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Conceptualizing an Environmental Software Modeling Framework for Sustainable Management Using UML

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ABSTRACT. The concept of sustainable environmental management is expressed on the basis of ecosystem services as it enables getting to the quantitative measures. A practical utilization of this interpretation of sustainability requires a mechanism whereby all the goods and services provided by ecosystems are adequately quantified, valuated and incorporated in the decision-making process. Each of these tasks is substantially non-trivial. In order to deal with said complexity, a sophisticated information system has to be available to the stakeholders of environmental sustainability. An environmental software modeling framework, as a tool implementing the tasks of sustainability, is conceptualized in the meta-model of the Unified Modeling Language. The task of sustainable management is articulated as an optimal control problem, though other articulations are also possible. The overall multi-layered architecture of the framework and its key software components are discussed in the paper. Internal functional logic of each software component is described in terms of UML diagrams due to their proven semantic, descriptive and visual power in modeling and presenting of the software requirements and related artifacts, full compatibility with the object-oriented paradigm of the software systems development and a round-trip engineering feature supported by a spectrum of commercial and free CASE-tools. An approach presented in the paper can be suggested as a standardized methodology suitable for a broader range of software undertakings in the domain of environmental informatics.

Keywords: Decision-making, Ecosystem services, Environmental software modeling framework, Resources management and planning, Sustainable management, Stakeholders, UML

1. Introduction

The scale of anthropogenic alteration of the planet's ecosystems is a substantial and growing factor to be regarded in policy- and decision-making procedures. Human society and its economic development cause adverse side effects such as habitat destruction, over-harvesting and pollution of environmental niches (i.e., air, soil, fresh waters, oceans, etc.). The current rate of biological species extinction due to human activities is about 8,000 per year (Saier, 2006). As predicted by Trainer (1999), if continue to use timber, water and other natural resources at the rate people in rich countries do today, most biological resources would be exhausted in a few decades at most. According to the estimates of the World Wildlife Fund (WWF, 2006), the demand on planet's ecosystems (the ecological footprint index) has more than tripled since 1961 and now exceeds the world's ability to regenerate by about 25 per cent.

There is a common understanding among the scientists and stakeholders that social and economic development should be more responsible in a sense of reducing the unfavourable impact on the environment and carefully foresee the likely consequences of societal development for the planetary leaving systems (e.g., Clark et al., 2001). This new paradigm can be broadly defined as environmental sustainability. In the most generic sense, environmental sustainability can be understood as maintaining natural capital and resources (Goodland, 1995). The frequently cited Brundtland report defined sustainability as "development that meets the needs of present [generations] without compromising the ability of future generations to meet their needs" (Our Common Future, 1987). The attempts to concretize the notion of sustainability have been done, e.g., through the concept of the optimum carrying capacity (Barett and Odum, 2000), thermodynamic laws of energy and entropy (Norde, 1997; Jørgensen and Svirezhev, 2004) and eco-exergy (Jørgensen, 2006). Neither of these definitions offers a quantitative criterion or measure of sustainability to be applied in the practice of environmental management.

In our view, an idea of sustainable environmental development is best approached on the basis of ecosystem services whereby all the goods and services generated by ecosystems are adequately quantified, valuated and incorporated in the decision-making process at the earliest stages (Khaiter, 2005). In such a way, ecosystem services become a key notion for the

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concept of environmental sustainability which calls for a systematic integration of knowledge developed across a broad range of fields, such as economics, ecology, psychology, sociology, hydrology and agronomy (Kelly et al., 2013), as well as corresponding models and tools facilitating their interactions (Jakeman and Letcher, 2003; Voinov and Bousquet, 2010; Carnevalle et al., 2012).

In order to successfully deal with the aforementioned challenges, and incorporate and tie together all of these diverse subjects, concepts and ideas, an adequate theoretical framework is needed and a sophisticated information system utilizing modern information technologies (Huang and Chang, 2003) has to be offered to the stakeholders of environmental sustainability. Moreover, a software tool should assess ecosystem services at the level of details, at which policy and management decisions are made (Ausseil, 2013).

At the same time, it was noted that just a few studies of environmental sustainability incorporate the information systems perspective (Melville, 2010). Most of the reported environmental management information systems (EMISs) approach the concept of sustainable development from the corporate perspectives in a sense of an adequate IT support for businesses to comply with environmental protection laws and regulations (Freundlieb and Teuteberg, 2009) and eco-friendly operations of companies, including corporate environmental reporting, sharing environmental maps, data and models, decision support for environmental investment site selection (El-Gayar and Fritz, 2006) and establishing green processes in organizations (Pernici et al., 2012). While carrying industry-specific features (e.g., energy sector (Nuss, 2015) or chemical industry (Liew et al., 2014)), EMISs have been categorized into information systems for external reporting, eco-controlling systems for internal operations research, life cycle assessment systems, key performance indicator-based systems, environmental accounting systems, sustainability reporting systems, input-oriented systems, output-oriented systems, process-oriented systems and production-related systems (Teuteberg and Straβenburg, 2009).

In this paper, we present an effort to address a certain lack of research in the area of EMISs operating at a trans-corporate level, incorporating environmental management of territories and objects (e.g., lake, forest, shore, river, etc.) and thus supporting corresponding sustainable policy- and decision-making. It is always desirable that software development of environmental information systems could follow a certain standardized process, similar to the Systems Development Life Cycle (SDLC) of industrial IT projects, thus allowing for the benefits of modularity, reusability and other fundamental design principles and making solutions found in one undertaking suitable for a broader range of tasks in the domain of environmental modeling and management. Stakeholders, functions, data requirements and software components of the environmental information systems are substantially unique and differ from those in business IT projects. In accordance with these considerations, we demonstrate an environmental software modeling framework (ESMF) as a formalized approach to the entire process of software development aimed at supporting sustainable environmental management on the basis of ecosystem services. The overall multi-layered architecture of the ESMF, its key software components and their internal functional logic is conceptualized in the meta-model of the Unified Modeling Language (UML). The choice of the UML is stipulated by a number of advantages, including its full compatibility with the object-oriented paradigm of the systems development, semantic, descriptive and visual power in modeling and presenting of the software requirements and related artifacts as well as a spectrum of commercial and free CASE-tools, featuring round-trip engineering, readily available to the IT developers.

2. Methodology

2.1. Ecosystem Services

Ecosystems generate many useful benefits, some of which are even crutial for human well-being, collectivelly called ecosystem services. The UN-led Millennium Ecosystem Assessment initiative (MA, 2005) classified ecosystem services in four broad groups: *provisioning*, such as the production of food and water; *regulating*, such as the control of climate and disease; *supporting*, such as nutrient cycles and crop pollination; and *cultural*, such as spiritual and recreational benefits. The interpretation of sustainability on the basis of ecosystem services draws a number of underlying non-trivial issues, e.g.:

- Ecosystem services are formed under a complex interplay of natural and anthropogenic factors. Their quantitative assessment and prediction are only possible in computer experiments with simulation models of the investigated phenomena.
- There is no common technique to valuate ecosystem services handy in environmental economics. Moreover, many services have no market values, and their pricing can be done through some indirect, predominantly artificial, exercises.
- Decision-making, as a formalized process, becomes quite complex from both mathematical and computational perspectives.

Assuming that these methodological problems are successfully resolved, the most favourable strategy of development can be chosen from the criterion of maximum net environmental value (MNEV) of the set of complementary ecosystem goods and services.

2.2. Theoretical Framework

As a means of coupling the concepts and ideas of environmental sustainable management, a theoretical framework has been suggested. The initial steps in developing the framework were mostly concerned with the task of quantifying the ecosystem services in the scenarios of environmental management (Khaiter and Erechtchoukova, 2010). As a further development, the framework has been extended to include the modules implementing valuation and decision-making activities at the upper structural levels (Khaiter and Erechtchoukova, 2012).

The next step towards integration of the environmental sustainability in the decision-making on the basis of ecosystem services requires an information system realizing the main elements of the framework in corresponding software components, i.e., transforming a theoretical framework into an environmental modeling frameworks and thus enabling its practical use by the policy- and decision-makers as well as by the wider categories of stakeholders. In this paper, we conceptualize the main constituting software blocks of the modeling framework on the basis of the UML notation.

2.3. The Unified Modeling Language (UML)

David et al. (2013) note that constructing environmental modeling frameworks (EMF) requires a broad spectrum of modeling approaches originating from hydrology, biology, climatology and economic scientific domains (Argent, 2004). Designing domain-specific software frameworks is a challenging exercise, and it should, among many other aspects, take advantage of state-of-the-art software development practices, while facing the fact that environmental modelers are not software engineers (David et al., 2013). We suggest to overcome this contradiction by applying the benefits of modern software visual modeling with UML.

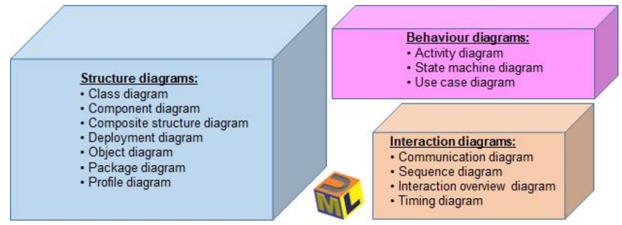

Figure 1. UML taxonomy and official logo.

The Unified Modeling Language (UML) is a standardized graphical language being used in object-oriented software development for analyzing, specifying, documenting and visual modeling of an IT project's artifacts or components (Rumbaugh, 1999; Fowler, 2004). Following its introduction by the three "founding fathers" Grady Booch, Ivar Jacobson and James Rumbaugh of the then Rational Software Corporation in the mid-1990s, the UML has been widely supported by

Table 1. UML Diagrams and Their Characteristics

Diagram type/diagram	Description
Structure diagrams:	
Class diagram	describes the types of objects in the system, their attributes and operations, and the various kinds of static relationships among them
Component diagram	shows reusable pieces of software and dependencies among these components which may be used to hierarchically decompose a system and represent its logical architecture
Composite structure diagram	depicts the internal structure of a class, decomposes classes into their constituent parts and models their runtime collaborations that this structure makes possible
Deployment diagram	describes hardware used in system implementations and the execution environments and the allocation of the artifacts deployed on the hardware nodes
Object diagram	shows the existence of objects and their relationships in the logical design of a system and provides a complete or partial view of the object structure of a modeled system at a specific time
Package diagram	describes logical grouping of a system into the packages and the dependencies among these grouping constructs
Profile diagram	operates at the meta-model level, creates a coherent group of stereotypes for a particular purpose, such as business modeling
Behavior diagrams:	
Activity diagram	shows the overall flow of control, describes procedural logic, the business and operational step-by-step workflows of components in a system
State machine diagram	describes the behavior of individual objects in terms of a serious of states and state transitions triggered by events and the related actions that may occur
Use case diagram	depicts the functionality provided by a system in terms of actors, their goals represented as use cases, and any dependencies among those use cases
Interaction diagrams:	
Communication diagram	shows the linkages and interactions between objects or parts, describing both the static structure and dynamic behavior of a system
Sequence diagram	is used to trace the execution of a scenario and shows how objects communicate with each other in terms of a sequence of messages; also indicates the lifespans of objects relative to those messages
Interaction overview diagram	is a combination of activity diagram and other interaction diagrams intended to provide an overview of the flow of control between interaction diagram elements
Timing diagrams	is a specific type of interaction diagram showing how the states of an element or elements change over time and how events change those states

a considerable number of Computer Aided Software Engineering (CASE) tools and, in November 1997, adopted by the Object Management Group, an international consortium that creates and maintains standards for the IT industry (Booch, 2007; Vanderperren et al., 2008). The UML provides a graphical notation to model an information system being built. The complexity of modern software development cannot be captured by a single diagram. The UML offers different types of diagrams to address all the aspects of the system. These diagrams are classified into structure diagrams and behaviour diagrams. The latter group also includes a subset of interaction diagrams. The most recent version of the language, UML2.x, totals 14 types of graphical models subdivided into seven structure diagrams, three behaviour diagrams and four interaction diagrams (Figure 1).

Structure diagrams show the static structure of elements in the information system. Behaviour diagrams describe their dynamic properties. Interaction diagrams emphasize the flow of control and data among the components of the system. A summary of the UML diagrams and their characteristics are given in Table 1 (Fowler, 2004; Booch, 2007).

2.4. UML in Environmental Information Systems

As a *de facto* standard and the primary modeling tool (Booch, 2007), UML has been utilized in the Systems Development Life Cycles (SDLCs) of business IT projects for many years (Satzinger, 2012). In our days, information systems have overstepped their original limits of business applications and penetrated into non-business areas of human activities, such as environmental protection and management. Environmental information systems (EIS) is a generic term that describes the class of systems that perform one or more of the following tasks: environmental monitoring, data storage and access, disaster description and response, environmental reporting, planning and simulation, modeling and decision making (Athanasiadis and Mitkas, 2004). Examples of UML applications in the designing of environmental information systems are demonstrated below.

Parajorgji and Schatar (2004) suggest a method for developing and documenting soil-water balance and irrigation-scheduling models, using UML. In particular, the common system elements (such as soil, plant and weather) have been expressed with a UML class diagram using Rational Rose software tool. As reported, the method simplifies documentation of model requirements, assumptions and calculations and provides a template for implementing the model in programming languages. It can simplify the processes of code re-use and model modification.

In a study on spatial data in EIS within the domain of agricultural spreading of organic matter, Pinet et al. (2007) applied the notation of a UML class diagram to present a partial database schema of the corresponding system. Wang at al. (2005) also relied on a UML class diagram in an object-oriented approach to the description and simulation of watershed-scale hydrological processes. Heisel et al. (2008) describe a method for the test case generation in the model-based software development process with the aim of UML state machine diagrams. Jansen and Dokas (2008) explore the potential use of UML for the development of a DSS for river management involving various decision criteria and different stakeholders. UML use case diagram and class diagram have been applied in that study. Gong and Wang (2011) present a conceptual Green Design Control System (GDCS) meant to regulate product concentration of hazardous substances and to integrate product design and production process management to help trace the status of hazardous products and their origin. The following UML diagrams are used to demonstrate the workflow and control function of a CGDCS through the use case view and the process view: use case diagrams, activity diagrams, class diagrams and sequence diagrams. Cara and Murraya (2013) demonstrate the role of UML use case diagrams in the requirements analysis for the Water Resources Observation Network’s Reference Model as a means facilitating interoperability and evolution of the software system.

This non-exhaustive review, nevertheless, allows us to conclude that the role of the UML in the design of environmental information systems remains limited and only a minimal set of UML diagrams is being employed in environmental software development. Applications of the UML in this domain are lacking a common methodology, and the known examples are rather sporadic. In the subsequent section of the paper, we present a formalized approach to the entire process of sustainable environmental management on the basis of UML and demonstrate the role of different UML diagrams in the conceptual design of environmental software tools.

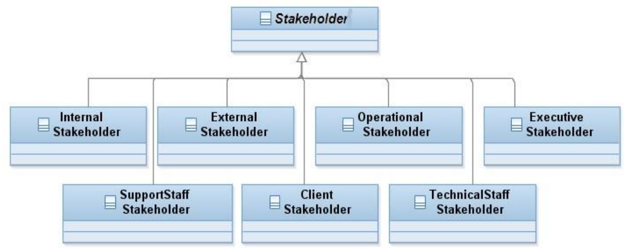

Figure 2. Categories of stakeholders in software development from the institutional point of view shown in the notation of a UML class diagram (formalized from: Satzinger et al. (2012)).

2.5. Stakeholders and Actors in the EIS

In software development, stakeholders are broadly defined as individuals or groups who have an interest in the successful implementation of the information system (Satzinger et al., 2012). This all-encompassing definition can be categorized from the institutional point of view as shown in Figure 2.

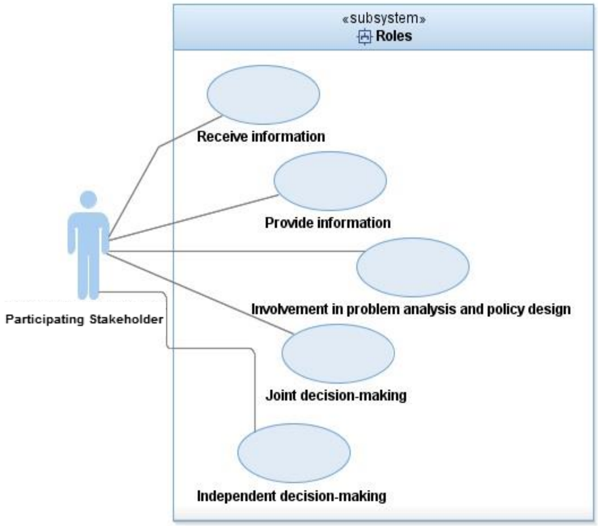

Figure 3. Roles of participating stakeholders in environmental management presented in the notation of a UML use case diagram (formalized from: Mostert (2003)).

The domain of environmental management, environmental modeling and the development of environmental information systems is unique from a number of perspectives. The diversity of stakeholder groups is one of the factors contributing towards said uniqueness. In addition, there is a number of perspectives, numerous potential stakeholders who may participate, different goals and roles of their participation (see Figure 3) and many potential participatory methods designed to achieve them (Hare et al., 2003). For example, surveys of stakeholders from governmental authorities, researchers, IT specialists, environmental agencies, NGOs, general public and private sector reveal varying interpretations and perceptions held by these different groups of stakeholders regarding potential benefits and environmental values of the information provided by the EISs (e.g., McIntosh and Diez, 2008; Mysiak et al., 2008; van Delden et al., 2008).

While noting different perspectives on the part of scientists, policy- and decision-makers, Voinov et al. (2014) argue for their tighter integration and direct engagement in value-setting process as a crucial factor for the success of any exercise in the subject field. Participatory methods suggest to structure group processes in a way that stakeholders play a central role and articulate their knowledge, values and preferences for different goals (van Asselt et al., 2001).

Modeling of software functions with the UML begins with identifying the actors, i.e., persons outside the system that interact with the system. In bringing together ideas of participatory modeling and UML-based development, we determine the following categories of actors-stakeholders: Ecologist, Modeler, Governmental authority, Policy maker, Environmental agency, NGO, Monitoring specialist, Lab technician, IT specialist, DB specialist, and Environmental economist. Participatory goals of each category are considered in the respective sub-sections below.

3. Results

For its practical application, the theoretical framework outlined in sub-section 2.2 is to be implemented in software components within a software tool and in a form of a software framework. A software framework can be defined as a software library providing domain specific functionality in a reusable form (Gamma et al., 1995), supporting modular approach to model development and targeting data manipulation, analysis and visualization (Argent et al., 2006). Environmental modeling frameworks also support aggregation of model components into functional units, component interaction and communication (David et al., 2013). Many environmental modeling frameworks have been developed using an "individualistic" approach (Argent et al., 2006), and this situation calls for a standardized solution suitable for a broad range of tasks in the environmental problem domain. In this section, we present a conceptualized approach to environmental modeling frameworks on the basis of the UML.

3.1. Environmental Software Modeling Framework: Architectural Design

According to Lloyd et al. (2011), software frameworks help define the software architecture of applications by: 1) providing a reusable design which guides software development in partitioning functionality into units, commonly referred to as components, classes or modules; and 2) specifying how units communicate and manage the thread of execution. Most architectural solutions for large-scale information systems employ an idea of multi-layered designs originating in Model-View-Controller (MVC) paradigm introduced as part of Smalltalk-80 programming environment (Krasner and Pope, 1988). Modern examples of such architectural designs are clearly seen in the Core J2EE architecture (Alur et al., 2003) and the PCBMER architectural model (Maciaszek and Liong, 2005), but they do not concern the environmental problem domain.

To present the system architecture of an environmental software modeling framework (ESMF), we use the key structural decisions of these multi-layered designs and the principle of platform independence making implementations of the framework suitable for various targeting environments. The framework implies multiple categories of interacting actors, multiple non-trivial tasks, multiple concepts and multiple methodologies – all of which contribute towards its multi-dimensional complexity. As a means of overcoming the issue of complexity, the architecture of the ESMF applies separation of responsibilities into four tiers: Client tier, EMMVM tier, Data Source (DS) tier and Data Warehouse (DW) tier as shown in the notation of a UML deployment diagram in Figure 4. A UML deployment diagram is intended to model physical architecture or the realization of a software product in terms of nodes, communication paths between them, and the artifacts that reside and execute on them (Fox, 2007). Accordingly, each tier of the ESMF appears in the diagram as a UML note.

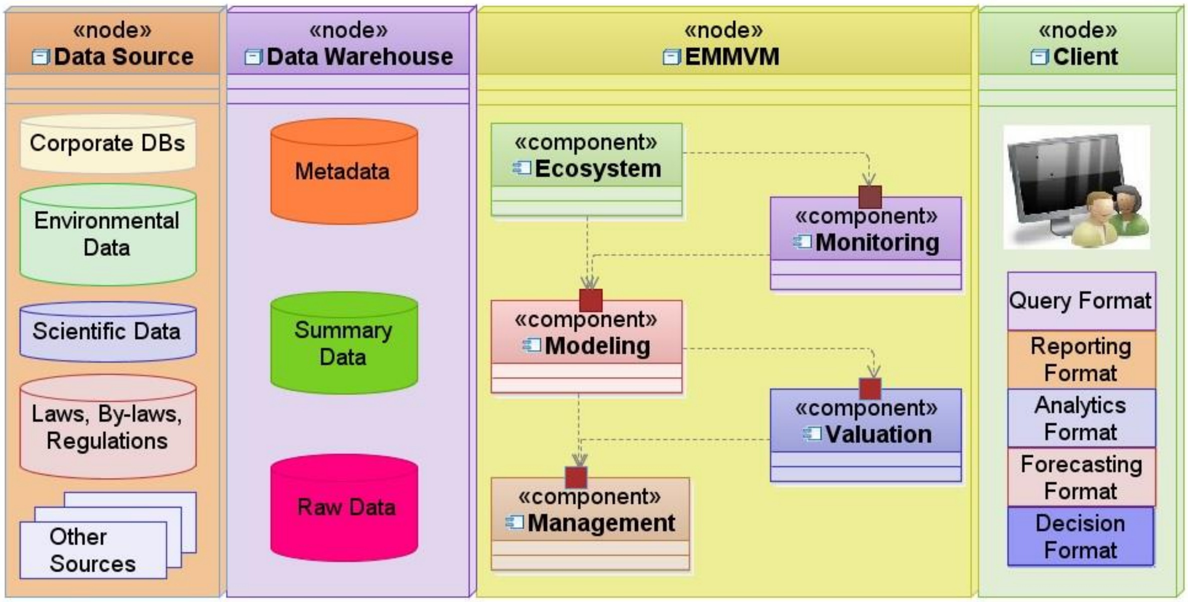

Figure 4. Architecture of the ESMF in the notation of a UML deployment diagram.

The Client tier is accountable for the communications of various categories of actors identified in section 2.5 with the system which can be realized as a programmable client, a Web browser client, a WML mobile client or an XML-based Web service client with an option to be executed on the client machine or from a Web or application server (Maciaszek, 2007). The tier offers the users multiple alternative regimes of operations: query format, reporting format, analytics format, forecasting format and decision-making format.

Procurement of the framework with relevant data is a challenging issue. It should be noted that not all desirable data are appropriately standardized or even readily exist in whatever formats. Due to their intrinsic unique features, it is unrealistic to shape even an exemplary set of data or their sources for any sustainability project of this kind. Possible sources of data presented in DS tier comprise corporate DBs, environmental data provided through connecting to external environmental portals (Freundlieb and Teuteberg, 2009) or to monitoring networks on meteorology, hydrology, pollutant emissions, etc., sets of laws, by-laws, regulations and standards as well as scientific data acquired through research publications, ad-hoc pilot projects, surveys and dedicated data collection.

Data conveyed by the DS tier are acquired in the DW tier by means of ETL (extract-transform-load) processes and can additionally be verified and transformed (e.g., filtering, cleaning, merging, summating, averaging, etc.). Not all of the data sources are within an easy reach, and no standardized retrieval approaches are readily available, but potential mechanisms may involve conventional web search and text and data mining. This tier operates as a repository of metadata, summary data and raw data providing structural information concerning heterogeneous data integrated from various data sources (Nuss, 2015). The ultimate goal of this tier is to feed the EMMVM tier with all information needed for its functioning. The exchange between the DW and EMMVM tiers can be supported by standardized protocols and formats (e.g., XML, SOAP, CSV).

The EMMVM tier is the backbone of the ESMF implementing its application logic in response to the users' requests placed through the Client tier. It also communicates with the DW tier to retrieve or store any required data sets. As seen in Figure 4, the tier is structured in five hierarchical layers: Ecosystem, Monitoring, Modeling, Valuation and Management. Each layer is visualized by a UML component to indicate modular self-containing units and their relationships (interfaces). Once implemented in a particular framework, components are able to be reused in other models or frameworks (Lloyd, 2011). Therefore, the UML components satisfy the component-based software development and reuse principle. Internal contents of each layer of the EMMVM tier is the main focus of this paper, and they get a detailed consideration in the relevant sub-sections below.

3.2. Ecosystem Layer

Ecosystem services can be considered as derivatives of ecosystem existence and functioning. Consequently, any study of the ecosystem services assumes the specification of the ecosystems affected by the planned human activities. In general systems theory (von Bertalanffy, 1969), any system is characterized by: 1) the structure (i.e., parts and their composition); 2) behaviour (i.e., inputs, internal processing and outputs of material, energy or information); 3) interconnectivity (i.e., functional as well as structural relationships between the various parts of a system); and 4) emergentness (i.e., properties and functions arising out of combining the ecosystem components within a single structure). From the thermodynamic perspective, an ecosystem is an open system. In light of these provisions and following classical ecology (Mueller, 1997; Odum, 1983), for each ecosystem, we need to identify the border separating it from the environment, interfaces (i.e., inputs and outputs), constituents and their composition and interrelationships (i.e., the structure), and processes which govern the ecosystem functioning.

As an adequate description of an ecosystem (E), we suggest a five-set tuple which includes a set $\{C\}$ of biotic and abiotic constituents and factors (i.e., ecosystem composition), a set $\{S\}$ of their particular assemblages and interrelationships (i.e., ecosystem structure), a set $\{P\}$ of ecosystem parameters designating quantitative values of the ecological processes involving constituents and interactions between them, a set $\{In\}$ of environmental inputs and a set $\{Out\}$ of ecosystem outputs:

$$E = \left\langle \{In\}, \{C\}, \{S\}, \{P\}, \{Out\} \right\rangle.$$

At any given time t, the constituents (or sub-systems) of an ecological system can be represented by a non-negative n-dimensional state vector:

$$\mathbf{x}(t) = (x_1(t), ..., x_n(t)) \in \Omega \subseteq \Re^n.$$

The state variables quantitatively designate elements of the set $\{S\}$, i.e., both biotic and abiotic constituents of the ecosystem and their properties, such as richness and density of species or their assemblages, concentrations of organic and inorganic matters and polluting substances, etc. Parameters of the ecosystem, i.e., elements of the set $\{P\}$, are represented by an m-dimensional vector:

$$\mathbf{p}(t) = (p_1(t), ..., p_m(t)) \in \mathrm{P} \subseteq \Re^m.$$

The rules governing the natural and anthropogenic dynamics of each set as well as respective stressors have to be understood. The steps forming internal tasks of the Ecosystem layer involve an interaction of two actors: Ecologist and Modeler. A format of a UML use case diagram is applied to demonstrate the contents of the Ecosystem layer (Figure 5).

3.3. Monitoring Layer

Implementation and functioning of the ESMF requires diverse observation data collected by a monitoring system in a standardized way and in conformity with a certain monitoring program. In any monitoring system, the latter is determined

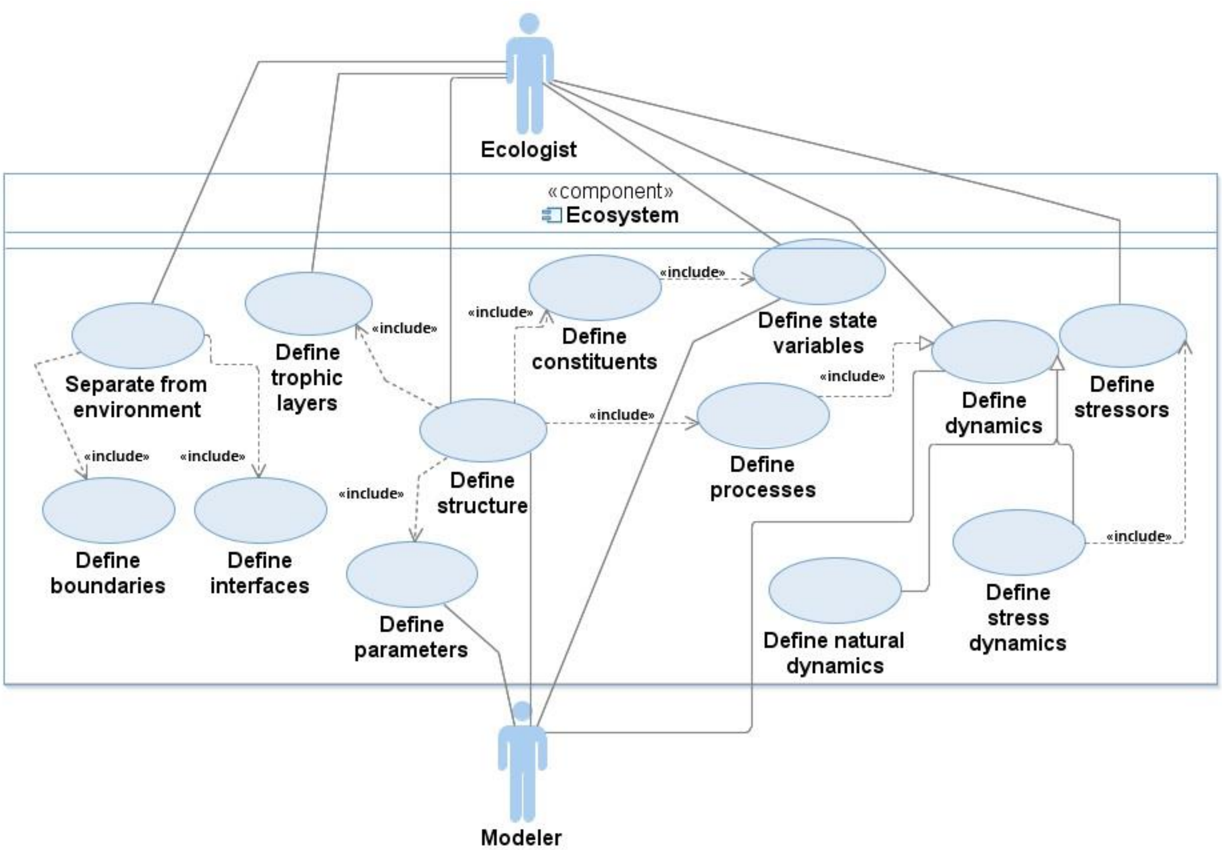

Figure 5. Internal steps of the Ecosystem layer shown as a UML use case diagram.

by the scientific, environmental and/or managerial objectives formed under budgetary, technical and other constraints in a dialogue between such groups of actors as Governmental authority, Policy makers, Environmental agency, NGO and Monitoring specialist.

A monitoring program can be defined in terms of monitoring indicators, sampling designs and a set of observation sites (Erechtchoukova et al., 2013). It will also specify laboratory analyses and procedures, and include recording of monitoring data, data analysis and interpretation as well as reporting and follow-ups (WQTG, 2006). The aims of a monitoring system can be: 1) assessment of trends in indicators; 2) attainment of environmental quality standards; 3) assessment of environmental impact; and 4) general surveillance (Whitfield, 1988). The Lab technician, IT specialist, Ecologist and Modeler actors are also involved in these steps. Processing of samples is performed by the Lab technician actor. The DB specialist actor supports recording of monitoring data in the system. Relevant activities of the Monitoring layer are shown in the notation of a UML use case diagram (Figure 6).

3.4. Modeling Layer

The Modeling layer consists of modules responsible for Modeling natural dynamics, Modeling anthropogenic dynamics and a module of Quantifying ecosystem services. These modules are represented as the UML packages in Figure 7.

In environmental decision-making, we are dealing with ecological systems whose behaviour is highly complex, with dynamics and feedbacks spanning multiple spatial and temporal scales (e.g., Levin, 1999). In addition to the inherent complexity, ecological systems are impacted by human actions. As noted by Vitousek et al. (1997), human alteration of Earth has become a substantial and growing factor. In any planned undertaking, there is an obvious and urgent need to carefully foresee the likely consequences of societal development for the leaving systems (e.g., Clark et al., 2001). Predictions of this kind are, however, possible only if adequate models describing ecosystem dynamic behaviour are in place.

3.4.1. Modeling Natural Dynamics Package

Nowadays, quantitative models play an important role literally in all of the sciences. But the importance of models in environmental management, where experiments on real world objects are significantly limited, if not entirely forbidden, is hard to overestimate. Models in ecosystem science serve a number of functions. They allow the investigators to test hypotheses, to uncover patterns embedded in observation data, to synthesize data on disparate components into an integrated view of ecosystem functions, and to ultimately predict the

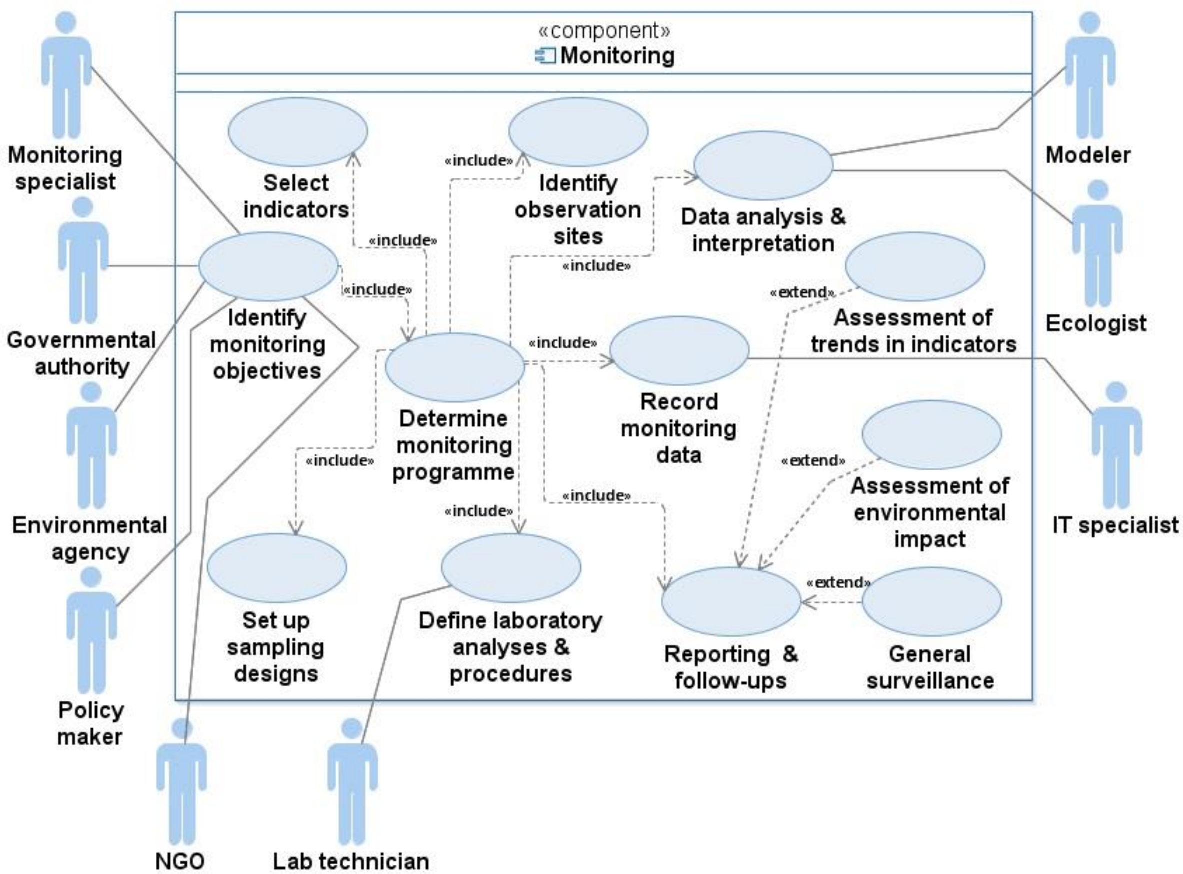

Figure 6. Activities of the Monitoring layer shown as a UML use case diagram.

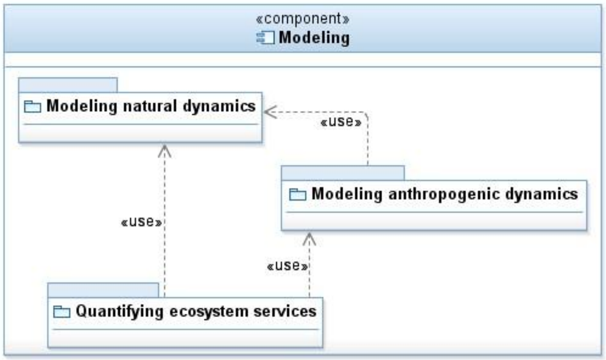

Figure 7. Modules of the Modeling layer shown as UML packages.

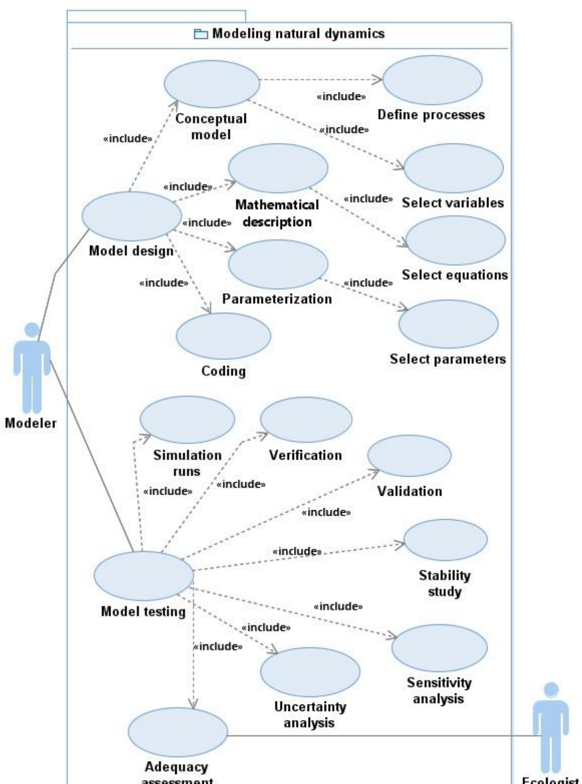

Figure 8. Internal steps in the Modeling natural dynamics package shown as a UML use case diagram.

future behaviour of some aspects of the ecosystem under given scenarios of future external drivers (Canham et al., 2003).

Any model in environmental management is expected to represent a real-world ecological system or some of its aspects of a particular interest. At the same time, a model is unavoidably a simplification of objective reality (Straškraba and Gnauck, 1985). Due to the complexity of real ecological systems, the model always reflects only substantial properties of the system rather than all its details.

Generally, model development involves a sequence of required stages. Jakeman et al. (2006) state a standard procedure for good modeling practice to include ten iterative steps in development and evaluation of environmental models from the scientific point of view. Voinov and Bousquet (2010) suggest a nine-step approach to participatory modeling engaging stakeholders in the modeling process.

In an attempt to satisfy both perspectives, the Modeling natural dynamics module is largely divided into the model design stage and the model testing stage. Its internal steps are demonstrated on a UML use case diagram in Figure 8. The stage of model design includes: 1) development of a conceptual model (i.e., selection of major variables and processes); 2) mathematical description of the conceptual model in the form of equations; 3) parameterization (i.e., determination of quantitative values of model parameters); and 4) coding (i.e., translation of the mathematical equations into computer-based software).

The model testing stage involves: 1) simulation runs; 2) verification (i.e., comparison of results obtained from model simulation with values observed in the system); 3) validation (i.e., a proof that the reactions and dynamics generated by the model are similar with the behaviour of the real system); 4) stability study of simulation results (i.e., investigation of model reactions to perturbations of initial values of model variables), mostly in a sense of the Liapunov stability; 5) sensitivity analysis to major parameters (i.e., a series of tests in which the modeler varies the values of model parameters to see the corresponding changes in model outputs); 6) uncertainty analysis (i.e., a measure of an error in the model simulation of given observations due to parameters, state variables and model structure); and 7) overall model adequacy assessment.

As it is seen in Figure 8, all the steps involve the Modeler actor; the Ecologist actor participates in model adequacy assessment.

The outcome of these activities is a model of the natural evolution of the system, which, in a unified notation by Ide et al. (1997), can be written as follows:

$$M[t,\ \mathbf{in}(t), \mathbf{x}(t), \mathbf{p}(t),\ \mathbf{F}(t)] = 0, \qquad (1)$$

with the initial conditions $\boldsymbol{x}(0) = \boldsymbol{x}_0$. Here M is the model dynamics operator, t is the time variable, $\boldsymbol{p}(t)$ is the vector of model parameters, and $\boldsymbol{in}(t)$ is the vector of inputs of environmental factors, i.e., elements of the set $\{In\}$. The vector-function of ecosystem processes $\boldsymbol{F}(t)$ expresses an interplay of environmental inputs, state variables and parameters. Depending on the aim of the research, a particular ecosystem being modelled and observation data available, the operator M may be in a form of an algebraic expression, or differential or integral operator. Often in ecological applications, M characterizes ecosystem dynamics in terms of ordinary differential equations. The structure $\{S\}$ of the modelled real-world ecosystem is revealed through the values of the state variables and parameters and a particular mathematical form of functions $f_i (i=\overline{1,n})$ in $\boldsymbol{F}$.

3.4.2. Modeling Anthropogenic Dynamics Package

The system may experience the influence of exogenous management perturbations denoted as an *r*-dimensional vector:

$$\mathbf{u}(t) = (u_1(t), \ldots, u_r(t)) \in \mathrm{U} \subseteq \Re^{\mathrm{r}}.$$

When analyzing ecosystem dynamic behaviour, it is important to differentiate between the contribution of natural factors and the impact caused by anthropogenic factors making a particular emphasis on anthropogenic stress for the following reasons: (i) anthropogenic stress alters the rate of the ecosystem development, dramatically speeding it up in most cases; (ii) human-caused disturbances are novel and, hence, "unfamiliar" to the ecosystem, which means that there are no evolution-developed compensatory reactions or adaptive mechanisms within the ecosystem to cope with and sustain the stress (Khaiter and Erechtchoukova, 2007).

The internal logic of the Modeling anthropogenic dynamics package is depicted as a UML use case diagram (Figure 9). In the first step, the Ecologist actor determines a particular type of stress caused by a planned human activity. For example, human-induced impact onto forest ecosystems can be caused by deforestation, harvesting, cultivation, burning, recreation, air pollution, soil acidity and toxicity.

Exogenous perturbations caused by anthropogenic impacts may affect and change different components of the real-world ecosystem as represented by its mathematical model Equation (1), including: (a) initial conditions; (b) environmental abiotic factors; (c) biological populations in biotic assemblages and the corresponding values of the model variables; (d) parameter values; and (e) ecosystem structure. The two latter kinds of stresses may alter the strength and qualitative nature of inter- and intra-specific community interactions whereby, for example, initially non-interacting species may begin competing or exhibiting other non-neutral interactions, and *vice versa* (Justus, 2006).

In environmental management, ecosystem behaviour in response to each type of stress needs to be predicted. It has been demonstrated that there are common patterns in the behaviour of ecosystems as they respond to anthropogenically caused perturbations and, following classical papers by Holling (1973) and Odum (1983), five scenarios in ecosystem dynamics have been determined: (i) resistance; (ii) deformation; (iii) resilience; (iv) degradation; and (v) shift (Khaiter and Erechtchoukova, 2007).

The understanding of ecosystem dynamics and stability properties in response to exogenous perturbations is a crucial part of environmental management. Patterns in ecosystem behaviour allow for the prediction of the under-the- and post-stress dynamics of ecological systems in the study. They also offer the possibility to assess the maximum allowable levels of anthropogenic impact that the system would sustain without drastic, sometimes irreversible, alterations of its structure and functions as well as to judge on what will happen to the system if a critical level of stress is exceeded.

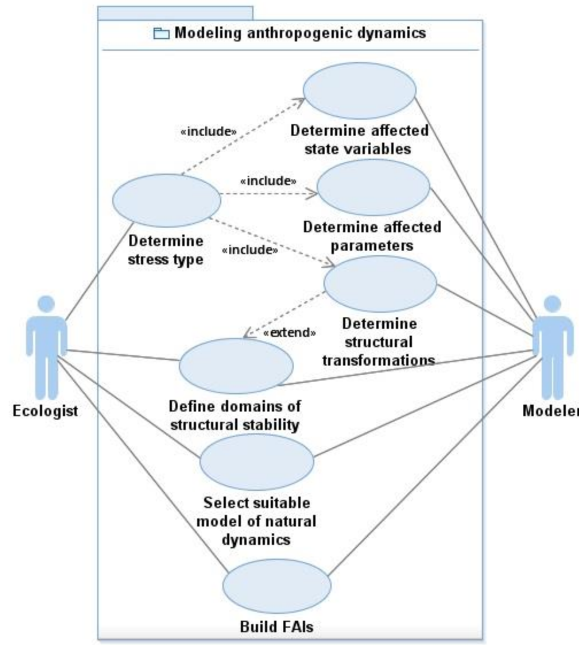

Figure 9. Logic of the Modeling anthropogenic dynamics package shown as a UML use case diagram.

Through the interaction, the Modeler actor and the Ecologist actor decide on the particular affected state variables and parameters as well as possible structural transformations within the studied ecosystem. It, in turn, enables the definition of domains of ecosystem's structural stability. It has been argued (Khaiter and Erechtchoukova, 2009) that a model is only suitable for a certain domain where the ecosystem maintains its structure and that, generally speaking, a new model has to be built if a structural transformation occurs, though a new model can, to a different extent, inherit certain features of the old one (Pusachenko, 1989). In terms of the generalized ecosystem model Eq. (1), critical transformations appear as a sequence of models, each one suitable only for a certain "stability" domain where the ecosystem maintains its structure:

$$M_0 \underset{t_1^{crit}}{\overset{S\text{-}stress}{\dashrightarrow}} M_1 \underset{t_2^{crit}}{\overset{S\text{-}stress}{\dashrightarrow}} \ldots \underset{t_l^{crit}}{\overset{S\text{-}stress}{\dashrightarrow}} M_l.$$

Consequently, a new model has to be built and analyzed once the ecosystem has crossed a critical point and has fallen within a new domain of structural stability. It gives rise to several important questions:

- What change in the ecosystem should be considered as a critical transformation leading to a new structural domain?
- Will one species' extinction mark a critical transformation?

- Is the critical transformation reversible or irreversible?

An ecosystem can be viewed in terms of its dominant species (e.g., Mueller-Dombois, 1988). A switch from one group of dominant species to another one is an example of a structural transformation. Myster (2001) suggests that an ecosystem's structural pattern must be tied to the functions that are critical for the continued operation of the ecosystem. Primary plant-based functions of productivity/respiration/decomposition (Watt, 1947) as well as nutrient cycling and energy transfer/loss are the most important ecosystem functions. These characteristics can be used as indicators of critical transitions leading the ecosystem to a new structural domain.

Therefore, ecosystem services have to be quantitatively assessed only from a model suitable for a given domain of structural stability. As one of the approaches to the modeling of stress dynamics, we suggest to first determine a suitable model of natural dynamics and then construct transformation functions of anthropogenic impact for each affected state variable and for each type of stress (Khaiter, 1991; Pusachenko, 1989), i.e.:

$$x_i^{\mathrm{A}} = FAI_{i,k} * x_i^{\mathrm{N}}, \forall i = 1,..,n; \forall k = 1,..,K, \quad (2)$$

where x_i^N and x_i^A are the ith coordinate of the state vector **x** before (i.e., natural, untouched state) and after an anthropogenic impact of the kth type, respectively; $FAI_{i,k}$ is the transformation function of anthropogenic impact of the kth type onto the ith coordinate of the state vector $\boldsymbol{x}$. It has been shown that transformation functions *FAI*s can be built either from the perspectives of the ecosystem's critical conditions (Puzachenko, 1989) or their anthropogenic dynamics (Khaiter, 1991).

In real life, natural and anthropogenic factors rarely occur in isolation, but are displayed in an interplay or complex influence of multiple factors at any given moment. If individual *FAI*s are quantified and built, their resulting interplay *FAIR* can be evaluated either from the Liebig's law of the minimum of limiting factors (Equation (3)) or from the multiplicative form (Equation (4)):

$$FAIR = \min_{k=1,..r} \{FAI_k\}, \quad (3)$$

$$FAIR = \prod_{k=1}^{r} \{FAI_k\}. \quad (4)$$

3.4.3. Quantifying Ecosystem Services Package

The task of the Quantifying ecosystem services package is to produce the absolute measures of ecosystem services. A recent study of multiple services in New Zealand was entirely based on biophysical measures (Ausseil et al., 2013). As shown in Figure 7, the quantitative values of services are computed outputs of either models of natural dynamics or models of anthropogenic dynamics, or a certain composition of both model types.

For example, to quantify the hydrological service of a forest, it is necessary to estimate a delayed runoff from a given watershed as the difference between slow and quick items of the water budget. When we study the impact of deforestation on this ecosystem service, watersheds with various percentages of forest cover have to be compared, but such "paired" watersheds are not always readily available. To that end, a comprehensive simulation model of the processes of moisture transformation has to be run twice emulating natural conditions and anthropogenically perturbed regimes, and the associated results compared (Khaiter, 1993):

$$\Delta QUSE = \sum_{t=1}^{T} \left\{ \begin{aligned} &\left[\Delta SM^{f}(t) + Q_{SUB}^{f}(t) + Q_{GR}^{f}(t)\right] - \\ &\left[\Delta SM^{\circ}(t) + Q_{SUB}^{\circ}(t) + Q_{GR}^{\circ}(t)\right] \end{aligned} \right\}, \quad (5)$$

where the superscripts f and o denote forested and open (forestless) watersheds, respectively; t is the time variable; T is duration of a specified time interval, Q_{SUB} is the sub-surface flux; Q_{GR} is water recharge to the groundwater table and ΔSM is the variation of soil moisture contents.

3.5. Valuation Layer

Any decision-making pertaining to natural resources or environmental systems would certainly involve valuation issues, because we need to choose from a set of possible alternatives and determine which of them is more preferable than the others. The latter cannot be reasonably implemented without attributing some monetary value to a whole spectrum of ecosystem services or applying broader valuation techniques. As Goulder and Kennedy (1997) state, it always "requires to indicate which alternative is deemed to be worth more." Moreover, it has been argued the inadequacy of microeconomic theory and the necessity to go beyond profit maximization principles in environmental management (Filatova et al., 2011; Sun and Mueller, 2013).

The economic assessment of ecosystem services is based on "the central environmental principle of full-cost pricing" (Porter, 1996). At the same time, services are not isolated, but interrelated displaying competitive relationships. The competitive or even mutually exclusive nature of services has to be taken into the consideration in the valuation exercises.

The lack of accounting for interactions between services in resource management is noted by Ausseil et al. (2013). In practical terms, a full set of all the ecosystem services is not an attainable value but rather an ideal one, and a subset of the mutually compatible services has to be determined for each planned scenario of management practice. Another problem is that, at the moment, many of the services have no direct market price. From the perspectives of economic theory, they reveal themselves as positive externalities. Valuing these benefits is a crucial component of a sustainable management. Techniques developed in environmental economics for valuation of ecosystem benefits are summarized in Table 2.

Evolving approaches to economic valuation can be found in several studies (e.g., Baskaran et al., 2009; Ash, 2010). Applying these techniques, the output produced by the Valuation package will be an integral monetary value of the mutually compatible services. Figure 10 demonstrates the steps in the valuation process in the form of a UML use case diagram, in which three actors (i.e., Ecologist, Modeler and Environmental economist) interact with the system.

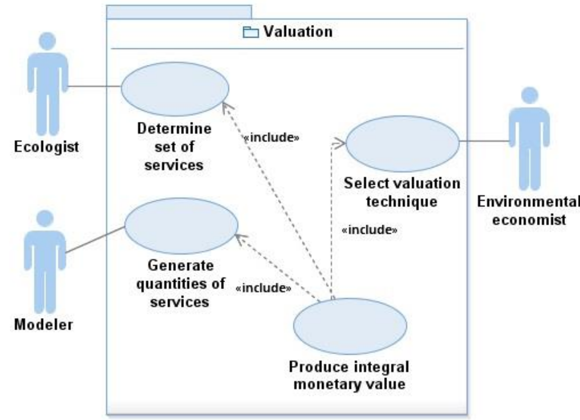

Figure 10. Steps in the valuation process shown as a UML use case diagram.

3.6. Management Layer

In management fundamentals, decision-making is a systemic process composed of three major phases: intelligence, design and choice (Simon, 1960). During the choice phase, the best possible or satisficing alternative is selected using certain criteria developed on the design phase. Given the complexity of environmental problems resulting in a large number of potential alternatives, one of the possible articulations of sustainable management can be expressed in terms of optimal control theory. As it was discussed in previous subsections, the integral monetary value of the ecosystem benefits V_O depends on a chosen management strategy of exploitation u_k, i.e.

$$V_o = V_o(u_k). \tag{6}$$

Environmental objects are characterized by the long-time spans. It is, therefore, realistic to assume that the management strategy is not constant over the whole period (t_0, T) but it may be determined for shorter time intervals, e.g., every 5 - 10 years, and re-evaluated afterwards. This will split the whole period of consideration into n intervals (t_0, t_1), (t_1, t_2),.., (t_{n-1}, T). The choice of a management strategy, $u_k(t_j)$, occurs in the moments t_j, at the beginning of each interval (t_j, t_{j+1}) (j = 0, .., T-1), and the integral monetary value $v_0(u_k(t_j))$ of the benefits is computed for each time interval separately. Then, the problem of sustainable management can be formulated as finding the vector of optimal controls $\mathbf{u}^*$ = ($u^*(t_0)$, $u^*(t_1)$, …, $u^*(T$ - 1)) which delivers the most "expensive" set of ecosystem services, i.e., maximizes the overall integral value $V_O(\mathbf{u})$, from the condition:

$$\mathbf{u}^* = Arg \max_{u_k \in \mathbf{U}} \sum_{j=0}^{T-1} v_0(u_k(t_j)). \tag{7}$$

Solving the problem (Eq. (7)) on the basis of models presented in the Modeling and Valuation layers is the core purpose of the Management layer. The flow of operations within the Management layer is shown in Figure 11 as a UML activity diagram.

It is noted that other mathematical articulations of sustainability are also acceptable, e.g., as multi-objective optimization, and any of them can easily be plugged-in and integrated in the framework due to its open architecture and the modular principle of implementing software components.

Table 2. Methods for Valuation of Ecosystem Services

Valuation method	Description
Direct valuation	market prices can be applied to the ecosystem goods or services that have a direct consumptive use as food or raw material
Willingness to pay	employs a utilitarian basis determined through the amount that people would be willing to pay or sacrifice in order to enjoy ecosystem services
Travel-cost	is used to ascertain some of the values provided by parks, lakes and rivers. In this method, the overall travel cost is a sum of the transportation cost, the entry fee (if any) and the time cost expended to visit a particular site
Contingent valuation	relies on surveys to determine how much value people place on non-consumptive uses. A random survey samples people's willingness to prevent ecological harm of a certain sort, or alternatively, their willingness to accept compensation for that injury to the natural ecosystem
Avoided cost	is evaluated through the cost or expenditures that society or businesses would have to pay if there is no ecosystem providing the services (e.g., pest control, flood control, soil fertilization and water filtration)
Replacement value	is based on calculating the cost of replacing the ecosystem services by industrial, agricultural or other methods in the case that they are lost as a result of some human activity

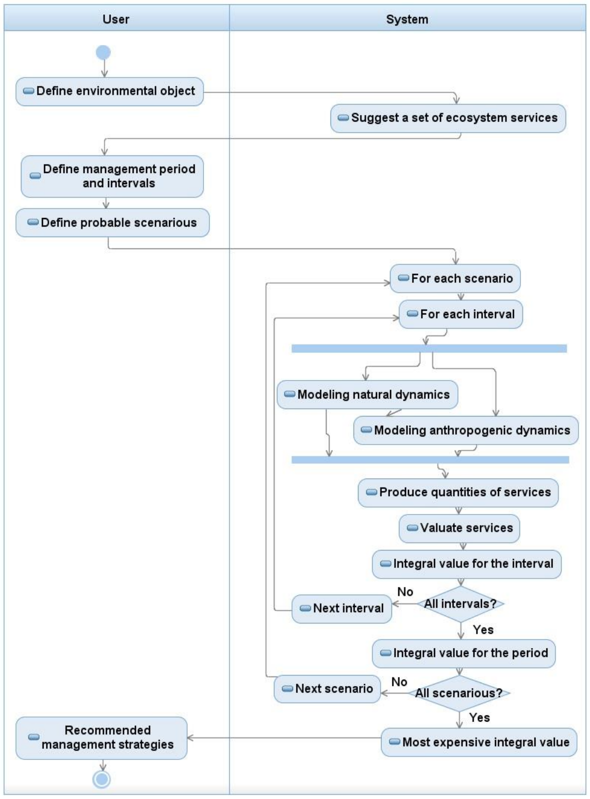

Figure 11. Logic of the Management layer shown as a UML activity diagram.

4. Discussion and Conclusions

For many years, the UML has been successfully utilized in the systems development life cycles of business-type IT projects. It is supported by multiple commercial and free CASE-tools, including those featuring forward and reverse engineering. At the same time, despite obvious advantages, the UML has not been widely adopted or used in environmental modeling and software development, and its applications in the field of environmental information systems remain rather limited. The paper presents a formalized approach to the entire process of software development and design in the area of sustainable decision-making on the basis of ecosystem services.

Applying participatory methods to the domain of environmental management, modeling and development of environmental information systems, the key stakeholders are identified and their participatory goals are considered. An environmental software modeling framework (ESMF), as a tool implementing the tasks of sustainability, is conceptualized in the meta-model of the Unified Modeling Language (UML). With the three groups of graphical models (i.e., functional, object and dynamic), the UML is aimed to provide a standard notation and describe different aspects of a software project. We demonstrate the ways in which the UML can be applied in information system development for the needs of environmental management. The constituting software blocks of an information system implementing the ESMF are visualized in the following UML graphical models:

- the overall system architecture of the ESMF is depicted as a UML deployment diagram;
- internal logic of the Ecosystem layer is shown as a UML use case diagram;
- activities of the Monitoring layer are shown in the notation of a UML use case diagram;
- modules of the Modeling layer are presented as UML packages;
- internal steps within the Modeling natural dynamics module are shown as a UML use case diagram;
- logic of the Modeling anthropogenic dynamics module is demonstrated as a UML use case diagram;
- internal steps of the Valuation layer are shown as a UML use case diagram; and
- flow of operations within the Management layer is presented as a UML activity diagram.

The set of presented diagrams can be suggested as a blueprint for potential projects in environmental software development. It provides software developers and broader stakeholders in the domain of environmental sustainability with a standardized view of the decision-making process, its underlying concepts, necessary steps and supporting software tools. The diagrams were developed through a detailed systematic analysis of the domain of sustainable environmental management. For each activity, an issue-specific mathematical articulation and subsequent implementation are to be identified and coded. However, a well-defined structure of an information system realizing the framework ensures the conformity with the fundamental principles and best practices. In addition, the UML diagrams are regarded in the SDLC as a means of elicitation, specification, validation and verification, and visual modeling of the information system requirements. In the latter capacity, they facilitate communications between various groups of stakeholders. An advantage of the UML diagrams is their proven semantic, descriptive and visual power in modeling and presenting of the software requirements and related artifacts, full compatibility with the object-oriented paradigm of the systems development and a round-trip engineering feature supported by a range of commercial and free CASE-tools.

While at present a common methodology on the application of the UML in the domain is still to emerge, it is reasonable to expect growing interest towards the UML among environmental software professionals as a tool combining the power of visual and simulation modeling and facilitating automated construction and synthesis of environmental information systems.

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