Computers and Electronics in Agriculture 76 (2011) 148–160

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Original papers

Linking models for assessing agricultural land use change

Sander Janssen[a,b,*], Ioannis N. Athanasiadis[c], Irina Bezlepkina[d], Rob Knapen[b], Hongtao Li[c], Ignacio Pérez Domínguez[d], Andrea Emilio Rizzoli[c], Martin K. van Ittersum[e]

[a] Wageningen University, Business Economics Group/Plant Production Systems Group, Hollandseweg 1, 6706 KN Wageningen, The Netherlands
[b] Alterra, Environmental Sciences Group, Wageningen University and Research Centre, Droevendaalsesteeg 3, 6708 PB Wageningen, The Netherlands
[c] Democritus University of Thrace, Electrical and Computer Engineering Dept, GR 67100, Xanthi, Greece
[d] Agricultural Economics Research Institute (LEI – Wageningen UR), Alexanderveld 5, 2585 DB Den Haag, The Netherlands
[e] Wageningen University, Plant Production Systems Group, Haarweg 333, 6709 RZ Wageningen, The Netherlands

ARTICLE INFO

Article history:
Received 6 July 2009
Received in revised form 8 October 2010
Accepted 19 October 2010

Keywords:
Knowledge
Ontologies
Integrated assessment
OpenMI
Scaling
Model chain

ABSTRACT

The ex-ante assessment of the likely impacts of policy changes and technological innovations on agriculture can provide insight into policy effects on land use and other resources and inform discussion on the desirability of such changes. Integrated assessment and modeling (IAM) is an approach that can be used for ex-ante assessment. It may combine several quantitative models representing different processes and scales into a framework for integrated assessment to allow for multi scale analysis of environmental, economic and social issues. IAM is a challenging task as models from different disciplines have a different representation of data, space and time. The aim of this paper is to describe our strategy to conceptually, semantically and technically integrate a chain of models from different domains to assess land use changes. The models that were linked are based on different modeling techniques (e.g. optimization, simulation, estimation) and operate on different time and spatial scales. The conceptual integration to ensure consistent linkage of simulated processes and scales required modelers representing the different models to clarify the data exchanged and interlinking of modeling methodologies across scales. For semantic integration, ontologies provided a way to rigorously define conceptualizations that can be easily shared between various disciplines. Finally, for technical integration, OpenMI was used and supplemented with the information from ontologies. In our case, explicitly tackling the challenge of semantic, conceptual and technical integration of models forced researchers to clarify the assumptions of their model interfaces, which helped to document the model linkage and to efficiently run models together. The linked models can now easily be used for integrated assessments of policy changes, technological innovations and societal and biophysical changes.

1. Introduction

Agriculture uses more than 40% of the European land. Changes in agriculture due to policies or technological innovations are likely to have a big impact on European land use and other natural resources. Increasingly agricultural and environmental policies aim at promoting natural resource quality in addition to traditional aims such as economic viability of farms. Ex-ante assessment of the likely impacts of policy changes and technological innovations on agriculture can provide insight into policy effects on land use and natural resources and inform discussion on the desirability of such changes.

Integrated assessment (IA) is a method proposed by research for ex-ante analysis of the impacts of policy changes and technological innovations on agriculture. IA is defined by Rotmans and Asselt (1996) as an interdisciplinary and participatory process of combining, interpreting and communicating knowledge from diverse scientific disciplines to allow a better understanding of complex phenomena. Integrated assessment and modeling (IAM) is based on quantitative analysis involving the use of different modeling tools (Harris, 2002; Parker et al., 2002; Letcher et al., 2007). One particular challenge for IAM is to effectively transfer multi-disciplinary scientific and socio-cultural knowledge to an increasingly participatory policy domain (Oxley and ApSimon, 2007; Polhill and Gotts, 2009). Different types of IAM tools exist, e.g. meta modeling, Bayesian networks, agent-based systems and linking of comprehensive models into model chains. This paper focuses on this latter IAM approach, as frequently employed for assessing land use changes (Verburg et al., 2006), e.g. ATEAM (Rounsevell et al., 2005), EURURALIS (Van Meijl et al., 2006) and SENSOR (Helming et al., 2008).

The land use modeling community has been one of the early adopters of IAM, recognizing that a single disciplinary modeling

* Corresponding author. Tel.: +31 317 481908; fax: +31 317 482745.
E-mail address: sander.janssen@wur.nl (S. Janssen).

0168-1699/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.compag.2010.10.011

approach falls short of capturing the growing complexity in sustainable land use. Land use models are 'highly evolved, readily available and easy to use (Kok et al., 2007)' and are therefore suitable to be linked in model chains. Mono-disciplinary models cover only a few processes from a single domain, be it economic, agricultural or environmental and lack descriptions of some relevant processes. These models generally do not cover the relevant multiple scales to handle all assessment questions. Mono-disciplinary models can complement each other and thereby provide comprehensive and balanced assessments across scales (Van Tongeren et al., 2001; Pérez Domínguez et al., 2008).

In order to arrive at an operational model chain for applications in integrated assessment procedures, semantic, conceptual and technical integration of models is required. To show why different types of integration are required in IA studies, we present here the model linking of a set of (agricultural) models from different domains to arrive at a model chain that can be re-used for a range of IA questions. First, we address the meaning and content of the conceptual, semantic and technical integration by providing an overview of relevant literature. Second, we show how the integration effort to create a model chain can be described comprehensively with these concepts thereby enhancing the application for a range of IA questions. In this paper, we do not describe an application of the models, the integration of data-sources for such a model chain (Janssen et al., 2009a), or the definition of scenarios for such a model chain (Janssen et al., 2009b).

We present the model linking as achieved in the integrated project System for Environmental and Agricultural Modeling; Linking European Science and Society (SEAMLESS) (Van Ittersum et al., 2008) for an agronomic model, an agronomic-economic model and two economic models. Ultimately these linked models provide a means to achieve up-scaling and the interdisciplinary assessment of agricultural and agri-environmental policies, technological innovations and societal and biophysical trends, that would not be possible with the individual models.

Section 2 defines semantic, conceptual and technical integration for this paper by providing a background based on available literature. It also introduces the SEAMLESS-integrated framework (IF) and the integration approach as applied to SEAMLESS-IF. Subsequently, the semantic, conceptual and technical integration as achieved in SEAMLESS-IF is presented in Section 3. Section 4 discusses the lessons learned with respect to integration and the further use of the model chain. Finally, some conclusions are provided.

2. Case study and background

2.1. Purpose of model linking

In an IAM research project codenamed SEAMLESS (Van Ittersum et al., 2008) the causal chain of impacts of farmers' actions is modeled by linking and combining field, farm, regional and market models. When farmers' decisions on land use allocation and production intensity are aggregated to a higher scale, this may have profound market impacts and, hence, in turn influence agricultural commodity prices. Moreover, farmers' decisions in land allocation directly impact the environment through their crop choices (e.g. maize instead of wheat) and through their use of inputs (e.g. nitrogen fertilizer causing nitrogen leaching). Therefore it would not be adequate to study the land allocation patterns at the farm scale (e.g. through bio-economic farm models) without taking into account also the market (e.g. simulation of trade agreements and policy changes by the European Union through partial equilibrium market models) and field scale (e.g. technological innovation and integrated production by farmers through cropping system models).

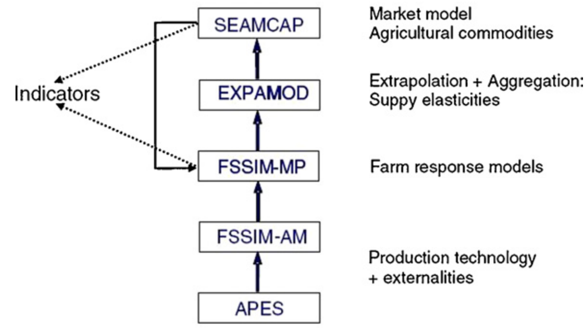

Fig. 1. The models in SEAMLESS (after Van Ittersum et al., 2008). APES: Agricultural Production and Externalities Simulator; FSSIM-AM: Farm Systems SIMulator-Agricultural Management; FSSIM-MP: FSSIM-Mathematical Programming; EXPAMOD: EXtraPolation and Aggregation MODel and SEAMCAP: adapted version of the Common Agricultural Policy Regional Impact (CAPRI) model.

The SEAMLESS-integrated framework (IF) (Van Ittersum et al., 2008) has been developed to assess the sustainability of agricultural systems in the European Union at multiple scales. In SEAMLESS-IF methods to conceptually and technically link different models (Fig. 1) are used to facilitate the re-usability of models for different purposes (Van Ittersum et al., 2008). By linking field-farm-market models in SEAMLESS-IF, the land use changes can be analyzed at multiple levels through a selected number of economic, environmental and social indicators, accounting for the impacts of farm responses that could not be analyzed by using only the individual models as stand-alone tools. A sample question is 'what are the impacts of policies restricting on-farm nitrogen use on farm income, on-farm labour, non-point source pollution and resource use in the European Union and in the regions Poitou Charentes (France) and Flevoland (Netherlands)?' With respect to this question, a bio-economic farm model can provide an estimate of the impacts on farm income in either Poitou Charentes or Flevoland, while a cropping system model can estimate the impacts on non-point source pollution and resource use. A market model can estimate the impacts on farm income, trade and markets in the entire European Union. When these models are linked, the impacts can be calculated at all scales and for all indicators in a consistent manner.

2.2. Semantic integration

Ambiguous terminology and a lack of shared understanding between disciplines have often been mentioned as important obstacles in integrated assessments (Jakobsen and McLaughlin, 2004; Scholten et al., 2007). Semantic integration means speaking a common language and achieving a shared understanding between all models and modelers working together. This is a crucial challenge for any integrated modeling project (Jakobsen and McLaughlin, 2004; Tress et al., 2007; Hinkel, 2008; Scholten, 2008), as it provides the building blocks for the technical and conceptual integration and as it ensures the consistency and transparency in definitions and terms required for the conceptual and technical integration. In the data and database community, the issue of semantic integration has been acknowledged (Rohn, 2010; Bright et al., 1994; Hakimpour and Geppert, 2005), and common challenges included matching schemas in different databases through algorithms (Rohn, 2010; Hakimpour and Geppert, 2005) and smart querying over databases (Bright et al., 1994).

Very few practical applications of possible methods for semantic integration of models could be found in literature, with the exceptions of Hinkel (2008), Scholten (2008), Nute et al. (2005), Rasinmäki et al. (2009), Parker et al. (2008) and Polhill and Gotts (2009). Possible methods are variable mapping, mathematical formalism, concept maps and ontologies. Variable mapping is an ad hoc process of investigating which variables could be exchanged between models and then mapping them to each other. Variable mapping is often not a formalized process with explicit products and documentation, leading to a black box integration. Hinkel (2008) uses mathematical formalism as a methodology to firstly align terminology between models and secondly the model equations across models and uses this to undertake a semantic integration for model linking in a number of modeling projects. One disadvantage of using mathematical formalism is as Hinkel (2008) mentioned, that non-modelers need explanation and training in order to be involved. Concept maps (Novak and Cañas, 2006) are graphs representing knowledge, in which concepts are expressed in circles and relationships are shown by lines connecting two concepts.

Finally, like concept maps ontologies consist of concepts and relationships between concepts (Antoniou and van Harmelen, 2004). SEAMLESS applied ontologies for semantic integration, since i. ontologies are in machine readable format, e.g. the Web Ontology Language (McGuinness and Van Harmelen (2004)), ii. ontologies are based on first order logic upon which a computer can reason, iii. the developed ontologies are a separate product independent of the models to which they are applied, leading to increased transparency and re-use in new integration approaches without the original models and iv. both modelers and non-modelers can contribute to the ontology development. In the context of integrated modeling, ontologies can be useful for defining data structures describing model inputs and outputs (Athanasiadis et al., 2006; Rizzoli et al., 2008; Scholten, 2008; Polhill and Gotts, 2009). Parker et al. (2008) developed the MR.POTATOHEAD ontology to compare a set of land use change models in their scope, set-up and datastructures.

Only the specification of the interfaces between the models has to adhere to the shared ontology, while the internal specification of the knowledge in the model does not have to adhere to the shared ontology (Gruber, 1993). An ontology separates knowledge captured in the model interface from the actual implementation in a programming language e.g. Java™, FORTRAN, Matlab, or STATA (Gruber, 1993) and thus ensures that knowledge is not hidden in programming languages (Athanasiadis et al., 2006). Ontologies help to formalize the knowledge exchanged between models, thus facilitating re-usability and exchangeability of model knowledge (Nute et al., 2005; Rizzoli et al., 2008; Rasinmäki et al., 2009; Villa et al., 2009), supporting portability (Gruber, 1993) and working in a multi-disciplinary environment.

2.3. Conceptual integration

The conceptual integration focuses on aligning different scientific methodologies and identifying required model improvements necessary for meaningful linkage. Conceptual modeling is a vital first step to facilitate communication between modelers, non-modeling researchers and stakeholders (Liu et al., 2008). Good practice guidelines (Refsgaard and Henriksen, 2004; Jakeman et al., 2006; Scholten, 2008) exist for conceptual development of a model in all steps of model building for a mono-disciplinary model. Challenges for land use models are to model appropriate '(1) level of analysis; (2) cross scale dynamics; (3) driving forces; (4) spatial interaction and neighbourhood effects; (5) temporal dynamics; and (6) level of integration (Verburg et al., 2004).'

Conceptual integration deals with calculations of a concept out of other concepts or converting one concept into another concept. Spatial and time scales are crossed through these calculations and conversions, e.g. moving from daily estimates to an estimate for one or several years or from the representative farms to regions or provinces. These calculations describe the behavior of the system (e.g. linked models) in mathematical terms and often include strong assumptions. All the calculations have to become explicit, preferably in mathematical terms. An example can be found in Hinkel (2009) based on mathematical formalism.

The models in SEAMLESS are a cropping systems model APES, a bio-economic farm model FSSIM, an econometric estimation model EXPAMOD, and a partial equilibrium optimization model SEAMCAP. The cropping systems model agricultural production and externalities simulator (APES) operates at the field systems level, and represents one hectare (or a point) (Donatelli et al., 2010). On the basis of agricultural activities, soil and climate data, APES simulates the yield and environmental effects resulting from those activities. It presently includes components for simulation of crops, grassland, vineyards and agroforestry. Examples of other components are those that simulate water balances in the soil, carbon–nitrogen dynamics in the soil, the fate of pesticides and agricultural management. It is a dynamic simulation and it usually simulates a period of 10–25 years with a daily time step.

The bio-economic farm model and partial equilibrium optimization model are both optimization models based on mathematical programming techniques. These models are built based on assumptions with respect to the functioning of economic agents, i.e. farms or market forces at continental scale. These models are comparatively static, i.e. they have no interdependence of outcomes across years, and model results represent the equilibrium situation for a year. The farm system simulator (FSSIM) is a bio-economic farm model developed to assess the economic and ecological impacts of agricultural and environmental policies and technological innovations (Louhichi et al., 2010; Janssen et al., 2010). A bio-economic farm model links decisions on management of farm's resources to current and alternative production possibilities describing input-output relationships and associated externalities (Janssen and Van Ittersum, 2007).

SEAMCAP is a variant of the Common Agricultural Policy Regionalised Impact (CAPRI) model adapted for inclusion in SEAMLESS-IF (Britz et al., 2010). CAPRI is a spatial economic model that makes use of non-linear mathematical programming tools to maximise regional agricultural income. It explicitly considers Common Agricultural Policy instruments in an open-economy and price interactions with other regions of the world are taken into account (Heckelei and Britz, 2001). Major outputs of the market model include bilateral trade flows, market balances and producer and consumer prices for the products and world country aggregates.

Finally, the econometric estimation model EXtraPolation and Aggregation MODel (EXPAMOD) is an econometric meta-model describing price-production responses of farms given specific farm resources and biophysical characteristics (Pérez Domínguez et al., 2009). EXPAMOD accounts for land use changes via production volume. After the calculations done in EXPAMOD, the regional supply models of the market model SEAMCAP can behave like a representative aggregate of the FSSIM models of the same region. The extrapolation routine operates with prices, farm characteristics and regional biophysical characteristics obtained from other models or European databases. The output of EXPAMOD are price-supply elasticities on which the regional supply functions in the market model SEAMCAP are calibrated.

2.4. Technical integration

To develop an integrated assessment tool as a computer program requires that models are linked together in a modeling framework with a common graphical user interface and data storage. A central repository for data storage for all models, scenarios and data sources (Janssen et al., 2009a) and a graphical user interface from which all models can be parameterized and executed (Wien et al., 2010) are available for the integrated assessment tool developed in SEAMLESS. A modeling framework supports the execution of models in a model chain (Liu et al., 2002; Hillyer et al., 2003; Rahman et al., 2003; Moore and Tindall, 2005). This paper only focuses on the use of modeling frameworks, since modeling frameworks are most relevant to the actual model linking and can have effects on the set-up of the models.

The linking of models assumes the exchange of data between models at runtime. Model linking is especially challenging when modelers from different domains use different programming languages, tend to stick to their own pre-cooked solutions and when the best type of model linking they can achieve is only through the exchange of data files. As long as model linking is a one time exercise, it is still possible to use an ad hoc file-based exchange, but when the linked models must be used to analyze a large number of scenarios, then the file-based exchange becomes excessively laborious, error-prone and non-repeatable. Automated, documented and standardized model linking in a modeling framework is preferred and recommended. Some available modeling frameworks exist. Open Modeling Interface and Environment (OpenMI – Moore and Tindall, 2005) is a software standard for dynamically linking models at runtime, which can potentially be used in many domains, but is currently mainly applied in the water domain. TIME (Rahman et al., 2003) is, like OpenMI, a generic computational framework for building and executing models that may be applicable across domains. ModCom (Hillyer et al., 2003) is used for linking biophysical process-based models in crop growth simulation. Moore et al. (2007) propose the Common Modeling Protocol which nests dynamic models in a hierarchy with a common interface on top and also focuses on dynamic and biophysical models. Finally, Triplex is a flexible and customizable modeling framework that links forest ecosystem simulation models (Liu et al., 2002). Modeling frameworks, with a stronger technical instead of methodological focus are lacking for the land use and socio-economic models, although frameworks like OpenMI, TIME, ModCom or Triplex might be useful.

In the development of SEAMLESS-IF The Open Modeling Interface and Environment (OpenMI – Moore and Tindall, 2005) was applied to link the models at run time into a model chain. OpenMI was chosen as it can in principle be applied to models from all domains and as it is a standard instead of an implemented modeling framework in a specific programming language. OpenMI represents a standard for the definition of the interface of a software component (Gregersen et al., 2007). The OpenMI standard aims at an easy migration of existing models to comply with the standard, without the need for re-implementing the whole models. To achieve such an easy migration, wrappers are proposed that comply with the OpenMI-standard and that leave the model internally unchanged with respect to specification and programming paradigm (Gregersen et al., 2007).

The OpenMI standard version 1.4 is based on a pull-approach in which the last model in the chain pulls its outputs from other models in the chain by calling "getValues( )"-methods, which means requesting outputs from a model or data source (Moore et al., 2007). Before "getValues( )"-calls can be successfully enacted at run time, the links between the two OpenMI-compliant models need to be defined by the modeler by specifying so-called "Links." These links define the output item of a model that is linked to an input item of another model.

3. Integration in SEAMLESS

This section describes the results of the integration efforts to link the models (i.e. APES, FSSIM, EXPAMOD and SEAMCAP). Fig. 2 provides the overview of the integration effort by separating the roles of semantic, conceptual and technical integration. Semantic integration defines the concepts and their relationships to represent reality. In conceptual integration one concept is translated into another concept through calculation procedures (i.e. scaling procedures, modeling techniques, process descriptions). Finally, through a technical integration the integrated models can be executed on a computer with data inputs and parameterization.

Following the overview shown in Fig. 2, this section starts with the semantic integration by describing three ontologies (e.g. crop-product, elasticity and activity) crucial to understanding the model linkage. The concepts in these ontologies provide the building blocks that are subsequently used to describe the conceptual and technical integration. For conceptual integration, the calculations to link on the one hand FSSIM, EXPAMOD and SEAMCAP and on the other hand FSSIM and APES are described, without describing all calculations of the models in detail. The techni-

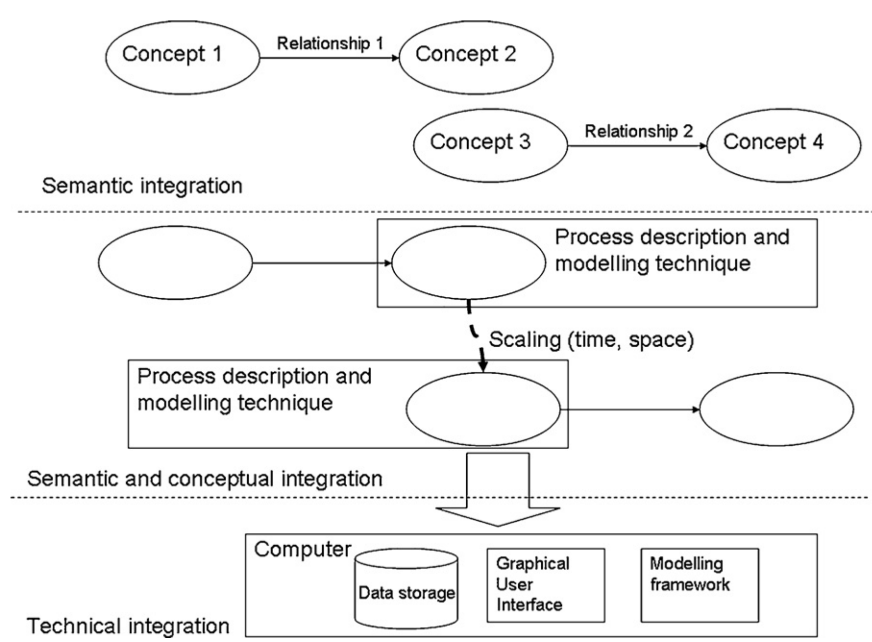

Fig. 2. Division of roles for semantic, conceptual and technical integration in the integration effort.

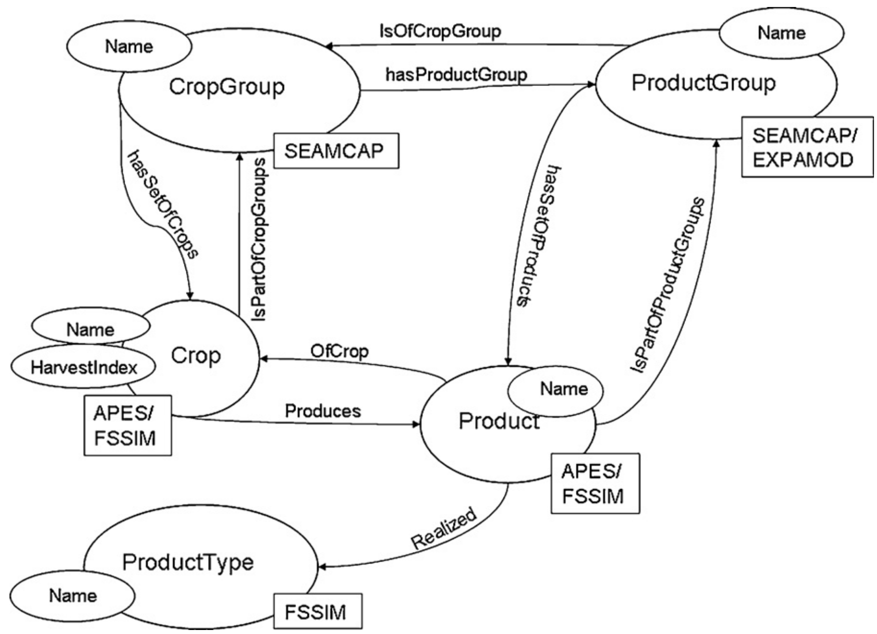

Fig. 3. The Crop-Product ontology showing the relationships (arrows) between the concepts Crop, Product, ProductType, CropGroup and ProductGroup (ellipses) and their properties (small ellipses). The models using the concept are indicated in the boxes. The figure can be read along the lines, while the dashed squares indicate the use of the concepts by the models. For example, 'a Crop Produces a Product (which has a name) and is Realized through a ProductType' by reading along the relationships (arrows) from concept Crop (large ellipse) to Product (large ellipse) and subsequently to ProductType (large ellipse).

cal integration describes the use of the ontologies derived in the semantic integration and the impact of OpenMI on the models. The SEAMLESS ontologies are discussed in detail in Athanasiadis et al. (2009).

3.1. Semantic integration

3.1.1. Crop-product ontology (APES–FSSIM–EXPAMOD–SEAMCAP)

In the initial discussion, it appeared that all models dealt with cropped areas and used crops and associated products as concepts. Each of the models referred to these concepts, although sometimes with different names (e.g. crop in APES, crop in FSSIM and activity group in SEAMCAP). It seemed that the ontology could thus be simple, only referring to Crop and Product-concepts and relationships between them. This simple structure proved to be invalid, when confronted with the list of Crops and Products used by each of the models. The reason for models to use different groupings of Crops is that they have originally been developed for different purposes and scales. For example APES models crop growth for a field whereas SEAMCAP models markets of crop commodities.

Consequently, these lists of Crops and Products were further investigated, and a suitable structure was found for the ontology as shown in Fig. 3. In this ontology, each Crop produces one or more Products, which are realized by a ProductType. Products and Crops can be grouped together in ProductGroups and CropGroups. These ProductGroups and CropGroups are an input to the higher scale models SEAMCAP and EXPAMOD, that operate on the region and market scale, while the Crops, Products and ProductTypes are used by the lower scale models APES and FSSIM, that operate on the field and farm scale.

An example of the data associated with the Crop-Product Ontology is given in Table 1a and b. From Table 1a, it can be read that the wheat CropGroup has a set of crops WinterSoftWheat, SpringSoftWheat, WinterDurumWheat and SpringWinterWheat, while the potato CropGroup has only one crop, which is Potatoes. Similarly, Table 1b displays that the Straw ProductType realizes the products WinterSoftWheatStraw, SpringSoftWheatStraw, WinterDurumWheatStraw and SpringDurumWheatStraw, while the crops Potatoes, Flax and Hemp produce the products WarePotatoes, WareHemp and WareFlax.

3.1.2. Price-elasticity ontology (FSSIM–EXPAMOD–SEAMCAP)

The unambiguous definition of crops and products as presented in the previous section is used to define other relevant concepts for the links between the models. Crucial concepts for the linking between FSSIM, EXPAMOD and SEAMCAP are price elasticity and supply response (Fig. 4). The concept price elasticity is the output of EXPAMOD and the input to SEAMCAP, whereas supply response is the output of FSSIM and the input to EXPAMOD.

A price elasticity is the percentage change in supply as a result of one percent change in price. Price elasticity in the ontology (Fig. 4) has three dimensions, as it refers to two ProductGroups through 'to'- and 'from'-relationships and a NUTS2-region. NUTS stands for Nomenclature of Territorial Units for Statistics (EC, 2008) and the NUTS2 level corresponds to provinces in most countries.

Supply responses describe the responses of representative farms to changes in prices (Fig. 4). Each representative farm (Janssen et al., 2009b) refers to sets of supply responses. Each supply response captures the price change for a product and multiple CropProductions in response to the price change. One CropProduction is the total farm production of a product for the representative farm.

3.1.3. Activity ontology (APES–FSSIM)

Farmers have many different production possibilities on their farm. They might decide to grow crops, plant trees, or have livestock. Within these three basic choices, many more choices exist between different crops, different trees or different types of animals. Also the intensity and type of management of a crop, animal or tree might change. To capture the broad range of options available to the farmer and make the linking between the models APES and FSSIM explicit, the activity ontology was created. Fig. 5 shows a small part of this activity ontology related to arable and animal activities and some illustrative relationships. According to this ontology, farmers can have on their farms arable activities and/or animal activities. An arable activity entails several CropYearMan-

Table 1
Examples of crops, products, product types, crop groups and product groups.

a. Example of crop groups with associated crops

CropGroup		Crop
Wheat	hasSetOfCrops	WinterSoftWheat SpringSoftWheat WinterDurumWheat SpringDurumWheat
Potatoes	hasSetOfCrops	Potatoes
Textiles	hasSetOfCrops	Flax Hemp

b. Example of products, product types and crops.

ProductType	Product		Crop
Straw Realises	Wi nte rSoftWh eatStraw SpringSoftWheatStraw Wi nte rD u ru m Wh eatStraw SpringDurumWheatStraw	IsProducedBy	WinterSoftWheat SpringSoftWheat WinterDurumWheat SpringDurumWheat
Grain Realises	Wi nte rSoftWh eatG rai n SpringSoftWheatGrain WinterDurumWheatGrain SpringDurumWheatGrain	IsProducedBy	WinterSoftWheat SpringSoftWheat WinterDurumWheat SpringDurumWheat
Ware Realises	PotatoesWare FlaxWare HempWare	IsProducedBy	Potatoes Flax Hemp

c. Example of products and product groups

Product		ProductGroup
WinterSoftWheatStraw, SpringSoftWheatStraw, WinterDurumWheatStraw, SpringDurumWheatStraw	isPartofGroup	Straw
WinterSoftWheatGrain, SpringSoftWheatGrain	isPartofGroup	SoftWheat
WinterDurumWheatGrain, SpringDurumWheatGrain	isPartofGroup	DurumWheat
PotatoesWare	isPartofGroup	Potatoes
FlaxWare HempWare	isPartofGroup	Textiles

agements that capture the unique combination of a crop (Fig. 5), a year and management. For example, in year 1 the farmer grows potatoes with an intensive management, while in year 2 he grows barley with an extensive management. Together potato and barley form a two-year rotation; the management within this rotation differs between the crops from intensive to extensive.

Both the construction and selection of agricultural activities for a specific farm type is done by FSSIM (Section 2.3). APES (Section 2.3) operates on the arable activity by simulating for each activity the succession of CropYearManagements over time and providing the yields and environmental effects as an output. The arable activity is thus a shared concept between FSSIM and APES. Different

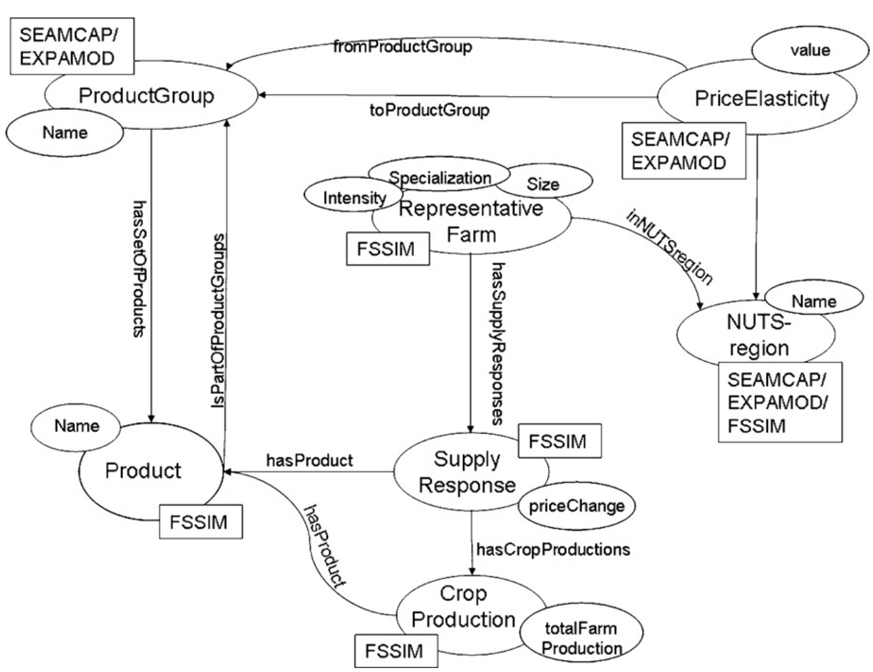

Fig. 4. Price elasticity ontology. The large ellipses show concepts, relationships can be read along the arrows, the small ellipses are data-properties of the concepts, and the boxes indicate the models using the concept. (For more explanation, see description of Fig. 3.)

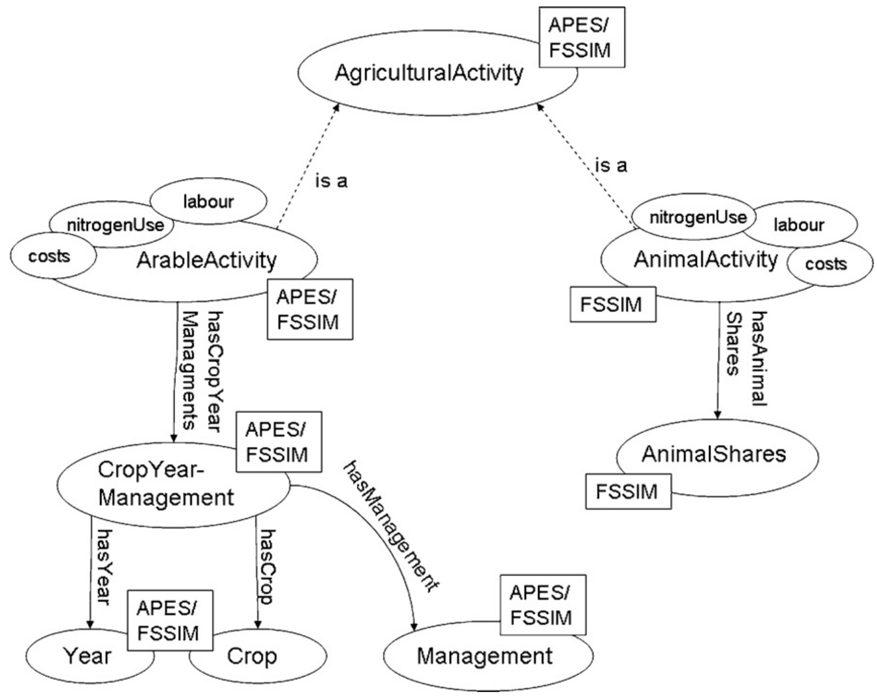

Fig. 5. Part of the activity ontology. The large ellipses show concepts, relationships can be read along the arrows, the small ellipses are data-properties of the concepts, the dotted arrows indicate an 'is a'-relationship and the boxes indicate the models using the concept. (For more explanation, see description of Fig. 3.)

models use different properties of a concept, as is shown in Table 2. Whereas the variable costs of an arable activity are of relevance to FSSIM, the sowing date and nitrogen use are of relevance to APES. The activity ontology captures the shared concepts used by the models and allows them to work on different parts of this shared concept (Table 2).

3.2. Conceptual integration

For conceptual integration two calculations representing scaling procedures are crucial. First, a calculation is required to aggregate supply responses at the farm scale in FSSIM to price elasticities of product groups at market scale for SEAMCAP. Second, the field scale APES model and the farm scale FSSIM model are interlinked through agricultural activities and upscaling procedures are required to move from field and annual simulations to averages across years and activities.

FSSIM provides supply responses (Fig. 4) at farm scale. These supply responses are the results of multiple runs of FSSIM with changed product prices (Fig. 4) (Pérez Domínguez et al., 2009). Each change in product price leads to another optimal solution in FSSIM, and thus to a changed supply of products. Through the multiple runs, FSSIM generates one price supply response for each product on each representative farm. EXPAMOD uses the supply responses as observations in its estimation procedures per product.

In the estimation, the supply responses are regressed on properties of the representative farm (e.g. machinery, buildings, size, climate and soil conditions) (Pérez Domínguez et al., 2009). The function obtained through this regression can subsequently be used to predict the supply responses of representative farms in regions, for which FSSIM has not been run. In both the regression and extrapolation the properties of the representative farm are multiplied by the weighing factor. This weighing factor is calculated as the area of the farm divided by the area of all representative farms in the NUTS2-region, under the assumption that the representative farms cover 100% of the region. Through the regression and extrapolation price elasticities per product in a region are derived. To derive the price elasticitices per product group as needed by SEAMCAP (Section 2.3), the price elasticities per product are averaged with the quantity shares of each product in total production.

APES receives as input data from FSSIM the specification of an arable activity and the specification of an agri-environmental zone. The arable activity has a limited rotation length from 1 to 8 years. The agri-environmental zone is associated with soil data, which is constant over time, and climate data for a period of 10–25 years. APES starts a simulation on the first day and ends with the last day

Table 2
Example of arable activities specified according to the activity ontology for the Auvergne Region in France.

Model	Crop	APES	APES	FSSIM	APES/FSSIM	APES
Year		Variable				
		Nitrogen use (kg N/ha)	Water use (m^3/ha)	Costs (euro/ha)	Grain yield (Tonnes/ha)	Sowing week (Week number)
Activity identifier = 1364	1 Maize	100	0	350	6.0	14
	2 Maize	200	1000	696	10.0	14
	3 Sunflower	40	0	288	2.0	15
Activity identifier = 1196	1 Maize	100	0	350	6.0	14
	2 Softwheat	90	0	318	4.0	43
	3 Winter Barley	100	0	300	4.0	42

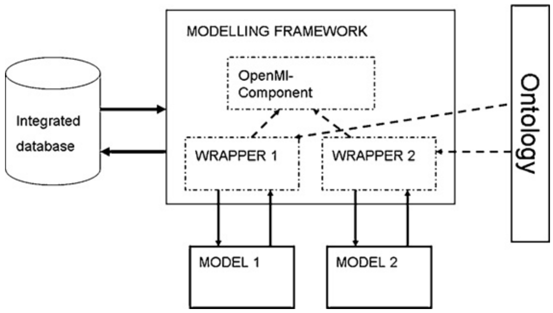

Fig. 6. Architecture of the modeling framework in SEAMLESS (*source*: Wien et al., 2010).

of the climate data period. The arable activity is iteratively run over the simulation period. This implies that year 1 of the arable activity coincides with year 1 of the climate data and is repeated after the last year in the arable activity, till the final year in the climate data has been reached. If an arable activity has a rotation length of 3 years (e.g. soft wheat, potato, sugar beet) and 25 years of climate data are available, then the arable activity runs 8 times with one additional run for the first crop during the simulation. This implies that years in the activity are associated with years in the climate data, e.g. activity year 1 with year 1 in the climate data and activity year 2 with year 2 in the climate data. Changes of values of soil variables are simulated by APES.

During its simulation, APES produces multiple estimates of yield and externalities (e.g. nitrate leaching, erosion) for an arable activity, depending on the number of runs of the activity. FSSIM requires only one single estimate and a standard deviation of the yield for each product of the activity (e.g. wheat grain or cows milk) and one estimate and a standard deviation of each externality (e.g. nitrate leaching or soil erosion) for the activity. To obtain these single estimates, the yearly simulated estimates are averaged over the number of years. For example, with a 3-year activity and a 25 years of climate data, 9 estimates of the yield of product grain of soft wheat grown in the year 1 of the activity and 25 estimates of the nitrate leaching for the activity are obtained. These 9 estimates and 25 estimates are then averaged to produce one estimate for the yield of grain of soft wheat and one estimate of nitrate leaching.

3.3. Technical integration

With the shared concepts clarified in the semantic integration and the conversion of these concepts clarified in the conceptual integration, a modeling framework (Fig. 6) was designed that supports the execution of the models APES, FSSIM, EXPAMOD and SEAMCAP in different model chains (Ewert et al., 2009). In the modeling framework the shared ontology achieved in the semantic integration is used to provide a common access to the data layer and to define the links between models as OpenMI components (Fig. 6). The ontologies in Web Ontology Language (OWL) were automatically translated into a relational database schema according to the specifications of the Semantic-Rich Development Architecture (SeRiDA) (Athanasiadis et al., 2007a, 2007b). The SeRiDA acts as a bridge between different programming languages, e.g. object-oriented programming, relational databases and ontologies (Athanasiadis et al., 2007a; See example in Fig. 7). The relational database schema was made accessible to the modeling framework and models through Enterprise Java Beans (DeMichiel and Keith, 2006), which can be used to develop the wrappers for the models as OpenMI components (see Fig. 7 for examples of source code of ontology, database schema and enterprise java beans). The models are linked to the database through Hibernate (JBOSS, 2008). The integrated database is running on a PostgreSQL database server (PostgreSQL, 2008).

The models all remain programmed in their native programming language (e.g. GAMS for EXPAMOD, SEAMCAP and part of FSSIM; C# for APES and Java^{TM} for the other part of FSSIM). Each model is encapsulated through a wrapper that translates the data into an appropriate format for the model, executes the model, and translates the model output data into a suitable format for the framework. The wrappers of the models have been developed as OpenMI-components, which implies that the models themselves are not aware of or affected by the OpenMI-standard. An extension of the OpenMI standard was required to make it usable for the SEAMLESS model chain (Knapen et al., 2009). This extension to capture the complex data types of the models implied that data exchanged between models are objects or complex data structures and not primitive data types (e.g. float, integer, string, character) like in the OpenMI standard v1.4. For models with complex data types from different disciplines such an extension of the OpenMI standard is required for OpenMI to be relevant.

4. Discussion

4.1. Overall lessons in the integration

Through semantic, conceptual and technical integration, we achieved a chain of agricultural models to assess the impacts of policy and technology changes on European agricultural systems. We experienced benefits of our integration approach, which will be described in this section.

As an overall benefit for future integration efforts of a set of existing models, the division in semantic, conceptual and technical integration is crucial for researchers trying to integrate legacy models to achieve a comprehensive model linking. This avoids the danger of focusing on one aspect of model linking and applying an advanced strategy for one aspect, while hardly treating other aspects. For future integration efforts, our analysis has yielded a set of aspects, that can be used as an umbrella to structure the integration effort, i.e. concepts and relationships in semantic integration, processes, scales and calculations in conceptual integration and finally, programming languages, modeling frameworks and model interfaces in technical integration. A first step in integration is explicitly and deliberately addressing these aspects by deciding on the relevant methods to use for conceptual, semantic and technical integration.

4.2. Semantic integration

Through the use of shared ontologies, we managed to explicitly establish a shared understanding between the modelers and their models. In our case, the use of ontologies forced researchers to clarify the assumptions of their model interfaces and to set forth parts of their modeling knowledge, typically kept within their models. An important benefit of this approach is that knowledge on model linking is not solely contained in the model source code or in the modeler's mind, but is documented as part of the framework and can help to explain model linkages to non-modelers. This documentation takes the form of ontology-files, that are structured according to a standard W3C definition (McGuinness and Van Harmelen, 2004). The ontologies open up the model linking to scrutiny from a wider community than just the modelers involved in the linking. These structured standardized files can subsequently be used in different available tools for source code generation, documentation and reasoning for data classification. In our case the ontologies were used for code generation (See Fig. 7). Using the ontology files in automated reasoning would be an interesting next step, and would allow to automatically classify data according to the ontology, and to verify the consistency of the ontology.

In our case study, a shared ontology has been developed for model linking of four models, as demonstrated through the examples in the previous section. The ontology is re-usable independently of the models and documents the concepts used and agreed upon for model linking. Concepts and relationships in the ontologies from SEAMLESS are available through their Uniform Resource Identifier (URI), e.g. concept Crop can be found on http://ontologies.seamless-ip.org/crop.owl#Crop. Other modelers can build upon, extend and improve the ontologies. The ontologies are supplied with metadata and browsable through a simple search tool, in order to facilitate their re-use (Brilhante et al., 2006).

A growing number of ready ontologies are available in the public domain through the World Wide Web, for example the core software ontology (Gangemi et al., 2008). Unfortunately many could not be re-used for our model linking tasks, as these were not yet specific to the agricultural domain and not concrete enough. Similarly, it might seem that the ontologies developed for SEAMLESS-IF are specific to the linking of the models APES, FSSIM, EXPAMOD and SEAMCAP. Although the ontologies have been made with the aim of linking these specific models, they exist independently of the models and there exists no concept like “SEAMCAP” or “FSSIM” in any of the ontologies. As a true test of the genericity of these ontologies one could re-use them for the linking or developing of models simulating cropping systems, farm responses and market behavior.

```
<owl:Class rdf:ID="Crop">
    <rdfs:label xml:lang="aps">Crop</rdfs:label>
    <rdfs:label xml:lang="en">Crop</rdfs:label>
    <rdfs:label xml:lang="gms">C</rdfs:label>
    <rdfs:comment xml:lang="en">This is the classification list of
crops we are using in Seamless. Crops are defined in the most fine
level </rdfs:comment>
  </owl:Class>
  <owl:Class rdf:ID="Product">
    <rdfs:label xml:lang="gms">P</rdfs:label>
    <rdfs:label xml:lang="en">product</rdfs:label>
    <rdfs:comment xml:lang="en">These are the Products  used in
Seamless. A Product is a unique combination of a Crop or Animal and a
Product Type</rdfs:comment>
    <persistence:factory
rdf:datatype="http://www.w3.org/2001/XMLSchema#boolean"
    >true</persistence:factory>
</owl:Class>
<owl:ObjectProperty rdf:about="#produces">
    <rdfs:comment xml:lang="en">Each crop produces some
products</rdfs:comment>
    <owl:inverseOf rdf:resource="#ofCrop"/>
    <rdfs:domain rdf:resource="#Crop"/>
    <rdfs:range rdf:resource="#CropProduct"/>
</owl:ObjectProperty>
```

(a) part of ontology file for products and crops and the relationship ‘produces’ and ‘ofCrop’ as inverse

```
CREATE TABLE crop (
    id bigint NOT NULL,
    label_en character varying(255),
    label_gms character varying(255),
    label_aps character varying(255),
    drymatterfraction real,
    harvestindex real,
    iswintercrop boolean,
    nitrogencontent real,
    watersensitive boolean,
    cropclimaterequirements bigint,
    cropsoilrequirements bigint
);
CREATE TABLE cropproduct (
    id bigint NOT NULL,
    label_en character varying(255),
    label_gms character varying(255),
    oftype bigint,
    ofcrop bigint
);
ALTER TABLE ONLY cropproduct
    ADD CONSTRAINT fkcd85501fb733a23d FOREIGN KEY (ofcrop) REFERENCES
crop(id);
```

(b) part of the relational database schema for crops and products and the relationship between crops and products is represented by the foreign key relationship between crop and product table on the ofcrop-column

Fig. 7. Part of ontology file in OWL (a), a database schema in SQL (b), enterprise java beans (c) for crop and product and the produces and ofcrop relationship between crop and product. By examining the source code of ontology, database schema and enterprise java beans the differences in representing concepts and relationships between the paradigms can be found, e.g. a bi-directional relationship in an ontology becomes a uni-directional foreign key in SQL and a bi-directional relationship through association in the java beans. For more information on all the details, see Athaniasidis (Athanasiadis et al., 2007b).

```
@ConceptURI("http://ontologies.seamless-ip.org/crop.owl#Crop")
public class Crop implements Serializable {

private Long id;
private Float harvestindex;
private String label_aps;
private Boolean iswintercrop;
public Set<ICropGroup> ispartofcropgroups= new HashSet<ICropGroup>();
public CropClimateRequirements cropclimaterequirements;
private String label_gms;
private Boolean watersensitive;
private Float drymatterfraction;
private Float nitrogencontent;
private String label_en;

public Crop() {}

public Long getId() {
 return id;
 }

@SuppressWarnings("unused")
public void setId(Long id) {
      this.id = id;
 }

Etc for other getters and setters.
}


@ConceptURI("http://ontologies.seamless-ip.org/crop.owl#CropProduct")
public class CropProduct implements Serializable,
org.seamless_ip.ontologies.crop.IProduct {

 private Long id;
public Set<ProductGroup> ispartofproductgroups= new
HashSet<ProductGroup>();
public Crop ofcrop;
private String label_gms;
public ProductType oftype;
private String label_en;
public CropProduct() {}

public Long getId() {
 return id;
 }
@SuppressWarnings("unused")
public void setId(Long id) {
      this.id = id;
 }

/*
* Setters and getters for the method */
@PropertyURI("http://ontologies.seamless-ip.org/crop.owl#ofCrop")
public Crop  getOfCrop(){
  return ofcrop;
  }

@PropertyURI("http://ontologies.seamless-ip.org/crop.owl#ofCrop")
public void setOfCrop(Crop arg){
  this.ofcrop = arg;

   }
 Etc. for other getters and setters
 }
```

(c) part of the source code for the java entity beans covering crop, product and cropproduct and the 'ofcrop'-relationship between crop and product using getters and setters

Fig. 7. (*Continued*).

4.3. Conceptual integration

A first conceptual benefit is that we identified calculations to link cropping systems models to bio-economic farm models, and bio-economic farm models to partial equilibrium market models in a sensible and consistent manner. These calculations are based on jointly setting parameters of activities and aggregating supply responses to price elasticities through an estimation model.

These calculations and links between cropping system models, bio-economic farm models and partial equilibrium models may be re-usable in future research linking these model types, because these links help to cross temporal and spatial scales of the different models and are based on standard outputs of these types of models.

A methodological benefit is that the explicit model linking helped to efficiently (re)run models in model chains. Examples are an application of FSSIM to a large number of regions to assess supply-responses for EXPAMOD (Pérez Domínguez et al., 2009) and an application of APES for a large number of activities to supply yields and environmental effects for FSSIM (Belhouchette et al., 2011). Such applications can now easily be repeated for different samples of regions or activities and are easily reproducible in the modeling framework, thereby ensuring scientific transparency and rigor.

For the conceptual integration no generic method was used to link the different models. Although many different loosely or tightly linked models (e.g. Rounsevell et al., 2005; NMP, 2006; Jansson et al., 2008; Verburg et al., 2008) are available, there is no generic method to achieve the conceptual integration of a set of models for land use modeling. Relevant aspects (e.g. time and spatial scales, process definitions, modeling techniques) of conceptual integration can easily be identified and have been discussed also for our conceptual integration. A generic method may facilitate the model linking by providing guidelines and a conceptual framework for scientists to achieve a model linking. An example of such a generic method is found in Letcher et al. (2007) for IAM of water allocation problems, which is based on the nature of interactions between decisions and the hydrological cycle and the assumptions with respect to perfect knowledge or uncertainty. Established scientific theories like hierarchical systems theory (Smith and Sage, 1973) may supplement a generic method, but such theories always represent a perspective of the model linking considered. A thorough review of the available linked models in the land use domain is a useful first step in the development of a more generic method for conceptual integration.

One important outcome of the conceptual integration is consistency across the linked models, especially in the case of legacy models. For example, two models might use two different process descriptions to calculate the same concept, and this might lead to conflicting outcomes for the same concept. In the conceptual integration, these duplications of process descriptions are identified and discussed in terms of the validity and usability in the model chain. In our case the representation of farm behavior in the market model was replaced by the representation of farm behavior simulated in the farm model. In the absence of any generic method, the identification of these duplications in process descriptions depends on the diligence of the researchers to jointly discuss and learn about each other models.

4.4. Technical integration

The use of OpenMI and the development of a modeling framework helped to execute the model chain on a computer. Our use of OpenMI demonstrates that OpenMI can be applied to models outside the water domain, as OpenMI facilitated the link between agronomic and economic models. The use of OpenMI had two benefits. First, the definition of data exchanged in Links and getValues( ) (e.g. outputs) forced models to be specific about their inputs and outputs. Second, wrapping the model as an (OpenMI) component facilitated the definition of models independently of each other, of data sources and of the graphical user interface. In our case, the OpenMI standard version 1.4 was extended to work with complex data types. This extension could be incorporated in future updates of the OpenMI standard (OpenMI, 2009), if the OpenMI standard targets applicability in different domains and models based on different modeling techniques. OpenMI is based on the use of wrappers that allow it to keep the model in its original programming paradigm. Disadvantages are that the wrappers require maintenance and updating with changes in the model and that the model itself is quite distant from OpenMI. This distance may lead to problems in developing the wrapper, if the wrapper-developer and modeler are not the same person.

The ontology achieved in the semantic integration was intensively used in the technical integration by translating it to source code through the SeRiDA-framework. A benefit of a tight link between semantic and technical integration is that modelers are forced to focus on content of their model and not on the implementation of a model into programming language. A second benefit is the explicit separation of data from model specification as is advocated in good modeling practices (Jakeman et al., 2006), allowing to easily validate a model against other data sources. This separation is facilitated through the database schemas which are built on the basis of ontologies (Athanasiadis et al., 2007a) and provide a natural container for data persistence. A disadvantage from the modeling perspective and an advantage from the model integration perspective is that the models cannot easily change their input and output data specification, as this first has to be aligned with the ontology in the semantic integration.

5. Conclusion

The models APES, FSSIM, EXPAMOD and SEAMCAP are now linked in the modeling framework SEAMLESS-IF. These models allow assessment of the socio-economic, biophysical and environmental impacts of changes in agricultural and environmental policies and technological innovations across spatial and temporal scales. Examples of possible applications at EU, individual region or farm scale are the assessment of the impacts of a trade liberalization as discussed in the frame of the World Trade Organization (Adenäuer and Kuiper, 2009), the introduction of the EU Nitrate Directive (Belhouchette et al., 2011), the EU Water Directive, the consequences of increases in bio-fuel production, the changes in production due to high commodity prices and of the introduction of agricultural technologies (e.g. zero-tillage, improved irrigation implements). Our integration effort led to a credible and transparent model linking with an explicit consideration of the concepts (e.g. activities, crops, products, product type, crop group, product group, price elasticity, supply response) and calculations (e.g. parameter calculation of activities and aggregation of supply responses to price elasticity) of relevance implemented in an advanced modeling framework based on OpenMI and semantic modeling.

The subdivision of the integration effort in conceptual, semantic and technical aspects was useful to comprehensively consider all aspects of integration and to avoid a bias to one of them. In future research projects that link models, it is advised to first define the semantic and conceptual integration, if models are linked that have yet to be developed. If existing models are linked, conceptual integration across models is the most suitable starting point.

Acknowledgements

We gratefully acknowledge the help and support of many scientists in building the integrated model chain in the SEAMLESS project and two anonymous reviewers for their valuable comments. The work presented in this publication was funded by the SEAMLESS integrated project, EU 6th Framework Programme for Research Technological Development and Demonstration, Priority 1.1.6.3. Global Change and Ecosystems (European Commission, DG Research, contract no. 010036-2) and by the Knowledge Base

Research Grants of the Dutch Ministry of Agriculture, Nature and Food.

References

Adenäuer, M., Kuiper M., 2009. A typical application of SEAMLESS-IF at macro level: a trade liberalization scenario applied to the EU. SEAMLESS Report no. 43, SEAMLESS integrated project, EU 6th Framework Programme, contract no. 010036-2, www.seamlessassociation.org, 51 pp., ISBN no. 978-90-8585-586-6.

Antoniou, G., van Harmelen, F., 2004. A Semantic Web Primer. The MIT Press, Cambridge, Massachusetts; London, England.

Athanasiadis, I., Rizzoli, A.E., Donatelli, M., Carlini, L., 2006. Enriching software model interfaces using ontology-based tools. In: Voinov, A., Jakeman, A., Rizzoli, A. (Eds.), The iEMSs Third Biannual Meeting "Summit on Environmental Modelling and Software Third Biennial Meeting". International Environmental Modelling and Software Society, Burlington, USA.

Athanasiadis, I.N., Villa, F., Rizzoli, A.E., 2007a. Enabling knowledge-based software engineering through semantic-object-relational mappings. In: Stojanovic, L., Sabbouh, M. (Eds.), 3rd International Workshop on Semantic Web Enabled Software Engineering, 4th European Semantic Web Conference. Innsbruck, Austria, 15 pp.

Athanasiadis, I.N., Villa, F., Rizzoli, A.E., 2007b. Ontologies, JavaBeans and relational databases for enabling semantic programming. In: 31st IEEE Annual International Computer Software and Applications Conference (COMPSAC) , Beijing, China, pp. 331–346.

Athanasiadis, I.N., Rizzoli, A.E., Janssen, S., Andersen, E., Villa, F., 2009. Ontology for Seamless Integration of Agricultural Data and Models. In Metadata and Semantic Research (MTSR'09). Communications in Computer and Information Science 46, 282–293.

Belhouchette, H., Louhichi, K., Therond, O., Mouratiadou, I., Wery, J., Van Ittersum, M., Flichman, G., 2011. Assessing the impact of the Nitrate Directive on farming systems using a bio-economic modelling chain. Agricultural Systems. 104, 135–145.

Bright, M.W., Hurson, A.R., Pakzad, S., 1994. Automated resolution of semantic heterogeneity in multidatabases. ACM Transactions on Database Systems 19, 212–253.

Brilhante, V., Ferreira, A., Marinho, J., Pereira, J.S., 2006. Information integration through ontology and metadata for sustainability analysis. In: Voinov, A., Jakeman, A., Rizzoli, A. (Eds.), The iEMSs Third Biannual Meeting "Summit on Environmental Modelling and Software Third Biennial Meeting". International Environmental Modelling and Software Society, Burlington, USA.

Britz, W., Pérez Domínguez, I., Heckelei, T., 2010. A comparison of CAPRI and SEAMLESS-IF as integrated modelling systems. In: Brouwer, F., van Ittersum, M.K. (Eds.), Environmental and Agricultural Modelling: Integrated Approaches for Policy Impact Assessment. Springer, pp. 257–274.

DeMichiel, L., Keith, M., 2006. Enterprise javabeans 3.0 specifications. In: Java Specification Request 220.

Donatelli, M., Russell, G., Rizzoli, A.E., Acutis, M., Adam, M., Athanasiadis, I., Balderacchi, M., Bechini, L., Belhouchette, H., Bellocchi, G., Bergez, J.E., Botta, M., Braudeau, E., Bregaglio, S., Carlini, L., Casellas, E., Celette, F., Ceotto, E., Charron-Moirez, M.E., Confalonieri, R., Corbeels, M., Criscuolo, L., Cruz, P., Guardo, A.D., Ditto, D., Dupraz, C., Duru, M., Fiorani, D., Gentile, A., Ewert, F., Gary, C., Habyarimana, E., Jouany, C., Kansou, K., Knapen, M.J.R., Filippi, G.L., Leffelaar, P., Manici, L., Martin, G., Martin, P., Meuter, E.C., Mugueta, N., Mulia, R., Noordwijk, M.v., Oomen, R., Rosenmund, A., Rossi, V., Salinari, F., Serrano, A., Sorce, A., Vincent, G., Theau, J.P., Therond, O., Trevisan, M., Trevisiol, P., Van Evert, F.K., Wallach, D., Wery, J., Zerourou, A., 2010. APES: the agricultural production and externalities simulator. In: Brouwer, F., van Ittersum, M.K. (Eds.), Environmental and Agricultural Modelling: Integrated Approaches for Policy Impact Assessment. Springer Academic Publishing. 63-108.

EC, 2008. Nomenclature of territorial units for statistics – NUTS Statistical Regions of Europe. In: European Commission, Brussels.

Ewert, F., van Ittersum, M.K., Bezlepkina, I., Therond, O., Andersen, E., Belhouchette, H., Bockstaller, C., Brouwer, F., Heckelei, T., Janssen, S., Knapen, R., Kuiper, M., Louhichi, K., Olsson, J.A., Turpin, N., Wery, J., Wien, J.E., Wolf, J., 2009. A methodology for integrated assessment of policy impacts in agriculture. Environmental Science & Policy 12, 546–561.

Gangemi, A., Grimm, S., Mika, P., Oberle, D., Lamparter, S., Sabou, M., Staab, S., Vrandecic, D., 2008. Core Software Ontology – Core Ontology of Software Components – Core Ontology of Services.

Gregersen, J.B., Gijsbers, P.J.A., Westen, S.J.P., 2007. OpenMI: open modelling interface. Journal of Hydroinformatics 9, 175–191.

Gruber, T.R., 1993. A translation approach to portable ontology specifications. Knowledge Acquisition 5, 199–220.

Hakimpour, F., Geppert, A., 2005. Resolution of semantic heterogeneity in database schema integration using formal ontologies. Information Technology and Management 6, 97–122.

Harris, G., 2002. Integrated assessment and modelling: an essential way of doing science. Environmental Modelling & Software 17, 201–207.

Heckelei, T., Britz, W., 2001. Concept and explorative application of an EU-wide regional agricultural sector model (CAPRI-Projekt). In: Heckelei, T., Witzke, H.P., Henrichsmeyer, W. (Eds.), 65th EAAE Seminar Bonn University, Vauk Verlag, Kiel, Germany, pp. 281–290.

Helming, K., Pérez-Soba, M., Tabbush, P. (Eds.), 2008. Sustainability Impact Assessment of Land Use Changes. Springer Publishing.

Hillyer, Bolte, Evert, V., Lamaker, 2003. The ModCom modular simulation system. European Journal of Agronomy 18, 333–343.

Hinkel, J., 2008. Transdisciplinary knowledge integration – cases from integrated assessment and vulnerability assessment. Wageningen University, Wageningen, 198 pp.

Hinkel, J., 2009. The PIAM approach to modular integrated assessment modelling. Environmental Modelling & Software 24, 739–748.

Jakeman, A.J., Letcher, R.A., Norton, J.P., 2006. Ten iterative steps in development and evaluation of environmental models. Environmental Modelling & Software 21, 602–614.

Jakobsen, C.H., McLaughlin, W.J., 2004. Communication in ecosystem management: a case study of cross-disciplinary integration in the assessment phase of the Interior Columbia Basin Ecosystem Management Project. Environmental Management 33, 591–605.

Janssen, S., Van Ittersum, M.K., 2007. Assessing farm innovations and responses to policies: a review of bio-economic farm models. Agricultural Systems 94, 622–636.

Janssen, S., Andersen, E., Athanasiadis, I.N., Van Ittersum, M.K., 2009a. A database for integrated assessment of European agricultural systems. Environmental Science & Policy 12, 573–587.

Janssen, S., Ewert, F., Li, H., Athanasiadis, I.N., Wien, J.J.F., Thérond, O., Knapen, M.J.R., Bezlepkina, I., Alkan-Olsson, J., Rizzoli, A.E., Belhouchette, H., Svensson, M., Van Ittersum, M.K., 2009b. Defining assessment projects and scenarios for policy support: use of ontology in Integrated Assessment and Modelling. Environmental Modelling and Software 24, 1491–1500.

Janssen, S., Louhichi, K., Kanellopoulos, A., Zander, P., Flichman, G., Hengsdijk, H., Meuter, E., Andersen, E., Belhouchette, H., Blanco, M., Borkowski, N., Heckelei, T., Hecker, M., Li, H., Oude Lansink, A., Stokstad, G., Thorne, P., van Keulen, H., van IttersumF M., 2010. A Generic Bio-Economic Farm Model for Environmental and Economic Assessment of Agricultural Systems. Environmental Management 46, 862–877.

Jansson, T., Bakker, M., Boitier, B., Fougeyrollas, A., Helming, J., van Meijl, H., Verkerk, P.J., 2008. Cross sector land use modelling framework. In: Helming, K., Pérez Soba, M., Tabbush, P. (Eds.), Sustainability Impact Assessment of Land Use Changes. Springer, Berlin, pp. 159–180.

JBOSS, 2008. Hibernate. Access online 6 March, 2008 www.hibernate.org.

Knapen, M.J.R., Athanasiadis, I.N., Jonsson, B., Huber, D., Wien, J.J.F., Rizzoli, A.E., Janssen, S., 2009. Use of OpenMI in SEAMLESS. In: Proceedings of Integrated Assessment of Agriculture and Sustainable Development: Setting the Agenda for Policy and Society (AgSap). Egmond aan Zee.

Kok, K., Verburg, P.H., Veldkamp, T., 2007. Integrated assessment of the land system: the future of land use. Land Use Policy 24, 517–520.

Letcher, R.A., Croke, B.F.W., Jakeman, A.J., 2007. Integrated assessment modelling for water resource allocation and management: a generalised conceptual framework. Environmental Modelling & Software 22, 733–742.

Liu, J., Peng, C., Dang, Q., Apps, M., Jiang, H., 2002. A component object model strategy for reusing ecosystem models. Computers and Electronics in Agriculture 35, 17–33.

Liu, Y., Gupta, H., Springer, E., Wagener, T., 2008. Linking science with environmental decision making: experiences from an integrated modeling approach to supporting sustainable water resources management. Environmental Modelling & Software 23, 846–858.

Louhichi, K., Kanellopoulos, A., Janssen, S., Flichman, G., Blanco, M., Hengsdijk, H., Heckelei, T., Berentsen, P., Lansink, A.O., Van Ittersum, M.K., 2010. FSSIM, a bio-economic farm model for simulating the response of EU farming systems to agricultural and environmental policies. Agricultural Systems 103, 585–597.

McGuinness, D., Van Harmelen, F., 2004. OWL Web Ontology Language Overview. In: W3C Recommendation. WWW Consortium.

Moore, A.D., Holzworth, D.P., Herrmann, N.I., Huth, N.I., Robertson, M.J., 2007. The Common Modelling Protocol: a hierarchical framework for simulation of agricultural and environmental systems. Agricultural Systems 95, 37–48.

Moore, R.V., Tindall, C.I., 2005. An overview of the open modelling interface and environment (the OpenMI). Environmental Science & Policy 8, 279–286.

NMP, 2006. Integrated modelling of global environmental change. An overview of IMAGE 2.4. In: Bouwman, A.F., Kram, T., Klein Goldewijk, K. (Eds.), Report no. 500110002. Netherlands Environmental Assessment Agency, 228 pp.

Novak, J.D., Cañas, A.J., 2006. The theory underlying concept maps and how to construct them. In: Technical Report IHMC CmapTools 2006-01. Florida Institute for Human and Machine Cognition.

Nute, D., Potter, W.D., Cheng, Z., Dass, M., Glende, A., Maierv, F., Routh, C., Uchiyama, H., Wang, J., Witzig, S., Twery, M., Knopp, P., Thomasma, S., Rauscher, H.M., 2005. A method for integrating multiple components in a decision support system. Computers and Electronics in Agriculture 49, 44–59.

OpenMI, 2009. The OpenMI Association. Access online 20 May, 2009 www.openmi.org.

Oxley, T., ApSimon, H.M., 2007. Space, time and nesting Integrated Assessment Models. Environmental Modelling & Software 22, 1732–1749.

Parker, D.C., Entwisle, B., Rindfuss, R.R., Vanwey, L.K., Manson, S.M., Moran, E., An, L., Deadman, P., Evans, T.P., Linderman, M., Mussavi Rizi, S.M., Malanson, G., 2008. Case studies, cross-site comparisons, and the challenge of generalization: comparing agent-based models of land-use change in frontier regions. Journal of Land Use Science 3, 41–72.

Parker, P, Letcher, R., Jakeman, A., Beck, M.B., Harris, G., Argent, R.M., Hare, M., Pahl-Wostl, C., Voinov, A., Janssen, M., 2002. Progress in integrated assessment and modelling. Environmental Modelling & Software 17, 209–217.

Pérez Domínguez, I., Gay, S.H., M'Barek, R., 2008. Agricultural modelling for european policy makers: a user's perspective. In: The EAAE Congress Ghent, Belgium.

Pérez Domínguez, I., Bezlepkina, I., Heckelei, T., Romstad, E., Oude Lansink, A., Kanellopoulos, A., 2009. Linking farm and market models by means of response functions. Environmental Science & Policy 12, 588–601.

Polhill, J., Gotts, N., 2009. Ontologies for transparent integrated human-natural system modelling. Landscape Ecology 24, 1255–1267.

PostgreSQL, 2008. PostgreSQL. Access online 6 March, 2008 www.postgreSQL.org.

Rahman, J.M., Seaton, S.P., Perraud, J.-M., Hotham, H., Verrelli, D.I., Coleman, J.R., 2003. It's TIME for a new environmental modelling framework. In: Proceedings of MODSIM 2003 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand Inc., Townsville.

Rasinmäki, J., Mäkinen, A., Kalliovirta, J., 2009. SIMO: an adaptable simulation framework for multiscale forest resource data. Computers and Electronics in Agriculture 66, 76–84.

Refsgaard, J.C., Henriksen, H.J., 2004. Modelling guidelines—terminology and guiding principles. Advances in Water Resources 27, 71–82.

Rizzoli, A.E., Donatelli, M., Athanasiadis, I.N., Villa, F., Huber, D., 2008. Semantic links in integrated modelling frameworks. Mathematics and Computers in Simulation 78, 412–423.

Rohn, E., 2010. Generational analysis of variety in data structures: impact on automatic data integration and on the semantic web. Knowledge and Information Systems 24 (2), 283–304.

Rotmans, J., Asselt, M., 1996. Integrated assessment: a growing child on its way to maturity. Climatic Change 34, 327.

Rounsevell, M.D.A., Ewert, F., Reginster, I., Leemans, R., Carter, T.R., 2005. Future scenarios of European agricultural land use: II. Projecting changes in cropland and grassland. Agriculture, Ecosystems & Environment 107, 117–135.

Scholten, H., 2008. Better Modelling Practice: an ontological perspective on multidisciplinary, model based problem solving. Wageningen University, Wageningen, 313 pp.

Scholten, H., Kassahun, A., Refsgaard, J.C., Kargas, T., Gavardinas, C., Beulens, A.J.M., 2007. A methodology to support multidisciplinary model-based water management. Environmental Modelling & Software 22, 743–759.

Smith, N.J., Sage, A.P., 1973. An introduction to hierarchical systems theory. Computers & Electrical Engineering 1, 55–71.

Tress, G., Tress, B., Fry, G., 2007. Analysis of the barriers to integration in landscape research projects. Land Use Policy 24, 374–385.

Van Ittersum, M.K., Ewert, F., Heckelei, T., Wery, J., Alkan Olsson, J., Andersen, E., Bezlepkina, I., Brouwer, F., Donatelli, M., Flichman, G., Olsson, L., Rizzoli, A., van der Wal, T., Wien, J.-E., Wolf, J., 2008. Integrated assessment of agricultural systems—a component based framework for the European Union (SEAMLESS). Agricultural Systems 96, 150–165.

Van Meijl, H., van Rheenen, T., Tabeau, A., Eickhout, B., 2006. The impact of different policy environments on agricultural land use in Europe. Agriculture, Ecosystems & Environment 114, 21–38.

Van Tongeren, F., Van Meijl, H., Surry, Y., 2001. Global models applied to agricultural and trade policies: a review and assessment. Agricultural Economics 26, 149–172.

Verburg, P., Eickhout, B., van Meijl, H., 2008. A multi-scale, multi-model approach for analyzing the future dynamics of European land use. The Annals of Regional Science 42, 57–77.

Verburg, P.H., Rounsevell, M.D.A., Veldkamp, A., 2006. Scenario-based studies of future land use in Europe. Agriculture, Ecosystems & Environment 114, 1–6.

Verburg, P.H., Schot, P.P., Dijst, M.J., Veldkamp, A., 2004. Land use change modelling: current practice and research priorities. GeoJournal 61, 309–324.

Villa, F., Athanasiadis, I.N., Rizzoli, A.E., 2009. Modelling with knowledge: a review of emerging semantic approaches to environmental modelling. Environmental Modelling and Software 24, 577–587.

Wien, J.J.F., Rizzoli, A.E., Knapen, M.J.R., Athanasiadis, I.N., Janssen, S.J.C., Ruinelli, L., Villa, F., Svensson, M., Wallman, P., Jonsson, B., Van Ittersum, M.K., 2010. A web-based software system for model integration in agro-environmental impact assessments. In: Brouwer, F., Van Ittersum, M.K. (Eds.), Environmental and Agricultural Modelling: Integrated Approaches for Policy Impact Assessment. Springer Academic Publishing, pp. 207–234.