
Artificial Snow	154,024.39	154,024.39	636,193.90	636,193.90	158,200.00	158,200.00	6,439.02	6,439.02
Transfers	495,251.82	323,430.46	374,737.10	194,319.67	309,004.15	193,936.87	658,990.23	419,434.95
Gini nVisitors	0.44	0.21	0.25	0.18	0.42	0.22	0.40	0.20

In Table 6 we summarized the outcomes of the sensitivity analysis. We regarded a currency as sensitive to a certain parameter if the mean value for that currency resulting from the simulations with one varying parameter is more than 10 % (single X), 20% (double X), and 30% (triple X) greater or lower than the mean value with the base parameter setting, for at least one of the development strategy.

Table 6. Sensitivity in a nutshell

Parameter Name	Arrivals	Av. Expense	Tourist Nights	Cost of Energy	Human Labor	Artificial snow	Transfers	Gini nVisitors
group-size	X	X	XXX		XXX			
stay		X	XXX		XXX		XX	
prob-of-stay=0	XX		XX		XXX		XX	X
km-threshold	XX	X	XX		XXX		XXX	X
snow-threshold								
kids-prob								
s-shoes-prob								
comp-factor	XXX		X		XX		XXX	XXX

Note to Table 6. The number of Xes represents the magnitude of variability of the currency's value, with minimum and maximum parameters, with respect to its value in the base parameters setting: grater or lower than 10 % (single X), 20% (double X), and 30% (triple X).

The first result is that two currencies, the cost of energy and the production of artificial snow are not sensitive to any of the considered parameters. This is an expected result as the first depends more on the tourism supply structure than on the tourist behavior, while the second depends on the skiing areas supply and on the weather conditions.

The second result is that three parameters, the threshold of requested snow cover, the probability of having kids and the probability of practicing snow-shoeing, do not produce sensible changes in any of the currencies.

Third, there are four currencies that are particularly sensitive: the arrivals, the tourist nights, the variable cost of human labor, and the internal transfers.

The arrivals are particularly sensitive to the competition factor. Indeed, if there is more competition less tourists are expected. The data about the arrivals shows that results are not as sensitive to low values of competition as to high values, meaning that the effect of the completion factor is not linear. This same currency is in minor terms sensitive to the probability of day trip because day trippers are not accounted as arrivals, by definition, and to the threshold of desired km of pistes, because it affects the attractiveness of the destination for two main tourist profiles (i.e. TSI, SPT). However, this currency is also sensitive to the threshold of desired km of tracks for own discipline, showing that this parameter has a lot of influence in the process of selecting the potential tourists and in defining the effective ones.

The tourist nights are particularly sensitive to the group size and to the duration of stay. The first is due to the amplification effect that changing the average group dimension has on this indicator, which is approximately linear for low and high values of this parameter. The same effect influences, in minor terms the indicator on arrivals. The latter is the designed multiplier which defines the tourist nights from the arrivals. So the sensitivity to this parameter is included by the model structure on purpose. However, there are enough market data to consider the base values quite consolidated.

The variable cost of human labor is the most sensitive currency because it depends on the usage of the tourist facilities which is linked to many parameters and in particular to the group size, the duration of stay, the probability of day trip and the threshold of desired km of pistes for own discipline. We are aware of the fact that results on this indicator will have to be considered more critically.

The seasonal internal transfers of tourist agents are linked to the number of tourist agents[15] that visited the destination and to the amount of time that they spent in it. Indeed, as in the case of the arrivals, this currency is sensitive to the desired km of tracks for own discipline and to the competition factor.

The Gini index of the number of daily visitors is much sensitive to the competition factor. This is because less external competition increases the amplitude of the variation among the number of visitors in peak and low season periods.

In summary, the model is sensitive to five over the eight considered parameters. Three of those are of major concern, because there are not available references to consolidate their base value: (1) the group size of the tourist (divided per tourist profile), (2) the competition factor, and (3) the threshold of desired km of tracks for own discipline.

However, while the first two produce mainly scale effects, the third is presumably more insightful, being an extremely subjective and perhaps case specific parameter that may vary a lot across a population of winter tourists, whose value seems extremely difficult to parametrize. As a consequence we used this insight for the analysis of the robustness of the model's results among all the combined scenarios.

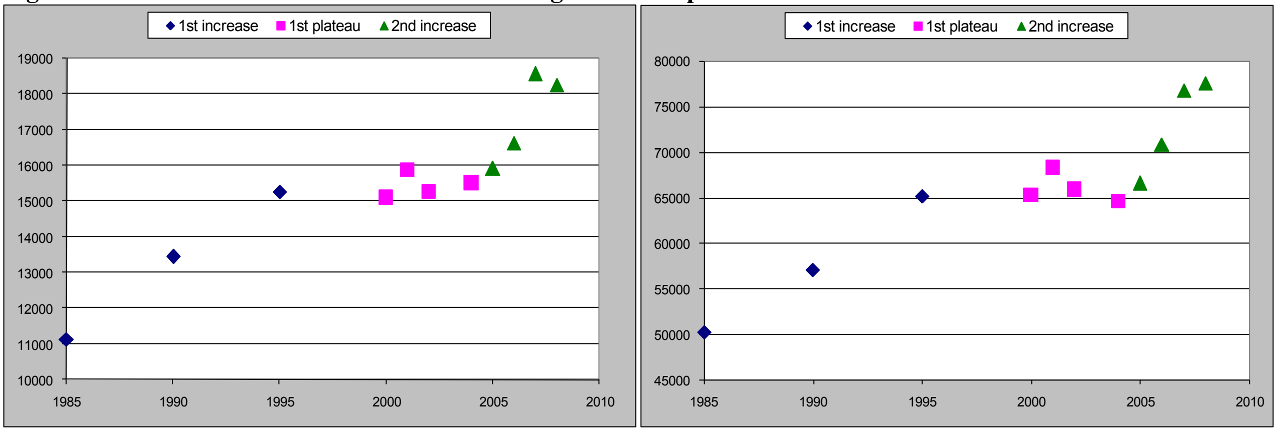
3.1.2 Parametrization

For the purpose of calibration and empirical validation, historic data about arrivals and tourists nights in the municipality of Auronzo on the period 1985-2008 are available. However, these are given on a seasonal basis only from year 2000 (with the exception of 2003). Before we have five years distant records, meaning four points between 1985 and 2000, which is the period of reference

[15] As mentioned before, a tourist agents is not a single tourist, but a group of tourists behaving homogeneously also with regards to transfer needs within the destination. In other words we assume that the individual tourists, composing one tourist agent, move together within the destination.

for the base-line climate data. The data (reported in Figure 3) shows a growing linear trend on the period 1985-1995 and a plateau for the period 1996-2004 followed by another increasing period until 2007. Then, on the basis of our field surveys and data we assume that a stable second plateau begins from 2008.

Figure 3. Historic data on arrivals and tourist nights for the period 1985-2008



As the destination didn't change much of the tourist offer, within this period of reference, we interpret those trends as the results of changes related to the catchment area. The catchment area was mainly Italian at the beginning of the period, and subjected to a demographic increase, and than increasingly opened to the eastern European market partly substituting the Italian crowd.

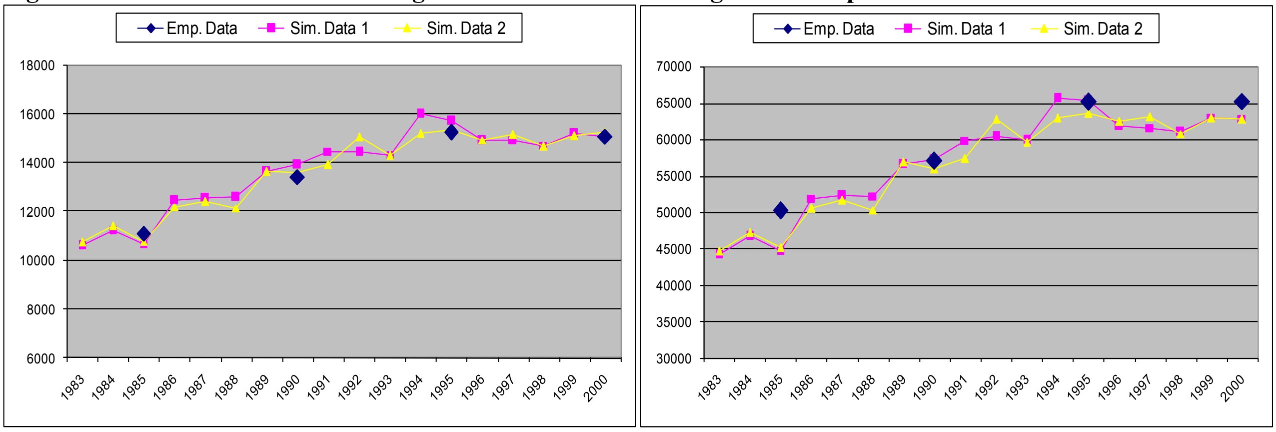
Parametrization was carried on with a limited set of historic data about the arrivals and the tourist nights of the winter seasons 1984/1985, 1989/1990, 1994/1995, 1999/2000. The simulations made use of the climate projection given by the base-line of SkiSim 2.0 that renders data on the period 1981-2000, on which no delta concerning temperature and precipitation is processed. The selected development strategy was BAU, and competition “generic”.
This process led to the necessity of dynamically vary the number of tourist agents within the simulation, in contrast to our initial assumption of a fixed parameter. Indeed, the total number of agents of the simulation was yet one of the unknown parameters and needed to be calibrated[16]. We assumed that for the base-line climate scenario the number of agents varies according to Equation 5 up to a maximum of 9,500 agents[17]:

(Eq. 5) *nAgents = 5800 + 230 * (season) with season =[1..40]*

According to this equation the simulation reaches 9,500 agents during the 15th season (i.e. 1995), which is the beginning of the first plateau. We also calibrated the parameter on the duration of stay (reducing it from 0.5 to 0.42) to better fit the data. For the rest of the parameters the base setting seems good enough. Results are shown in Figure 4.

[16] This is related to the fact that the number of tourist agents does not correspond to the number of tourists (i.e. arrivals), because individual tourists are grouped (see parameter group-size) to constitute one tourist agent.
[17] 9500 is the number of agents that allows AWS1.0 to reproduce the first plateau starting in 1995 of approximately 15,000 arrivals and 65,000 tourist nights (with base-line climate projection, BAU strategy, and generic competition).

Figure 4. Calibration and data fitting of arrivals and tourist nights for the period 1985-2000



3.1.3 Validation

In this section, we intend to show the efforts that were made in order to analyze if and how different parts of the model were consistent with empirical data and with observed patterns.

The first issue was related to the appropriate number of tourist agents to be used for the simulation of the period 2011-2050 and the resulting data, in terms of arrivals and tourist nights, to be compared with empirical data. As anticipated in the previous section, empirical data and field surveys led us to assume a stable second plateau, of approximately 18,000 arrivals and 77,000 tourist nights, from 2007/2008.
The parametrization phase turned to be insightful, as Equation 5 could be re-used to find the value for this parameter to reproduce this second plateau of arrivals and tourist nights. Re-applying Equation 5 translated for the duration of the first plateau (1996-2004) led to a number of agents of approximately 11,250 during season 2011/2012. With this number of agents a simulated BAU strategy with a base-line climate projection (that re-applies the climate conditions of the period 1981-2000), for the period 2011-2050, delivers data about the initial population (i.e. arrivals and tourist nights in 2011/2012) that is coherent with the latest empirical data of 2007 and 2008.

For the subsequent simulations of the period 2011-2050 (for all the combinations of development strategy, climate projection and competition) we further assumed that without any optimistic market refreshment the number of agents sticks to 11,250 (i.e. conservative scenario). Conversely with the optimistic scenario we assumed the number of agents increasing with the linear steepness of Equation 5 up to 14,000 agents[18].

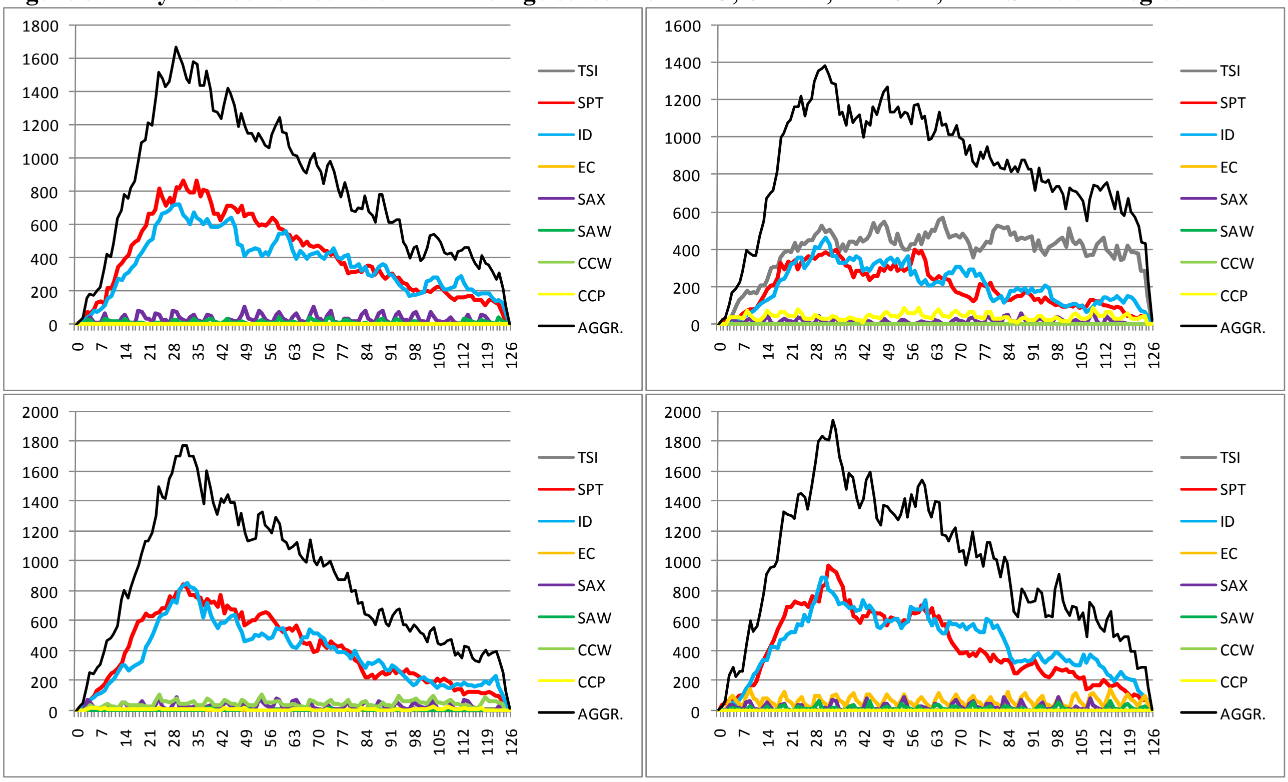
Other elements included in the validation process concern the capacity of the model to reproduce two observed patterns, namely the seasonal peaks of the tourism fluxes and the profile of expense related to each tourist profile.

As in many destinations, where the seasonality of winter tourism is particularly exacerbated, also in Auronzo it is empirically established that the tourists tend to concentrate on the period from

[18] In this case, 14,000 is a purely symbolic value that has been calibrated against data about arrivals and tourist nights of a neighboring and better performing Alpine winter destination. The purpose is to represent an optimistic performance, in terms of tourists' in-flow, compared to the current situation, and at the same time an achievable objective, with regard to the destination comfortable carrying capacity.

Christmas to Epiphany. However, detailed intra-seasonal empirical data are not available.
In Figure 5 the daily number of visitors per category (and aggregated) is plotted, in an average season, for the four strategies, with A1B climate projection, conservative societal scenario and generic competition. The model showed the ability to reproduce the expected seasonality with the Christmas peak as a cumulative effect of the booking behavior of the individual tourist agents divided per tourist profiles.
In the left quadrants, BAU and ALTSKI, the main profiles participating to the simulation are SPT and ID and the seasonality is more evident. In the upper-right quadrant, that is the SKINT strategy, the activation of TSI tourists profile mitigate the tourist seasonality significantly, because TSI are more keen to go on skiing vacation from February to March. In the bottom-right quadrant, that is the BYDSNW strategy, a less evident mitigation effect of seasonality is achieved by means of the activation of EC tourists.

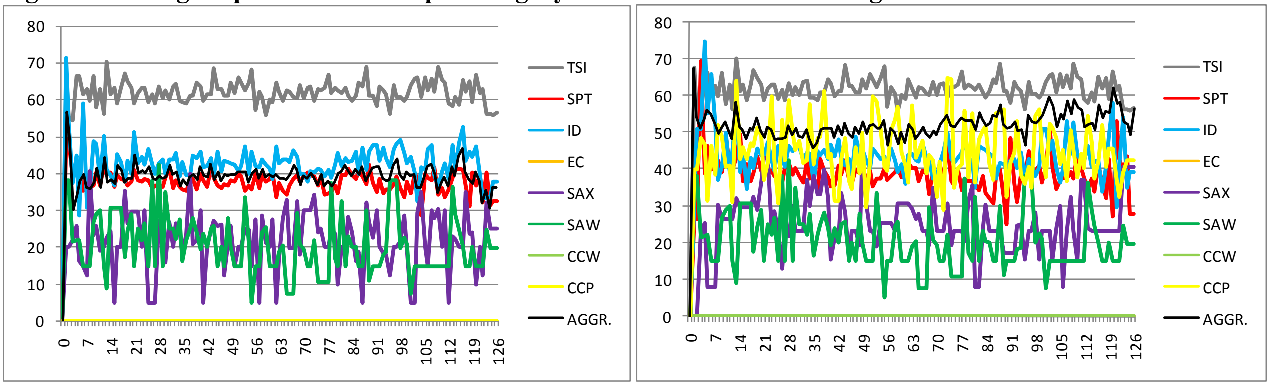
Figure 5. Daily number of tourists in an average season for BAU, SKINT, ALTSKI, BYDSNW strategies



Further, when elaborating from the literature the narratives describing the tourist profiles we made some hypotheses about the tourists' daily amount of expenses. We also cited some quantitative references for some profiles, based on the market surveys of the province of Bolzano. In the model the expenses emerge as a consequence of each individual tourist fruition and are not super imposed on each tourist profiles. We didn't expect to produce the same results with our model for two reasons. Firstly, AWS1.0 can only consider the expenses that are explicitly modelled as part of the tourism supply side. For instance, transportation is not included. Secondly, our case study is certainly positioned on a lower market/price segment, with respect to most of the destinations of the province of Bolzano. However, it must be mentioned that AWS1.0 delivers a ranking of the tourist profiles with respect to their average daily expense that is coherent with our initial hypotheses. One exception concerns the ID profile, whose expenses we assume that were overestimated at the beginning of the conceptualization phase.
In Figure 6 it is reported the daily average expense per tourist profile for two different strategic development options. In the right quadrant a SKINT strategy increases the total average daily

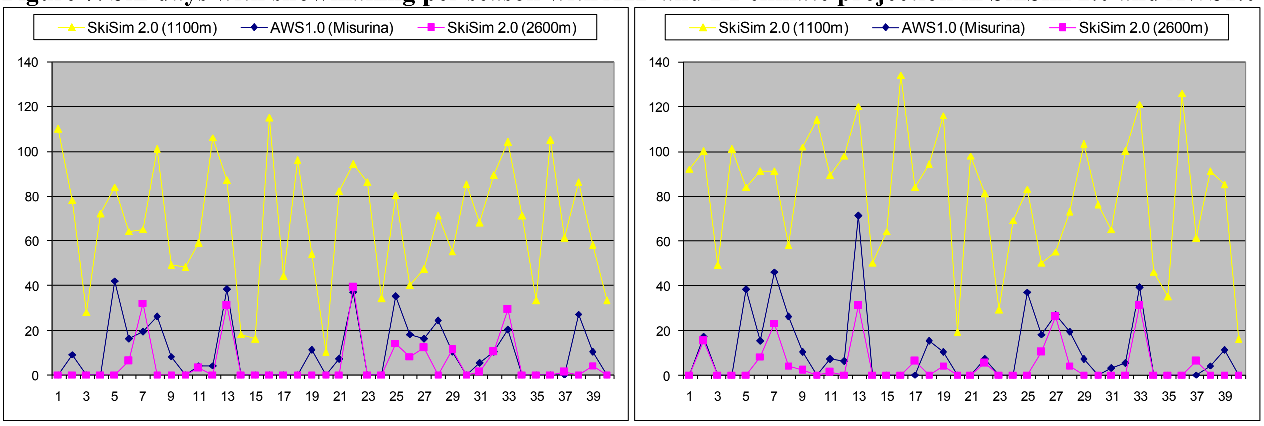
expense, compared to a BAU strategy (in the left quadrant), because it increases the number of TSI and CCP tourists that have a higher average expense with respect to SPT and ID tourists.

Figure 6. Average expense of tourists per category in BAU and SKINT strategies



A further element of validation taken into consideration regards artificial snow. The artificial snow-related part of the model has been compared with the snowmaking module of SkiSim 2.0, whose results weren't directly plugged into AWS1.0 for several reasons but mainly because with SkiSim 2.0 the duration of the season is variable and results are presented for each altitudinal band of 100m, while we opted for a more simplistic treatment of this aspect.
In Figure 7 are considered the days per winter season in which artificial snow was produced in the ski-area around Misurina (whose altitude varies from 1100m to 2600m above the sea level) according to AWS1.0 and the added ski days resulting from snowmaking at 1100m and at 2600 m from SkiSim 2.0. Simulations were run both with A1B (left quadrant) and B1 (right quadrant) climate projections.

Figure 7. Ski-days with snowmaking per season with A1B and B1 climate projection in SkiSim 2.0 and AWS1.0



These lines are not directly comparable because of the season length discrepancy, what is relevant is to highlight how the snow production trends are significantly coherent among the data simulated by the two models. AWS1.0 certainly simplifies the treatment of this kind of information with respect to SkiSim 2.0 because the data are processed on the average conditions of the ski-area. This probably leads to a certain underestimation of the artificial snow productions needs. However, as shown in the results section, this solution appears to be adequate to deliver clear signals about future issues related to the production of artificial snow.

3.1.4 Authentication

During the second workshop of the ClimAlpTour project we set a social experiment with the people of Auronzo whereby participants have tried to anticipate the outcomes of the model after they were briefed about the various typologies of tourists and scenarios' content.
They were asked to rank the strategies according to their expected performance regarding:
1. numerosity of attracted tourist,
2. effect on employment,
3. containment of seasonality,
4. containment of traffic,
5. attraction of tourists with higher average daily expense.

They were also asked to produce the same ranking concerning their comprehensive judgment on each category in two situations: (a) taking into account recent climate trends and (b) with the expected climate variations described in Table 2. The aim is to authenticate the model by comparing their aggregated ranking of the strategies with the one resulting from AWS1.0.

In general the results for individual indicator are poor, meaning that there is a weak correlation among the aggregated rankings produced by the stakeholders and those resulting from AWS1.0. In particular the stakeholders' expectations concerning the numerosity of tourists, seasonality and traffic are significantly distant from the model's indications. In the first case the SKINT strategy is much overestimated in comparison to one of the most surprising results of AWS1.0, as we'll discuss in the next section. In the second and in the third case it's the BYDSNW strategy to be regarded as very powerful while its simulated performance is not confirming it. One problem might be related to the concept of seasonality which we described as the variability (i.e. Gini index) among the distribution of tourists in one season while it's generally perceived as the capacity of enlarging the season duration.
However, the overall model results appear to be authenticated by the stakeholders. We asked the stakeholders to consider the appropriateness of the strategies taking into considerations the expected climate variations and rank them accordingly.
Indeed the comprehensive ranking scores resulting from the eight indicators across combined scenarios, further described in the results section, and the aggregated ranking scores produced by the stakeholders render the same final ranking. Results are shown in Table 7.

Table 7. Comprehensive ranking scores of strategies

	StakeHolders scores	AWS1.0 averaged scores	Shared final ranking
BYDSNW	1.64	2.11	1.00
ALTSKI	1.71	2.52	2.00
SKINT	2.88	2.59	3.00
BAU	2.93	2.79	4.00

3.2 Analysis of Results

We produced results for the four development strategies in eight combined scenarios of climate, society and competition for eight indicators:

1. seasonal arrivals (n),
2. seasonal tourist nights (n),
3. seasonal average daily expense of tourists (€),
4. seasonal cost of energy (€),
5. seasonal cost of human labor (€),
6. seasonal production of artificial snow (€),
7. variability of tourism fluxes (Gini index), describing the seasonality,
8. seasonal internal transfers of tourist agents (km).

A ninth indicator, which is more of a complementary element to the first three, concerns the composition of the tourists in terms of profiles effectively visiting the destination.

In the following section we comment on the results for each of the indicators. Further indicators not deriving from AWS1.0 and more oriented towards the environmental impacts of development have been included in the participatory and decision making phase of the study, whose description is beyond the scope of this paper.
In Table 8 we reported the comprehensive ranking scores per each indicator deriving from the rankings in eight (i.e. 2 power 3) combined scenarios (two societal, two climatic and two competition). The formula used to compute the score is the simple weighted average expressed in Equation 6, where the denominator is always equal to 8.

(Eq. 6) $Score = \Sigma N_i * i / \Sigma N_i \text{ with } i = [1..4]$

If the direction of the indicator is positive a strategy got 1 (i.e. first position) when it scored the highest value and 4 (i.e. last position) when it scored the lowest value, per indicator and per each combined scenario. Vice versa, when the direction of the indicator is negative a strategy got 1 when it scored the lowest value and 4 when scored the highest value.

Table 8. Comprehensive ranking scores per indicator

Indicator	Direction	BAU	SKINT	ALTSKI	BYDSNW
Arrivals	+	3.13	3.88	2.00	1.00
Labor	+	3.50	2.50	2.25	1.75
Energy	-	1.00	4.00	2.50	2.50
Expense	+	4.00	1.00	2.50	2.50
Transfers	-	1.5	1.75	2.75	4.00
Seasonality	-	3.88	1.00	3.13	2.00
Art. Snow	-	2.50	4.00	2.50	1.00
Tour. Nights	+	3.25	3.75	2.00	1.00

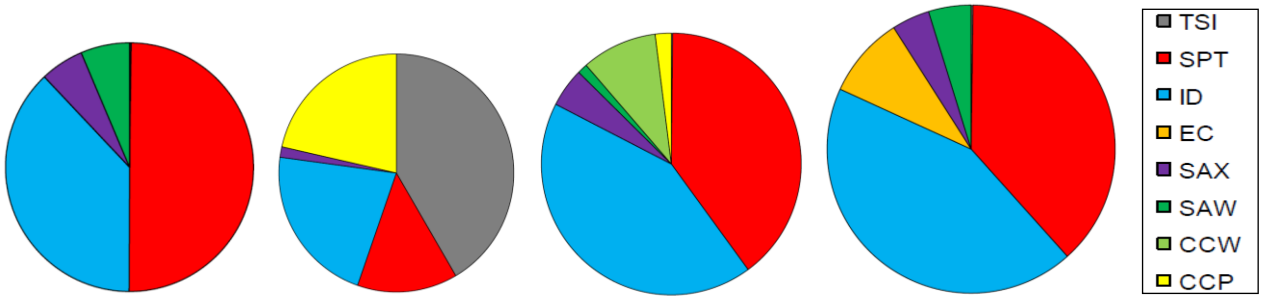
3.2.1 Observed Trends

Results on arrivals and tourist nights are highly correlated (R^2 = 0.99) and as arrivals have shown to be less sensitive we focus on this indicator[19]. The BYDSNW strategy clearly outranks the others across combined scenarios. This strategy is not much sensitive to competition and takes the final

[19] To avoid double counting the indicator on tourist nights has not been taken into account in calculating the averaged scores of Table 7.

averaged seasonal arrivals to approximately 22,000 with a conservative societal scenario and 29,000 with the optimistic one.
One may argue that this is not a benefit in absolute terms and that there could be a threshold for the local stakeholders above which the tourists are not welcome anymore. This could be easily implemented in a more refined evaluation exercise, however for the scope of this paper we decided to not go beyond the indicators' direction, therefore keeping the focus on the assessment process.
ALTSKI is consistently the second best strategy. A quite surprising result concerns the SKINT strategy, which is often regarded as a mass tourism strategy in the Alpine Region, that produces even fewer arrivals than a BAU approach. This is due to the fact that TSI tourists seem to compete with ID and SPT tourists especially on the level of pristine environment requested.
Therefore, a SKINT strategy appears to substitute a group of tourist with a less numerous one instead of building on the existing ones. This fact is exacerbated with combined scenarios of more evident climate change and higher competition. This is an unexpected result also with regards to the perception of the local stakeholders. In Figure 8 it is described the composition of the tourists per profiles in the four strategies, ordered in BAU, SKINT, alternative snow and BYDSNW. The dimension of the pie chart is meant to represent the relative ability of the strategies to attract tourists across combined scenarios[20].

Fig. 8. Composition of the tourists in the BAU, SKINT, ALTSKI and BYDSNW strategies



Results on average daily expense of a single tourist show that the SKINT strategy clearly outranks the others with an average of 50€ against approximately 40€ of ALTSKI and BYDSNW and 30€. Figures are consistent across combined scenarios. EC and TSI tourists are the tourists with the highest individual daily expense, with EC tourists slightly prevailing. However, the greater number of TSI tourists in the SKINT strategy, compared to the number of EC tourists in the BYDSNW strategy, lead the SKINT strategy to consistently be the one with the highest individual daily expense of tourists.

Results on human labor need for a season are unstable and depending on the societal and competition scenarios in place. However the model is showing that the BYDSNW strategy is the most robust one being only first best and second best. The SKINT strategy is first best with generic competition, and producing considerably higher results, but the worst with a competition very specialized on TSI tourists, and producing extremely disappointing results.

Regarding the seasonal cost of energy, the SKINT strategy is by far the most energy consuming, while the BYDSNW and the ALTSKI strategies are almost equivalent. BAU is the first best because any investment considered in our strategies involve more energy consumption in absolute terms.

[20] Therefore, a fixed figure about total arrivals cannot be assigned because it's varying among scenarios. The dimension of the pie chart is purely symbolic.

The production of artificial snow is an indicator very much hard-wired into the configuration of each strategy, therefore, as expected, the SKINT strategy is more demanding in terms of artificial snow resulting in an average seasonal consumption of water of between 240,000 and 280,000 m^3, depending on climate scenario. BAU and ALTSKI are equivalent showing an average utilization of water for producing artificial snow of varying between 57,000 and 67,000 m^3, depending on climate scenario.

Having previously checked the normality of the distribution of daily visitors, the seasonality of tourism[21] is herby described by means of the Gini index referring to the daily number of visitors within each simulation of 40 seasons (i.e. 5040 days).
Results show that the SKINT strategy is consistently the first best, because it's capable of smoothing the seasonal peak of the Christmas holidays in favor of the "white weeks" of February and March (see Figure 5). BYDSNW is the second best and it is slightly better than ALTSKI. They both rely on more alternating typologies of fluxes preferring short period holidays concentrated on the week ends. However, they also allow for the enlargement of the tourist season if compared to the current situation (i.e. BAU) where the tourism is totally concentrated on the festivities.
One element of interest is the fact that all the strategies produce a significantly higher variability of fluxes in presence of niche competition. A niche competition leads to releasing some of the competition's pressure to the bulk of the tourism of Auronzo constituted by ID and SPT tourists, which are the profiles that are keener to concentrate on certain periods of the season.

Finally, we considered a spatial indicator represented by the amount of movements of the tourist agents on an average season. We did not consider how the tourist agents might respond qualitatively to their transport needs but we simply considered how the development strategies could quantitatively influence the transportation needs of the tourists.
The results are not obvious. The BYDSNW strategy seems to consistently perform in the worst way. In fact, in the BYDSNW strategies tourists are stimulated to do multiple activities during one day in different places of the destination. The remaining strategies are not much divergent from each other, apart from the SKINT strategy in the conservative societal scenario combined with generic competition which performs as bad as the BYDSNW strategy. However, the ALTSKI strategy seems to consistently perform slightly better.

For each of the considered indicators it is important to highlight that results are not as sensitive to the climate scenarios as to societal and competition conditions, confirming that competition and demand are more effective drivers of change than climate.

A comprehensive look into this assessment is presented in Figure 10. According to the selected indicators, it is evident that the BYDSNW strategy is the most robust one. This result is quite surprising also because it's confirmed independently from the climate scenarios. ALTSKI is however not much diverging for many indicators and is consistently the second best. The SKINT strategy is peculiar. It's very good for certain indicators but very bad for others. BAU is mainly the point of reference from which looking at the future, but it also has certain advantages deriving from the absence of costs of investment and no increase on energy consumption in absolute terms.

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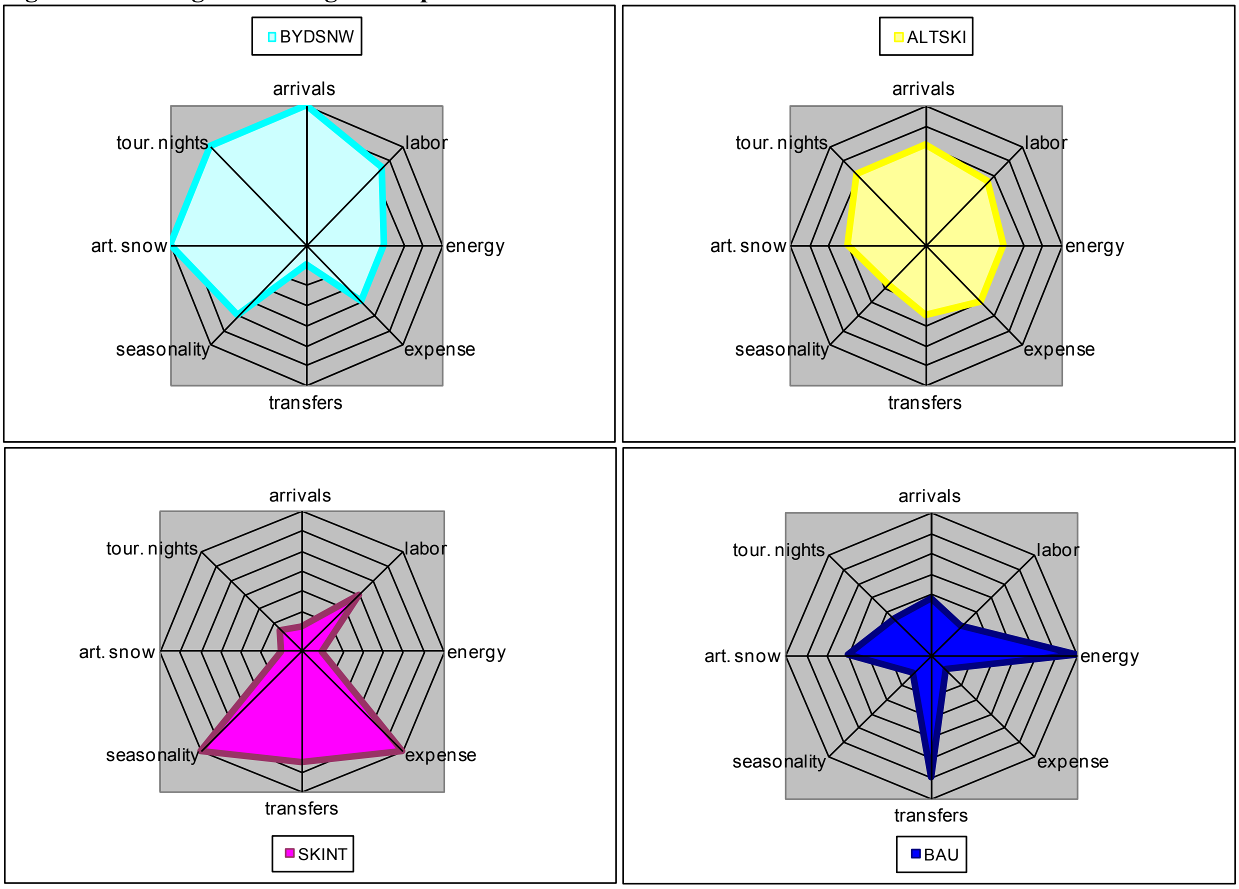
[21] See Karamustafa and Ulama (2010)

Figure 10. Strategies' ranking scores per indicator



3.2.2 Robustness analysis

We tested the results with the parameters of more concern, (1) the group size of the tourist (divided per tourist profile), (2) the competition factor, and (3) the threshold of desired km of tracks for own discipline. They were made to vary assuming the minimum and maximum values of Table 5. Differently from the section on the analysis of the results, and diverging from the scores in Table 8, we only considered the ranking scores deriving from maintaining a conservative societal scenario and a generic competition.

Very similar ranking scores are obtained with varied parameters as shown in Table 9. The ranking of strategies is never altered. We only found minor changes for labor and transfers, which slightly modify the ranking obtained with the base parameter setting. Scores are highlighted in bold in Table 9. In general the robustness of the results doesn't seem susceptible to the variations on the parameters' values.

Table 9. Strategies' ranking scores per indicator with conservative societal scenario and generic competition

Indicator	Parameters' setting	BAU	SKINT	ALTSKI	BYDSNW
Arrivals	base	3.00	4.00	2.00	1.00
	varied	3.25	3.75	2.00	1.00
Labor	base	4.00	**2.00**	3.00	**1.00**
	varied	3.75	**1.50**	3.25	**1.50**
Energy	base	1.00	4.00	2.50	2.50
	varied	1.00	4.00	2.50	2.50
Expense	base	4.00	1.00	3.00	2.00
	varied	4.00	1.00	2.75	2.25

Transfers	base	1.50	3.50	**1.50**	**3.50**
	varied	1.50	3.50	**1.75**	**3.25**
Seasonality	base	3.5	1.00	3.5	2.00
	varied	3.75	1.12	3.25	1.88
Art. Snow	base	2.00	4.00	3.00	1.00
	varied	2.00	4.00	3.00	1.00
Tour. Nights	base	3	4	2.00	1.00
	varied	3.25	3.75	2.00	1.00

3.2.3 Key messages for planners

Investing on the dimensions of winter tourism that are detached form the activities based on snow seems like the safest way to proceed for a destination with the characteristics of Auronzo di Cadore. A BYDSNW strategy should however be linked to a project of enhancement of the public transportation as the in-destination transfer needs of tourists may significantly increase.

An ALTSKI strategy could be the way to mediate between the lifts industry, which has already invested a lot in the past and the possible futures that the local winter tourism will have to face.

Apart from the snow-related risks and costs, a SKINT strategy could undermine the bulk of Auronzo’s traditional tourism rather than building on it, turning such a choice into a strategic error. Lift operators should rather take into account the optimization of the existing downhill skiing infrastructure and the related services.

Given the already high cost of energy for the accommodations compartment, in particular, local planners should focus on this issue before any new investment is made. A sound reflection about renewable energy based heating systems might be appropriate.

Doing nothing is not necessarily a bad thing in absolute terms, but it might be a strategy to focus on other issues that have not been considered here such as the development of a public transportation (permanently linking Auronzo to Misurina), or the enhancement of the standards of hospitality through investments in formation and awareness raising, etc. However, sometimes the costs of pursuing such kind of activities may require a greater magnitude of tourism fluxes in order to sustain them. That is why it is important to start developing tourism since today, in a proper direction.

All the development strategies other than a BAU approach have the merit of improving the tourism seasonality. However, this is not a measure that should be maximized per se (i.e. with a SKINT approach) renouncing to the flexibility of the destination in facing the tourists evolving needs and the natural cycles.

4. CONCLUSION

AWS1.0 is an agent-based tool capable of producing simulated data about relevant socio-economic indicators, linked to environmental implications, of the tourism system of Auronzo di Cadore. These indicators have been used to assess alternative tourism development strategies across scenarios of climate, society and competition for the period 2011-2050.

- Results show that a development strategy detached from snow-related activities, but focused on the qualification of the hospitality structures and on the indoor activities is likely to produce better outcomes, in particular regarding the mass of tourism attracted. This result is consistent across future scenarios and is mainly related to the capacity of this strategy to build on the bulk of the existent tourism, while dealing with the climatic, demographic and competition changes that could happen.
- The same applies to the second best choice, which is oriented towards the development of the all set of alternative outdoor activities that can happen on fresh snow, also with the assistance of lifts where needed, but in a lighter and more flexible way.
- Conversely, a SKINT strategy could undermine the fidelity of Auronzo's traditional tourists rather than building on them.

These results have shown to be robust even applying the parameters that have proved to produce the higher degree of uncertainty.

In this first version we only considered exogenous and hard-wired development strategies that are only considering changes about the tourism facilities. Some crucial virtual elements of tourism (e.g. hospitality culture and formation, and the satisfaction deriving from its quality) are therefore not captured and some important concrete elements, such as transportation, could be treated in a more exhaustive way. However, the model is complex enough to integrate the different dimensions of the problem at stake and to deliver some insightful results.

We acknowledge that the framework of the assessment is limited by the fact that we have considered diverging strategies that very unlikely could be implemented in a self-standing manner, while a possible real world solution could arise from the integration of elements belonging to different strategies. However, we still have the feeling, reinforced by the feedbacks coming from the local stakeholders, that this was a very appropriate way to approach the issue. It must be clear that this study is not suggesting to dismantle previous investments, but it's rather exploring the most robust directions for new ones.
In a nutshell, Auronzo is certainly well characterized to focus on traditional skiing families and BYDSNW activities, while Misurina could well become a point of reference for the ALTSKI emerging paradigm.

Further research could include the possibility of turning the supply side of the model endogenous. This would change the scope of this work from testing hard-wired strategies to observing the evolution of the destination supply structure, eventually looking at the conditions to drive it on the desired path.
Specific market surveys could consolidate the stratification of the tourist profiles leading to more detailed analytical translation of their behaviour. We are currently developing web tools to retrieve additional data from potential winter tourists.

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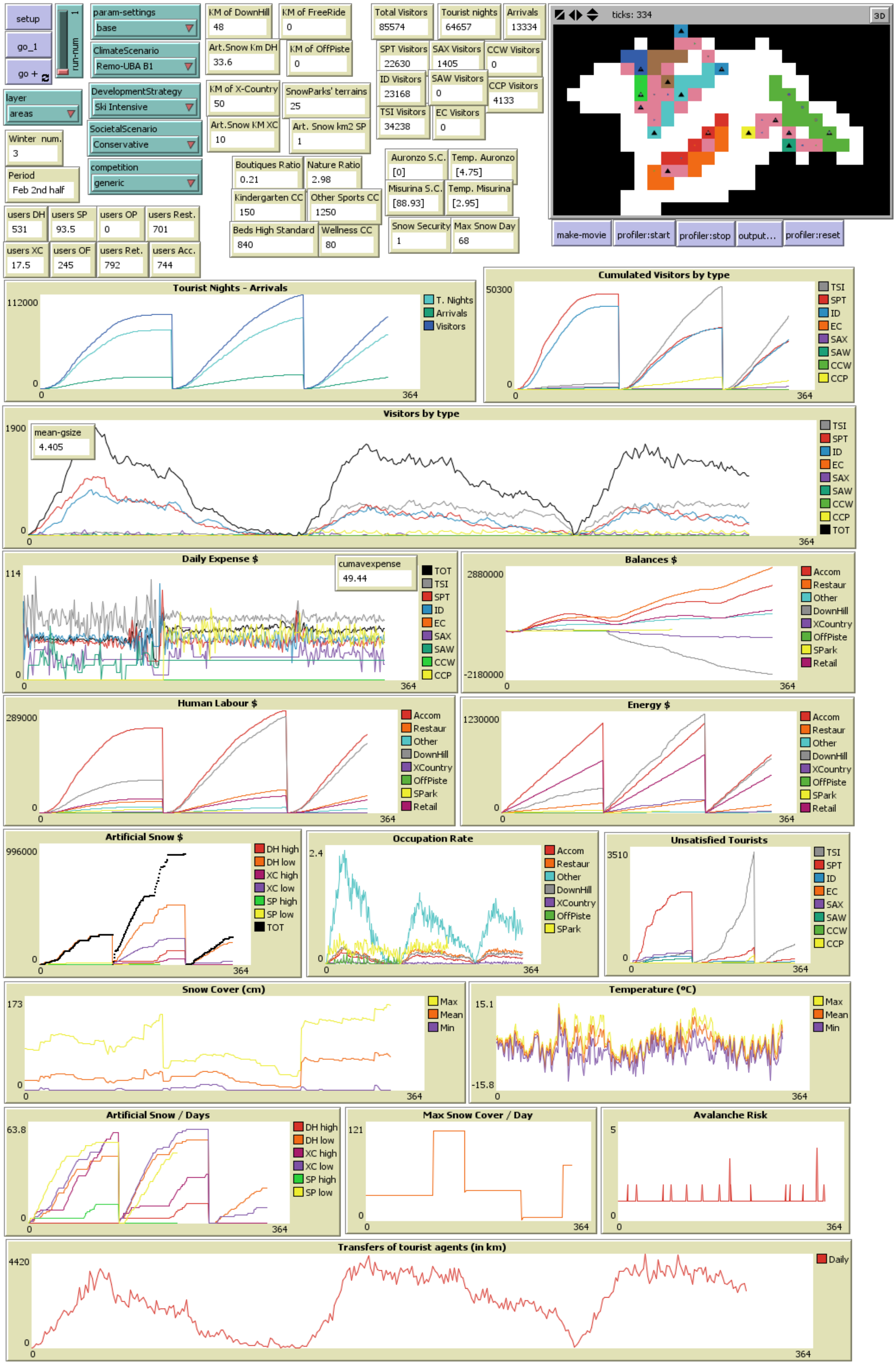
APPENDIX 1. Screenshot of the interface of AWS1.0.



CONCLUSION TO THE DISSERTATION

ABM seems well suited to the analysis of adaptation to climate change of local systems. In addition to the expected qualities of the methodology, i.e. the emergence of outcomes at the macro-level from micro-interactions, some specific strengths of ABM are particularly meaningful when dealing with climate change. The main advantages of ABM applied to climate change related issues are the abilities to take into account adaptive behavior at the individual or system level and to introduce a higher degree of heterogeneity resulting into a more natural representation of the system, compared to equilibrium-based models. The main disadvantage of ABM, as in other domains of application, stays in the challenges of testing the model which is not always very clear and often neglected. Where feasible, participatory approaches seem the most suitable solution. For this reasons local applications may appear more robust.
In fact, since recently, ABM has been increasingly combined with empirical methods. This study followed this stream of research, applying an agent-based approach to the analysis of adaptation to climate change and sustainable development in a local and case-specific context: a winter tourism destination in the Alpine Region.

AuronzoWinSim is a conceptual model of the winter tourism system of Auronzo di Cadore capable of gathering heterogeneous but incomplete information, to produce computer simulations about possible futures, and discuss them with local stakeholders. The model is an original concept in the sense that, to our knowledge, this is the very first application of agent-based modelling to investigate adaptation to climate change of winter tourism at a local level, integrating socio-economic and environmental components, and adopting a complexity science approach.
The scale of analysis and the level of detail represent a significant improvement in the climate change research, which is normally performed at a much higher level of spatial and temporal aggregation. This scale perfectly fits the crucial socio-economic dynamics of local adaptation that have to be investigated.
To our knowledge this is one of the first attempts to formalize the supply structure of a winter tourism destination in classes by means of UML. The result is simple and clear but is able to represent complex interactions, for alternative development strategies, in a spatially explicit way. This is extremely valuable giving our objective of assessing robustness and flexibility rather than finding optimal solutions. This conceptualization can eventually become a generic ontology, if it will be proved to fit the application to other case studies.
The simulation focuses on the feed-backs of the demand side of tourism, which is often missing in the existing tourism models. However, the tourists are the ultimate judges of a destination adaptation strategy, because they will decide the winners and losers of the future. This is why we regarded as fundamental to focus on their agency in an heterogeneous way, drawing from disciplines such as customer behavior, which could only be done by means of an the agent-based approach.
The model development itself is a novelty because we integrated some of the main practices of the ABM community which are never found together but can mutually benefit each other.

The implemented version of the model, AuronzoWinSim 1.0, is an agent-based tool capable of producing simulated data about relevant socio-economic indicators, linked to environmental implications, of the winter tourism system of Auronzo di Cadore. These have been used to assess alternative tourism development strategies across scenarios of climate, society and competition for the period 2011-2050.

Results showed that a development strategy detached from snow-related activities, but focused on the qualification of the hospitality structures and on the indoor activities is likely to produce better outcomes, in particular regarding the mass of tourism attracted. This result is consistent across future scenarios and is mainly related to the capacity of this strategy to build on the bulk of the existent tourism, while dealing with the climatic, demographic and competition changes that could happen. The same applies to the second best choice, which is oriented towards the development of the all set of alternative outdoor activities that can happen on fresh snow, also with the assistance of lifts where needed, but in a lighter and more flexible way. Conversely, a traditional SKINT strategy could undermine the fidelity of Auronzo's traditional tourists rather than building on them.

These results have also shown to be robust even applying the parameters that proved to produce the higher degree of uncertainty. In this first version we only considered exogenous and hard-wired development strategies that are taking into account changes about the tourism facilities. Some crucial virtual elements of tourism (e.g. hospitality culture and formation) are therefore not captured and some important concrete elements, such as transportation, could be treated in a more exhaustive way. However, the model is complex enough to integrate the different dimensions of the problem at stake and to deliver some insightful results.

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