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A design for a generic and modular bio-economic farm model

Wolfgang Britz [a], Pavel Ciaian [b], Alexander Gocht [c], Argyris Kanellopoulos [d], Dimitrios Kremmydas [b], Marc Müller [e,*], Athanasios Petsakos [b], Pytrik Reidsma [f]

[a] *Economic Modeling of Agricultural Systems Group, Institute for Food and Resource Economics, University of Bonn, Germany*
[b] *European Commission, Joint Research Centre (JRC), Spain*
[c] *Thünen-Institut of Farm Economics, Germany*
[d] *Operations Research and Logistics Group, Department of Social Sciences, Wageningen University and Research, Netherlands*
[e] *Wageningen Economic Research, Wageningen University and Research, Netherlands*
[f] *Plant Production Systems, Wageningen University and Research, Netherlands*

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ABSTRACT

Context: Past reviews of policy impact assessment studies using bio-economic farm models (BEFM) called for the development of a generic and modular implementation that can be maintained by a network of modellers. A main reason for these calls is the project-oriented way in which model developers receive funding. It favours the development of new models with case-study specific features over the maintenance and extension of well-tested, more generic ones which allow comparing results in a consistent way across many case-studies. The demand for more generic tools also reflects the dynamic landscape of policy measures within larger policy frameworks like the Common Agricultural Policy (CAP). These policy frameworks move increasingly away from a 'one-size-fits-all' approach of policy design towards more flexible systems, giving greater freedom to shape, implement, and target policy measures to specific regions, farm management systems and farm types. This creates new challenges for model-based impact assessment as applied models have to reflect the variety of policy measures and characteristics of targeted farmers and rural communities.
Objective: The aim of this paper is to first address key questions regarding the functionality and implementation of such a modular BEFM that can be maintained and expanded by a user group, and second to develop concrete proposals of necessary model features, model design and shared development.
Methods: This paper builds on literature research, including a detailed review of four models that are used extensively for impact assessment within the EU and were developed by multiple teams over a longer period of time. From there, necessary and desirable features of a generic and modular BEFM are identified and requirements for model design regarding modularity, software engineering, and shared development are discussed.
Results and conclusions: This feeds into the development of concrete proposals of how modularity and flexibility can be addressed in the development, application and maintenance of a BEFM. At the end, a list of design decisions and implementation steps is proposed to build a modular BEFM that can be maintained by a network of researchers.
Significance: The concept for a network-based generic and modular bio-economic farm model responds to the demand for analytical tools in agricultural policy impact analysis. The paper develops a research agenda to overcome observed limitations in the current landscape of such models.

1. Introduction

A review of bio-economic farm models (BEFMs) by Janssen and van Ittersum in 2007, covering 48 studies published between 1982 and 2007, observed that these models are often developed for specific case-studies and rarely re-used, for instance by applying them to new datasets, or by including alternative farming practices or behavioural assumptions. This led to them calling for "*an easily transferable BEFM with a generic and modular structure*" (Janssen and van Ittersum, 2007) to let researchers benefit from joint maintenance and development of additional functionalities. Around a decade later, Reidsma et al. (2018) re-visited the research agenda of Janssen and van Ittersum (2007) by

* Corresponding author.
E-mail address: marc.muller@wur.nl (M. Müller).

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surveying a larger number of BEFMs used in policy assessments. They found progress in fields such as depicting farmers' decision making or new and improved economic and environmental indicators, but no fundamental change with regard to aspects such as consistent evaluation procedures or more generic and modular approaches (Reidsma et al., 2018). For this reason, they proposed the organisation of a network focusing on the development and maintenance of a generic, modular, and easily transferable BEFM. Neither review elaborated on how such a generic and modular BEFM would be structured, jointly developed, and maintained. Attempts have been made to develop such a BEFM (e.g., Janssen et al., 2010), but none of them has been completely successful so far, and therefore we address this in this paper. It requires identifying the core of a generic BEFM comprising the minimum set of features to produce meaningful results as well as desirable functionalities. Implementation of modular design principles and especially the introduction of new features require attention to computational aspects of model implementation.

The review by Reidsma et al. (2018) covered 184 model-based impact assessment studies, focussing on European countries and covering the period between 2007 and 2015. They found that a majority of the applied BEFMs for farm-scale analysis considered farm diversity, e.g., by assessing impacts of policies on multiple farm types or distinguishing agro-ecological or socio-economic regions. This reflects that the Common Agricultural Policy (CAP) of the European Union (EU) shifted over the last decades from price support to farm income support, conditional on respecting specific environmental standards. To address the heterogeneity of European agriculture, policy instruments vary across regions and farms. Not surprisingly, especially after the 2013 CAP reform, the number of studies employing BEFMs increased substantially, indicating their usefulness for ex ante policy analyses of the current CAP (e.g. Cortignani et al., 2017; Gaudino et al., 2018; Louhichi et al., 2018a; Solazzo and Pierangeli, 2016; Ahmadi et al., 2015). Most of these models[1] covered certain Member States, regions and/or specific agricultural sectors (e.g., Solazzo et al., 2014; Cimino et al., 2015; Ahmadi et al., 2015) without an explicit consideration of a generic and modular structure or data organisation, preventing the re-use of concepts and code developments and hence applications of BEFMs with a broader regional and farm type coverage. It also hinders comparison of results across different studies as indicator coverage and definitions are not harmonized.

An important challenge for policy assessment with BEFMs will be the re-orientation of the CAP post-2020 based on the 'Green Deal' (European Commission, 2019). It aims, for instance, to reduce the use of chemical pesticides and antimicrobials by 50%, and of fertilizers by 20%, to support integrated nutrient management and production of EU-grown plant proteins and alternative feed materials, to increase the share of EU under organic farming to 25%, to improve animal welfare, and to promote various environmental practices (European Commission, 2020a, 2020b; European Commission, 2018a). Few of the existing models could address even some of these issues. A coordinated development in the community of modellers could tackle these gaps to make their models fit for the next generation of agricultural policies and strengthen evidence-based policy design. The recent proposal for the CAP post-2020 challenges the abilities of current BEFMs even further by aims such as stimulating farm structural change, enhancing the provision of public goods, including biodiversity, ecosystem services and climate change mitigation, and meeting societal expectations on animal welfare, food quality, food safety and health issues. To address these points, new indicators need to be developed and integrated into BEFMs and, for instance, their technology representation improved, opening further chances to benefit from joint development.

Such developments in the policy landscape do not necessarily require the development of entirely new analytical tools, but may be best addressed by building on and augmenting existing approaches. Reidsma et al. (2018) identified the prevailing project-related funding mechanism as a core reason why models are rarely maintained and extended. Particularly research projects emphasize new model developments over maintenance, integration, and extension of existing approaches. This observation is now addressed by major donors such as the European Commission. It funds since 2019 a cluster of research projects[2] to improve modelling capabilities to support evidence-based agricultural policymaking, all closely interacting with similar ongoing projects.[3] The new projects aim at the development of highly modular and customisable suites of tools, allowing for flexible use and further improvements on demand. The MIND STEP project, in particular, emphasizes the development of a modular and transferable farm-level model in their research agenda and further motivates this paper.

A complementary approach for long-term maintenance and extension of already existing tools are the so-called modelling platforms for policy analysis. They comprise multiple established tools with a track record, and their user and developer communities. An example is the 'integrated Modelling Platform for Agro-economic Commodity and Policy Analysis' (iMAP) (M'barek et al., 2012) that pools partial and computable general equilibrium models. Operational since 2006, iMAP is hosted by the European Commission's Joint Research Centre (JRC), in close cooperation with DG Agriculture and Rural Development (DG AGRI), as well as many academic and international research institutions. So far, no comparable platform for the continued development of a generic and modular BEFM exists, but the iMAP concept may serve as an example of how to let the developed tool survive and to render them useful in policy assessment.

Reflecting upon these points, this paper is structured as follows: Section 2 reviews four BEFMs (CAPRI- FT, IFM-CAP, FARMDYN, FSSIM) which have been maintained over a longer time horizon and are regularly applied. They are substantially different in aspects such as typical use case, depiction of production technology, objective function, decision variables, and time horizon. In addition, computational aspects are discussed, which are rarely covered in existing reviews, like ease of database updates, separation of code from data, user interfaces, and version control. Based on the reviews and the in-depth comparison of the four models, we identify required and desired features of farm models in Section 3, addressing the question of what do the terms 'generic' and 'modular' mean in the context of a BEFM. We propose a broad but operational list of desired attributes of a generic BEFM and highlight some implications for software development and engineering, like the potential for modularization and shared development. In addition, we review the structure of several known economic networks and draw some conclusions for a BEFM community approach. We conclude with an outlook on the development of a generic, modular, and transferable model.

2. A review of selected applied farming system models

2.1. Selection criteria

BEFMs form a specific category of agricultural systems models which have been defined as models that link optimization of farmers' resource management decisions to quantitative evaluations of inputs and outputs (including externalities) of alternative production possibilities (Janssen and van Ittersum, 2007). Other types of models that have been used in policy assessments are agent based models, life cycle analysis and agri-environmental impact simulation (Payraudeau and van der Werf, 2005).

[1] With the exceptions of CAPRI-FT (Gocht and Britz, 2011) and IFM-CAP (Louhichi et al., 2015) to which we will return later in Section 2.

[2] AGRICORE: https://cordis.europa.eu/project/id/816078),BESTMAP: https://cordis.europa.eu/project/id/817501,MIND STEP: https://cordis.europa.eu/project/id/817566

[3] SUPREMA: https://cordis.europa.eu/project/id/773499

Compared to other agricultural systems models BEFM have some advantages related to the detail of representing agricultural systems. For instance, they can incorporate large numbers of production options and technologies, thus capturing technical specifications in sufficient detail. Interactions between crop and livestock production activities can be taken into account explicitly (Janssen and van Ittersum, 2007). Finally, they enable analysis of the impact of uncertain parameters through sensitivity analysis (Wossink and Renkema, 1994). This section discusses aspects of four selected BEFMs in more detail. Detail is deemed important here to derive operational guidelines for the development of a generic and modular BEFM. Reviewing in detail might reveal if elements of existing models could be combined and/or if an existing model might be extended and enriched by features of others. Such code reuse and combination are interesting strategies for the development of a generic BEFM to partly skip development efforts and to draw on existing networks of model developers and users.

As a first step towards a generic, modular model, four BEFMs were selected, which have in common that they were developed by several teams over a longer time period and are based on a template approach. In addition, the selected models have been repeatedly applied in technology and policy assessments which are typically published in peer-reviewed papers. A further important common feature is that the selected models are coded in an algebraic modelling language (AML) rather than a general-purpose language. The use of an AML seems the dominant approach for mathematical programming (MP) based BEFMs, largely because it facilitates model coding and use by domain experts who are comfortable with writing algebraic expressions but may not have a formal training in computer sciences (Britz and Kallrath, 2012). The General Algebraic Modelling System (GAMS) (Bussieck and Meeraus, 2004) is a prominent example of an AML and used by all models reviewed. This could also greatly facilitate code re-usage and eases the comparison on how coders deal with issues such as flexible model set-up (modularity) and extension to multiple use-cases by a larger number of users and developers (scalability) in a given coding environment.

We included two models (CAPRI-FT, IFM-CAP) which cover all of Europe as one important desired feature of a generic BEFM. The CAPRI-Farm type layer (CAPRI-FT) covers 2.800 aggregate farm type models which represent all farms reported in the European Farm Structure Survey (FSS). It has been regularly applied in policy impact assessments and offers the widest coverage of regions. It is the only model reviewed that is integrated with a market model to consider price feedback. The model IFM- CAP covers all surveyed farms of the European Farm Accounting Data Network (FADN) in a template approach, i.e., the same structural equations are comprised in each model, such that differences are reflected in parameters only. It considers risk besides expected farm income in the objective and uses zero-one (binary) decisions related to some policy options, such as crop diversification as part of CAP ‘greening’. IFM-CAP provides an example of a model designed to fit a specific database and highlights challenges from applying a template to several thousand farms. Both CAPRI-FT and IFM-CAP are not bio-economic models in the narrow sense as bio-physical detail is limited (see Table 1). The two models are maintained by a national or European institute to provide national or EU wide policy impact assessment.

FSSIM, as the third reviewed model, has a root in close links to crop-growth models, a focus on arable farming and includes detailed agricultural management activities as a typical feature of a bio-economic model. When first developed, FSSIM worked with representative average farms based on the SEAMLESS database (Janssen et al., 2009a), but later applications also simulated existing single farms. CAPRI-FT, IFM-CAP and FSSIM are all calibrated using Positive Mathematical Programming (PMP) (Howitt, 1995), are comparative-static and do not comprise explicit investment decisions. We compare them with FARMDYN as the fourth candidate model which can accommodate any type of farm-specific data and comprises explicit investment decisions and can also be used in fully dynamic and stochastic fashions. FARMDYN adds especially detail for field operations, manure handling, ruminant production, and grass land management, coming close to the detail in typical farm systems models.

While the majority of developed farming system models are not being reused, some examples do exist (see Reidsma et al., 2018), like MODAM (Uthes et al., 2010) or FarmDesign (Groot et al., 2012). These do, however, not fulfil the criteria for this review as they are not typical mathematical programming models implemented in an AML, but aspects, specifically regarding biophysical detail, can be considered for a generic model.

2.2. CAPRI-FT

The introduction of farm-specific support schemes (e.g., direct payments) as part of the CAP motivated the development of a farm type module for Common Agricultural Policy Regionalized Impact model (CAPRI). CAPRI is a comparative static partial equilibrium model for the agricultural sector, developed for policy and market impact assessments from global to regional level. Its standard version links supply modules at sub-national (NUTS2[4]) level for Europe with a global partial equilibrium market module (Britz and Witzke, 2014). The market module provides prices to the supply models which cover a detailed representation of production activities. The CAPRI-FT layer consistently disaggregates production quantities, activity levels and input use from the regional NUTS2 models to 2800 farm models (Gocht and Britz, 2011), which ensures inter-operability with the global partial equilibrium market model.

Each farm type is represented by a nonlinear programming model that captures all activities associated with the farms of a certain typology in a specific region. The NUTS2 and farm type layer share the same model template, only the parameterization differs across models. Each model optimises the farm income under restrictions related to land balances, crop nutrient balances and nutrient requirements of animals. The decision variables include crop acreages, land use, herd sizes, fertilizer rates and feed mix. The direct payments paid under the CAP are captured in detail. The allocation response depends primarily on econometrically estimated terms (Jansson and Heckelei, 2011) in the objective function. The main data sources of the models are the Farm Structure Survey (FSS)[5] and FADN,[6] along with information from the regional database in CAPRI. Each farm type is characterised by its production specialisation (13 classes) and economic size class (3 classes). The resulting 39 possible farm types in each NUTS2 provide a compromise among model complexity and size, robustness of results, reporting limitations and data constraints. CAPRI-FT uses the Graphical User Interface Generator GGIG (Britz, 2014) to steer simulations and exploit results.

By depicting multiple farm types in each region, CAPRI-FT captures the heterogeneity of farming practices within a region and reduces the aggregation bias of the regional responses. It is hence especially suitable for analysis of policy instruments targeted at the farm level, such as the historically decoupled payments, or implemented based on farm characteristics, such as modulation of direct payments (Gocht et al., 2017, 2013; Schroeder et al., 2015).

CAPRI-FT has been applied for different policy-related impact analyses, such as for distributional effects of direct payment harmonisation in the context of the 2013 CAP reform (Gocht et al., 2013) and the economic and environmental impacts of CAP greening (Gocht et al.,

[4] https://ec.europa.eu/eurostat/web/nuts/background

[5] FSS provides harmonized data regarding the structure of agricultural holdings in terms of land use, livestock numbers, farm labour force, machinery and equipment, and participation in rural development programmes. The complete agricultural census is updated every 10 years (with intermediate sample surveys).

[6] FADN provides accounting data for a sample of commercial agricultural holdings. The survey is conducted annually.

Table 1
Comparison of models with respect to content features.

Model	CAPRI-FT	IFM-CAP	FSSIM	FARMDYN
Regional- and product coverage; technology representation				
Regional coverage in the EU	Covering EU	Covering EU	8 EU regions	5 EU countries + Switzerland
Coverage of farm population	Full	Almost full	Case studies	Case studies
Individual farms	No	Yes (≈80,000 farms)	Yes	Yes
Representative farms	2800	Yes		
Max. no. of crop & animal activities	35/16	35/16	Case specific	Case specific
Max. no. of crop & animal commodities	30/7	30/7	Case specific	Case specific
No. of animal activities per commodity	Multiple	Single	Multiple	Multiple
Catch or cover crops	Yes			
Grassland management	High and low input intensities	two type of grass	permanent and temporary grassland	grazing only or also for cuts, different management options[a]
Herd flow representation Herds (by age, sex, year, months)	Yes	Yes	Yes	Yes also breeds, feed regime
Manure types	One	No	Optional	Several
Management and technology options for activities	High & low intensity	No	Intensity[b]	Tillage options, intensity levels
Crop rotation		Yes	Yes	Possible
Temporal resolution	Year			Year, month
Plot representation (land quality)	No	No	Yes	Yes
Policy representation				
Direct payments and common organisation of the markets in agricultural products (CAP Pillar 1) (+ set-aside and quota, EU's greening reform)	Voluntary coupled support & ceiling of EU budget endogenous	diversification as binary decision	Yes	Yes
Nitrate and Water framework directive	Detailed NPK flows	No	Yes	In high detail
GHG policies (CO2 pricing, ceilings)	Yes	No	No	Yes
Trade and market policies, Tariff Rate Quotas, Tariff cut (e.g., liberalization, WTO G20 proposal)	Trade policies using market model link	Prototype link to CAPRI	Yes, in applications with link to CAPRI	
Link to other types of models	Market model	Market model	Link to crop growth models possible to generate I/O coefficients	
Factors				
Covered types of land endowments (arable/grassland/permanents)	All	All	No perm.	No perm.
Labour constraints	No	No	Family labour, hired labour	Block labour for management of farm and branches, available field working days, off-farm labour (fractional or in integers)
Temporal resolution of simulation steps towards baseline scenario	Instantaneous	Instantaneous	Instantaneous	Yearly, monthly
Machinery items considered	No			Multiple
Buildings considered				
Land markets	Land supply function for farm group UAAR	No	No	Lease and buying options
Emission accounting & indicator calculation				
Climate change adaptation		No	Yes	Scenario dependent
Environmental indicators	NH3, CH4, N2O, CO2, GWP[c], nutrient balance NPK	Intensification / extensification, pesticide risk, soil erosion, soil organic matter, crop diversity	e.g., Nutrient balance, nutrient losses	N- and C-emissions, N- and P balances, GWP, link to LCA with many indicators
Feed and fertilizer representation				
Feed activities	Tradeable and non-tradeable fodder activities	Tradeable and non-tradeable fodder activities	Tradeable and non-tradeable fodder activities	Herds, breeds, feed regime, feed, year, months
Feed constraints	Energy, protein, min/max shares			
Attributes of fertilizing activities	Crop, intensity, fertilizer	Constant intensities	Crop, intensity, fertilizer	Crops, plot, tillage, intensity, fertilizer, year, month
Temporal resolution & investments				
Multi-period optimization	No			Yes
Endogenous investment decisions				
Financial constraints				
Economic behavioural assumptions and calibration				
Objective function maximization	Farm income	Farm utility Including risk component	Utility maximization: gross margin in most applications	Maximization of discounted profit withdrawals plus returns from off-farm labour, after taxes. Stochastic setting: Several decision rules for risk utility possible
Model type	QP[d]	QP & MIP[e]	QP	MIP
Calibration approach	PMP[f]	PMP	PMP	Bi-level

[a] grazing, silage, bales, hay; by month.
[b] for animal intensity expressed as productivity and nutrient requirements (protein, energy).
[c] GWP: Global Warming Potential.
[d] Quadratic Programming.
[e] Mixed Integer Programming.
[f] Positive Mathematical Programming.

2017).

2.3. IFM-CAP

IFM-CAP is an EU-wide individual farm-level model which aims to assess the impacts of the CAP on farm economic and environmental performance. Its development by the JRC started in 2013 at the request of DG AGRI to enrich ex-ante CAP policy assessments with single farm modelling not offered by existing aggregate (regional, farm-group) models.[7] This reflects the increasing importance of farm-specific measures such as the Single Payment Scheme and greening measures asking for policy representation at micro level. A simplified IFM-CAP prototype version was finalised in 2015 (Louhichi et al., 2015), followed by an improved version in 2018 (Louhichi et al., 2018b).

IFM-CAP is a static positive mathematical programming model, covering more than 50 crop and animal activities and their interlinkage through feed supply and use. The primary data source of IFM-CAP is the individual farm-level data available from FADN, complemented by additional EU-wide data sources such as Eurostat and the CAPRI model database (Louhichi et al., 2018b). The model is applied to each of the over 80000 individual FADN farms, assuming that farmers maximize expected utility based on a constant absolute risk aversion specification, and subject to resource and policy constraints. Post-model reporting quantifies a set of environmental indicators, for instance, crop diversity, input expenditure intensity, and risk of soil erosion.

Like CAPRI-FT, IFM-CAP applies the same single model template to all modelled farms, which allows a uniform handling of all farm models and their results. Each farm model has hence an identical structure based on the same equations and variables, but model parameters and policy measures are farm-specific. No cross-farm constraints or relationship are considered, except during calibration where all farms in a NUTS2 region are pooled together to estimate behavioural function parameters (Louhichi et al., 2018b). Similar to CAPRI-FT, IFM-CAP applies a GGIG based user interface to configure and run working steps (raw-FADN data processing, construction of the model database, calibration, scenario runs). Reporting and visualization of the results is based on Qlik Sense[8] which is a web-based data-warehouse system that allows the user to take advantage of all the features of a business intelligence system providing services like data gathering, data storage, and data analysis. This includes features like 'drill down' and 'drill through',[9] visualizations, filtering, etc. (Maliappis and Kremmydas, 2016). Important applications of IFM-CAP cover the analysis of the future pathways for the European agriculture sector (M'barek et al., 2017), the evaluation of the impact of CAP greening (Louhichi et al., 2018a) and contributing to the impact assessment of the European Commission proposal for the CAP post-2020 (European Commission, 2018b).

2.4. FSSIM

The Farming Systems SIMulator (FSSIM) is a BEFM developed in response to Janssen and van Ittersum (2007), to assess economic and ecological impacts of agricultural and environmental policies and technological innovations as part of the SEAMLESS integrated framework (Louhichi et al., 2010; van Ittersum et al., 2008), where it was linked to CAPRI for price feedback and to bio-physical crop growth models to generate technology and yield varieties. This first operating version of FSSIM was a framework consisting of a management and a mathematical programming component to represent farmer objectives, risk, calibration, policies, current activities, alternative activities and was applicable to annual and perennial cropping and livestock (Janssen et al., 2010). Its agricultural management component delivers detailed information of required inputs (e.g., fertilizers, labour) and produced outputs (yields and externalities) to present the production possibilities surface of a farmer. Inputs and outputs of current agricultural activities (arable crops or crop rotations; perennials such as grassland, orchards, vineyards; keeping livestock) are specified based on surveys and databases operating on sampled farms across the EU-25, such as the FADN and SEAMLESS database. Alternative activity technologies are systematically generated using agronomic knowledge rules (Dogliotti et al., 2003; Hengsdijk and van Ittersum, 2003) but can also be linked to crop growth models. Its mathematical programming component is a comparative, static model with a non-linear objective function maximizing expected income considering risk aversion regarding prices and yields.

While the setup as part of SEAMLESS allowed a broad range of applications, it proved too data demanding to be kept operational without project funds. Therefore, a more flexible and less data demanding version was developed for specific data requirements, constraints and objectives. The new version also improves modularity and re-usability to allow optimizing a broader range of agricultural systems (Kanellopoulos et al., 2014). Its objective function can optimize any weighted linear combination of economic and environmental indicators covered by the model. A relational database helps to store information while a MS-Access front end is used to facilitate inputs and specify scenarios. For a more detailed comparison we refer to Tsutsumi (2015).

FSSIM has been applied to arable farming systems of representative regions of the EU and linked to EU market models to extrapolate results to the EU (Wolf et al., 2015). Other applications cover policy assessments in EU case studies (e.g. van Ittersum et al., 2008; Mouratiadou et al., 2010; Belhouchette et al., 2011) and China (Reidsma et al., 2012) as well as climate change scenarios and farm adaptation (Kanellopoulos et al., 2014; Reidsma et al., 2015). It was also used to assess impacts of climate change and greening on the performance of dairy farming systems (Gaudino et al., 2015; Paas et al., 2016). An application of FSSIM for developing countries and smallholder farming systems is available in Leonardo et al. (2018).

2.5. FARMDYN

The single farm model FARMDYN (Britz et al., 2016) allows simulating optimal farm management and investment decision under changes in boundary conditions such as prices, technology or policy instruments, for a wide range of farming branches (arable, pig fattening, sows, dairy, beef cattle including suckler cow-calf systems, biogas) in Germany and beyond. It is based on a model template for a fully dynamic or comparative-static bio-economic simulation building on Mixed-Integer Programming. The fully dynamic version can be extended to a stochastic dynamic model, combined with different risk behavioural models. Farm branches and other elements such as e.g. fertilization and manure policy restriction can be added in a modular fashion to the core model, as well as a module for large-scale sensitivity analysis. The model's default data and parameterization comprises detailed engineering data for Germany which cover field operations, a crop calendar for over hundred crops, detailed by tillage system, conventional versus organic farming and by plot size and farm-plot distance. The same data provider also offers matching data on yields, prices, direct costs for crop and animal processes and on machinery and stable costs. A bi-level

[7] The development of IFM-CAP was initiated by the workshop on 'Development and Prospects of Farm Level Modelling for Post-2013 CAP 2013 Impact Analysis' organized jointly by JRC and DG AGRI in Brussels on 6–7 June 2012 (Ciaian et al., 2013).

[8] https://www.qlik.com/us/products/qlik-sense

[9] 'Drill down' is the ability to go from a general view of a report to more specific layers of the data. For example, starting from some aggregated values of a result indicator at the EU level, the user can move to values of the same indicator at Member State, and NUTS2 level.'Drill through' is the ability to pass from one report to another while still analysing the same set of data. For example, while viewing the report for result indicator X for a specific Member State and farm type, the user can move to the report for result indicator Y for the same Member State and farm type.

estimation approach allows for automated calibration of the model against observed crop choices and animal herds (Britz, 2020).

The farming branches for dairy and cattle farming differentiate raising and fattening processes by month, grazing share and weight gains, and, where applicable, by month of calving and lactation period, and account for the possibility to consider cross-breeding and sexing (Pahmeyer and Britz, 2020). These options interact with multiple, seasonally differentiated grass land management options. A module describes in detail the measures of the German Nitrate and Water Framework directive (Kuhn et al., 2019). Arable farming can be depicted either by single crops in combination with maximal crop shares or crop rotations, both differentiated into tillage types, production system (conventional or organic) and intensity levels (Kuhn et al., 2020). FARMDYN further differentiates manure, related storage, and application chains.

Investments into a detailed machinery park, stables and other structures are depicted by integer variables, the same holds for the possibility to work off-farm. The model distinguishes on-farm labour needs for field operations, stable work, and management/maintenance. Management and maintenance work as well as differently sized investments in machinery and stables provoke increasing returns-to-scale in branch sizes and depict different labour-capital intensities endogenously.

FARMDYN was stepwise developed based on funds provided by research projects. It is currently maintained by a research unit at Bonn University and used, as well as extended, by several international partners. It is hosted on a revision control system, its coding follows guidelines and quality management measures include automated testing of the model on a larger set of test cases with reporting of differences in key results against previous revisions. Similar to IFM-CAP and CAPRI-FT, it features a graphical user interface (GUI) based on GGIG.

2.6. Summary of key features of the reviewed models

Table 1 reports in detail the key content-related features of the four reviewed models. It summarizes the models by the regional product coverage and technology representation, policy representation, production factors, emission indicator calculations, feed and fertilizer representation, temporal resolution and investment and economic behavioural assumptions and calibration. There is a clear dividing line between the first two models CAPRI-FT and IFM-CAP which capture the whole EU based on generally available statistics (FSS, FADN) and the more detailed models FSSIM and FARMDYN which are applied to case study farms for which surveys or specialized data sets, e.g. generated with crop-growth models, are necessary. Drawing on more differentiated data, they can offer more detail with regard to farm management and thus can generate richer and more diverse economic and environmental output indicators. This is particular the case of FARMDYN which can provide richer results for several output indicators such as for the investment performance, factor use and technology adoption. On the other hand, CAPRI-FT and IFM-CAP can deliver wider regional representation (i.e. at EU level) of the covered output indicators (e.g. land use, income, production, environmental indicators) as well as being better able to capture trade and market related output indicators like market price feedbacks, exports and imports (mainly CAPRI-FT). The four models cover the use cases discussed in the two reviews by Janssen and van Ittersum (2007) and (Reidsma et al., 2018) and also most features found in models applying MP discussed in these reviews. As such, Table 1 and Table 2 provide also a good overview of the current bandwidth and coverage of BEFMs, albeit some of the models in the reviews might cover, for instance, additional environmental indicators or policies.

In addition to the content features, model implementation features are also of interest with regard to the concept of a generic and modular BEFM as captured in Table 2.

Table 2
Comparison of models with respect to technical implementation features.

Feature	CAPRI FT	IFM-CAP	FSSIM	FARMDYN
		ICT aspects		
Programming language	GAMS	GAMS	GAMS	GAMS
Selection of farm branches	No	No	No	Farm branches as modules, policy blocks
Version control	SVN	SVN		SVN
Graphical User Interface	GGIG		VB-Access frontend	GGIG
Separation of model code and model database	Generally realized, some instances of 'hard-coded' parameters		Yes	Generally realized, some instances of 'hard-coded' parameters
Parallelization	JAVA-Based, governed by GUI		No	JAVA-Based, governed by GUI
		Data handling		
From raw data to database	Work steps in JAVA and GAMS	Several steps, using GAMS and R routines,	JAVA for intra model data exchange and Visual basic for scenario formulation	Several steps, using GAMS, PYTHON, and R routines
External data sources	Eurostat, FADN, CAPRI DB	Eurostat, FADN, CAPRI DB	Farm specific	Farm specific
Visualization of results	GGIG	Qlik Sense	case specific	GGIG, Web tool, PYTHON
Network				
Number of Institutions involved	2–3	2	1	2
Permanent staff	Yes	Yes	Yes	Yes
Training course/PHD course	CAPRI but not for FT	No	Yes	No

3. The design of a generic, modular BEFM

This section draws on the observations of the four surveyed models to discuss the desirable features of a generic and modular BEFM as outlined in Section 2. For this purpose, we focus on product coverage and technological detail, investment decisions and flexible choice of the objective function, as the most important features for a generic BEFM approach suggested by the reviews.

3.1. Typical application cases and desired generic model features

A generic BEFM should cover relevant application cases. Apart from purely methodological applications, Janssen and van Ittersum (2007) identified here two broad areas: the assessment of technological changes and innovations, and policy impact assessments. Examples for technology assessments range from the adoption of alternative farming practices, like soil preparation (no- or reduced tillage), fertilizing regimes (e.g., artificial and/or organic (Kanellopoulos et al., 2012)), investment in improved manure treatment and feeding practices in dairy production, to a complete change of the farm's orientation from non-organic to organic. This requires a sufficiently detailed representation both of technology and management. As expected, of the four models reviewed, the more technology rich models FSSIM and FARMDYN were used for these kinds of assessments.

With regard to policy assessments, the study by Reidsma et al. (2018) observes a wider range of analysed policy measures, reflecting the development and heterogeneity of EU agricultural policy. The majority of cases analysed changes in coupled and decoupled farm support schemes, production quotas and guaranteed prices, reflecting the major changes in the CAP. A generic BEFM hence needs to depict the relevant subsidization schemes. IFM-CAP, CAPRI-FT and FARMDYN focus so far on the schemes which are common across the EU, and not the Member State or even regional specific option measures under the CAP's second pillar. Additionally, policy measures with a focus on agro-environmental relations were addressed in the observed studies. Besides coverage of opt-in and command-and-control policy measures, this requires again an explicit representation of technology options and additionally, quantifying associated emission levels. The reviewed models deliver this in varying degrees. FARMDYN, for instance, comprises detailed emission accounting for greenhouse gases and different nitrogen compartments which are linked to different processes such as manure storage and application and grazing whereas FSSIM and IFM-CAP link emissions factors directly to the more granular defined production activities.

The adoption of alternative technologies is often linked to long-term investment decisions and might imply a complete farm re-orientation, such as to organic farming or to a different farm specialisation. Accordingly, decision variables in a generic model have to permit a distinction of intensity levels and related input- and output requirements. Of the four reviewed models, only FARMDYN permits endogenous adjustments of the farm's machinery and buildings endowments, and considers the timing of investments. The other reviewed models can only run scenarios in a comparative static way with changing endowments to identify potentially superior investments. However, no information can be obtained on the timing of the investment decision. Off-farm labour decisions are currently exclusively modelled in FARMDYN and very much depend on local information on off-farm alternatives. Together with intergenerational change, they are important in long-term modelling and often interlinked with production and investment decisions (Phimister and Roberts, 2006). Many, especially long-term decisions in farming are discontinuous, such as on investments in buildings and machinery, off-farm labour, or entering or exiting farm branches, a farming system or the farm, including opt-in policies like agri-environment measures (AEM)s. This can provoke returns-to-scale and requires a mix of fractional and integer variables. This has consequences for the equation structure as performant solvers for problems comprising integer variables require linear constraints and a linear or quadratic objective. CAPRI-FT is an exception here as it also uses non-linear constraints. In general, a generic approach should support multi-period investment decisions and hence several production periods. The implementation could allow also for a comparative static approach by parameterizing a single period that represents a steady state of investment decisions. However, if timing and sequence of investment decisions are important, only a multi-period approach can generate meaningful results. For a better transferability to other regions and farm types of multi period investment decisions, initial factor endowment (machineries, buildings etc.) and investments might come from default values, at least for specific farm types and regions. Alternatively, they might be treated as pure endogenous management or investment decisions, e.g., by allowing hiring or lending labour or renting in/out machineries, and hence avoiding the definition of initial farm specific endowments.

Reidsma et al. (2018) observe further that arable and dairy farming are most frequently modelled, followed by beef, perennials, and mixed farming. Focusing on specific farm types or production branches clearly reduced the development time and data requirements for a model applied in a case study. All four models reviewed in detail permit the analysis of a wide range of farm branches and related production activities. However, the review reveals important differences on how crop and animal production, mineral and organic fertilizer handling, feeding etc. are depicted, reflecting different typical use cases and data availability. Both for crop and animal production, the highest level of detail can be observed in FARMDYN which differentiates multiple intensities, tillage options, and different soil types for crops and sex, gender, age, intensity and breed for different types of animals. Due to less detail in EU wide databases, CAPRI-FT and IFM-CAP only differentiate animals by age and gender, while there is only one crop variant in IFM-CAP and two in CAPRI-FT (high-low intensity). However, the two models can be applied to all EU Member countries without additional data work as the underlying statistical sources are harmonized across the EU.

To address this trade-off between detailed production activities and regional coverage, a generic model should provide default values that allow deriving the technology coefficients in a bottom-up manner to analyse policy scenarios involving endogenous adjustments of input intensities and related emissions. In the case of FARMDYN, such default values are taken from datasets for individual field operations in Germany, or, as in FSSIM, from process models. This is an example for the use of a synthetic database, which is generated by running a crop-growth model over a range of input-output combinations to derive a dataset that permits parameterization of the BEFM for alternative cropping intensities. This approach seems rather attractive for the development of a generic BEFM but requires an interface to a process model with sufficient detail for inputs and a wide coverage of agro-ecological regions, at least in the EU, and a wide coverage of agriculturally relevant plant species. If detailed parameters are not available or not required, a less detailed representation of activities, activity groups, or technologies has to be an alternative option for model set-up and implemented in a generic manner. The approach in CAPRI-FT or IFM-CAP might be a good starting point for the development of such a low-resolution representation in the generic model to gain geographical coverage if detail on farming practices is not needed.

A further observation is that the majority of farm models rely on mathematical programming, i.e. they optimize an objective function subject to constraints (Hazell and Norton, 1986), often by maximizing profits to depict optimal farming decisions, as all four models discussed in detail. While 50% of the studies reviewed by Reidsma et al. (2018) maximize profits, 29% incorporate a measure of risk in the objective, or account for stochastic components of the decision-making process such as optionally in FARMDYN. This indicates that alternative specifications of the objective function, at least regarding risk and stochastics, are deemed relevant by model developers and users.

FARMDYN permits the specification of alternative decision rules in a stochastic setting, while in a deterministic setting, discounted farm withdrawals and other revenues, e.g., from off-farm labour are maximized. FSSIM maximizes a utility function, defaulting to the maximization of farm gross margins. Alternative specifications of the utility function are possible, as long as the objective function remains linear. IFM-CAP maximizes an expected utility function, accounting for expected farm income and its variance. Formally, a BEFM based on mathematical programming will always optimize one scalar, either a single-objective such as profits or a utility function which provides a linear or non-linear aggregation of multiple goals, potentially including environmental status or leisure. Other elements of decision making can be captured by constraints, such as depicting risk behaviour by a constraint restricting the probability of profits under a critical limit. In dynamic modelling, considering different financing options (equity, different loans) allows one to separate the individual discount rate of the decision maker from the market based one, an option considered in FARMDYN (see also Spiegel et al., 2020). A generic BEFM template should ideally allow flexibility in the choice of objective function (as found in FSSIM and FARMDYN) and switching between a comparative-static and a dynamic setting, and between a deterministic and stochastic one such as in FARMDYN.

These considerations drawing on the reviews of Janssen and van Ittersum (2007) and Reidsma et al. (2018) suggest the following minimum set of features of a BEFM to be sufficiently generic:

- Wide coverage of production activities to depict different farm branches

- Various technology representations: alternative input intensities for each farming activity with related detailed input-, output-, and emission coefficients
- Decisions relating to investments over a longer time-horizon, changes of farm specialisation and off-farm activities
- Coverage of relevant policies
- Alternative specifications of the objective function, e.g., to include risk preferences, other farmer's preferences, or cost of long-term capital goods

Fig. 1 depicts this concept of a generic and modular model. Its core comprises an objective function, variables and equations independent of currently covered farm branches, indicators, or policies. The structure of the core model should permit alternative specifications of the objective function to capture specific farmer's preferences. Such a core model could encompass the calculation of revenues, costs, labour and machinery requirements, cash flow, taxes, household withdrawals, investment requirements, and related constraints. Farm branch modules ('Dairy' and 'Arable' in Fig. 1) cover branch specific constraints, such as land availability by soil type, crop nutrient requirements, and crop rotational constraints for arable farming, as well as feed requirements, stable places, and herd dynamics for dairy farming. They comprise related decision variables such as acreages by intensity and soil type or fertilizer applications for arable farming, and herd sizes, feeding amounts, manure excretion, stable place use for dairy farming. Branch modules, depicted in the blue-framed part of Fig. 1 for dairy and arable farm branches, defines the variables required entering the core model such as output quantities and input requirements. The indicator modules, depicted in the blue-framed area of Fig. 1, quantify economic, social, and environmental indicators from the decision variables. These indicators can also feed into a multi-goal objective function or restrict the solution space. Policy modules define restrictions based on command-and-control measures or subsidies from opt-in schemes.

3.2. Modularity

The depicted modular structure is required to represent different case-study farms and policy scenarios, and to customize the objective function and activity-related equations as much as possible. In practical terms, this means that it should be possible to replace, activate, or omit blocks of equations and related variables, depending on the use case as core aspects of modularity.

Besides solving the model, the actual implementation of a generic BEFM covers data preparation, model set-up and parameterization, and reporting as depicted by Fig. 1, which are usually separated from model equations (separation of code from data). Particularly when relying on statistical sources, data preparation must deal with outliers or missing entries that can impair model execution, performance, and more so plausibility of results. This underlines that the generation of the model database is an integral part of the model workflow, particularly because it is instrumental for the model set-up and parametrization in a subsequent step before the model itself is solved.

Restricting data preparation, parameterization, model solving and reporting to the currently needed farm branches, farming systems or relevant policies greatly eases model application. A block of equations and variables with the related code-blocks for data preparation and reporting, for instance for dairy farming, can be jointly understood as a module if it can be switched off without impairing the use of the core model and other modules. The activation of modules can be data- or user-driven. Such a modular design is defined by Russell (2012) as:

"Modularity describes specific relationships between a whole system and its particular components. A modular system consists of smaller parts (modules) that fit together within a predefined system of architecture. Modules feature standardized interfaces, which facilitate their integration with the overarching system architecture. A key feature of each module is that it should encapsulate (or 'black box') its messy internal details […] to display only a consistent interface. The designers of modular systems are therefore able to swap modules in a 'plug-and-play' manner, which increases the system's flexibility." (Russell, 2012).

Flexibility in configuring a BEFM is required for a generic model. A modeller may not be interested in activating all aspects of a generic model for a given use case. Instead, modules directly relevant for the research question will be activated and others switched off, for instance by including a specific set of policies or an alternative objective function. Analysing policy effects on a potential farm exit might require a long-time horizon and the activation of modules relating to on- versus off-farm labour, equity use, and farm succession aspects. In contrast, for such an application, a monthly time scale related to detailed disaggregation of field operations might be switched off but might be required to assess agri-environmental measures. Such flexibility in model set-up keeps each instance of the model at manageable size and facilitates the parameterization from a case-study specific database.

Software engineering embraced modularization from the beginning and continues to conduct extensive research in this field (van der Hoek and Lopez, 2011). Quite early Parnas (1972) established the fundamental principle of reducing the information that a module opens for access, termed 'information hiding'. The related principle of 'low coupling and high cohesion' by Stevens et al. (1974) advocate for low dependence between modules (coupling) and strong dependence between elements inside a module (cohesion). 'Separation of concerns' as a further principle decomposes a computer program such that each module addresses different aspects of the problem at hand (Dijkstra, 1982). In the context of BEFMs, these principles lead to the following general advantages:

- *Transparency*: the model can be reviewed module by module, facilitating overall comprehension and quality control.
- *Maintainability*: Code and database updates of a module do not affect others.
- *Extensibility*: Modules can be extended or added to the core model without affecting others.
- *Distributed development*: Modellers focus on specific modules which eases coordination of coding efforts.

While desirable, achieving modularization for a BEFM is challenging. Cross cutting aspects/concerns limit the extent of low coupling, for example, most modules calculating indicators need information on all crop and animal activities. Conceptually, there is an unlimited set of possible modularizations. For instance, the yellow rectangles in Fig. 1 (or sub-divisions thereof) could be grouped into a large number of functional units, depending on pragmatic and conceptual considerations. Different viewpoints might suggest different organizations into modules, such as which data sources feed into which equations, domain knowledge of coders responsible for specific aspects, or the need to reflect regional detail in the equation structure, for instance related to policy implementation. Deciding on the number of modules and their delineation is hence a core design challenge. To advance here, the next section provides a more detailed review of selected BEFMs with a focus on modular design and generic features.

The four reviewed models show different degrees of modularization. Modules for 'database generation' and 'model statement' are distinguished in all models, see Fig. 1, to separate code and data. The database generation is usually only performed once for each case-study as this involves time consuming data work and possibly fairly complex statistical methods. A complete separation of code and data is still not fully implemented in any of the reviewed models, as numbers or references to specific list elements might still appear in equations, such as 'y = 3*x' instead of 'a = 3' and 'y = a*x', or "x['wheat'] = y" instead of "a = ['wheat']" and 'x[a] = y'. This is less the result of a design decision but often rather due to time shortage in project-based development, where ad-hoc changes of the model code were implemented and not revised at later stages, so that such blocks of code persist. Still, such observations

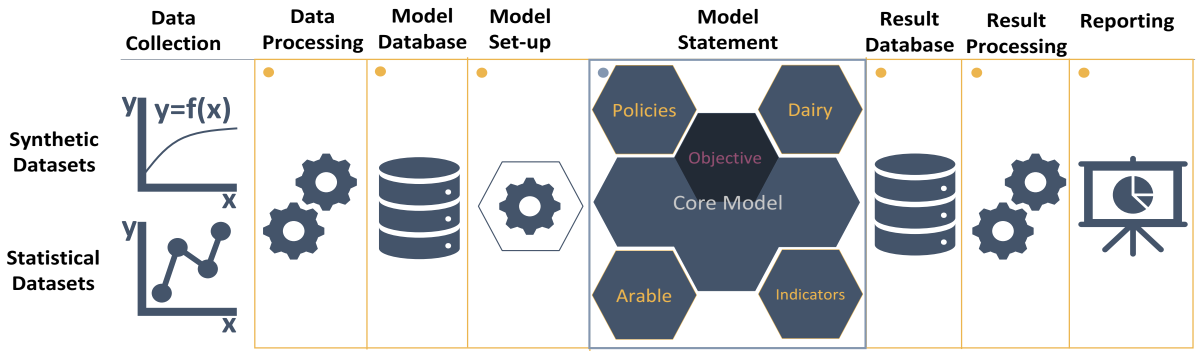

Fig. 1. Model Workflow from Data collection to reporting.

are the exception rather than the rule, and the models follow in general the principle to separate code from data. The possibility to parameterize a template model flexibly for new use cases, while ensuring the database fulfils certain minimum requirements, is a critical feature for a generic BEFM. However, this also implies that the same equations and variables will be used for all use cases, at least at the level of the core model. While this may not be problematic in some instances (accounting identities, bio-physical relations), the representation of policies or the calculation of environmental indicators may require further adjustments of the model code and are hence better placed within modules.

Such a modularization of equation blocks that are used in the model statement is particularly observable in FARMDYN, which is structured along functional units of code which can be arranged rather flexibly into a customized MP model for each farm instance. At the top-level, farm branches can be selected to add related blocks of equations to the core model. For instance, adding the dairy farming branch will integrate blocks of equations that govern herd composition, feeding requirements, and manure management. These modular blocks themselves can be replaced by alternative implementations as long as the input-output relations defining their interfaces with core model and related modules are maintained.

Exchangeable policy modules are also an important part of a generic BEFM to reflect case study specific implementation of measures. Policy modules can restrict the solution space and/or define subsidies as part of the objective, potentially depending on farm management choice in case of opt-in measures. This requires a generic approach to handle subsidies in the objective function. Policy modules might introduce constraints which restrict environmental indicators such as a soil-nutrient-balance as defined in the country- or region-specific regulations. These definitions of indicators might deviate to what the scientific state-of-the-art suggests. Indicators derived from legislation should hence be coded in the related policy module and kept separated from indicator modules that serve dominantly reporting purposes. If indicators enter the objective function, a modular choice of indicators requires a generic approach to handle varying lists of indicators.

The objective function can be regarded as a module itself. A purely profit-maximizing approach has been observed by Janssen and van Ittersum (2007) and Reidsma et al. (2018) for the majority of the reviewed models. Three of the four models we reviewed permit at least the inclusion of a farmer's risk preferences, either by weighing the expected profit against its variance in a comparative-static setting in IFM-CAP and FSSIM, or on demand in FARMDYN where different risk behavioural models can be used in a stochastic-dynamic programming framework. Apart from risk preferences, the objective function can include other factors that may influence a farmer's production plan. A typical example are preferences for leisure time and consumption of non-agricultural commodities in farm-household models (Singh et al., 1986). It is also conceivable that consideration regarding environmental outcomes of the farm plan influence the decision making process, which can be included by specifying multiple objectives, addressing economic and environmental aspects of the farm plan (e.g. Banasik et al., 2017). In all cases, the numerical solvers used for the optimization will require a scalar objective variable, so multiple objectives will have to be combined, which requires appropriate scaling and weighting of the sub-objectives. Furthermore, the choice of the functional forms used for specific objective has to respect restriction by the numerical solver, which would, for instance, require the linearization of some sub-objectives.

Validation is an important, albeit challenging part in a model construction process. As Hazell and Norton (1986) point out, the difficulty in validation of agricultural sector models stems from the availability of data against which a model can be validated. Validating a generic BEFM is even more challenging because farm-level data, other than accounting data found in some EU-wide databases like FADN, is scarce and model parameterization should rely on default values to address the trade-off between detailed production activities and regional coverage, as argued previously. Thus, the validation of some model components can involve a sensitivity analysis of the model solutions with respect to changes in parameters whose values have a high degree of uncertainty. Alternatively, validation can even be qualitative, focusing on the logic of a specific model component, and examining how reasonably it integrates with the overarching farm decision problem. Where data exists, validation often concerns only some specific model outputs, particularly production levels, which are closely linked to the questions that a BEFM is expected to answer as an ex-ante policy tool. This usually involves the calibration of the BEFM against observed output farm data, and/or can examine the forecasting capacity of the model against more recent (out-of-sample) data than what was used to parameterize the model, if such data is available (e.g. Kanellopoulos et al., 2010). All four reviewed models comprise code for calibration as an important feature of a generic model. IFM-CAP, FSSIM and CAPRI-FT draw on PMP which requires at least a non-linear objective function and relies on the first order conditions of the optimization problem to replicate the observed farm production decisions. More recent contributions to the literature combine PMP with econometric evidence on how input and output quantities react to changes in prices. This approach, which is implemented in IFM-CAP and CAPRI-FT, ensures that the calibrated model responds to parameter changes in a way that is consistent with real world observations and thus negates the requirement for sensitivity analysis with respect to price changes. However, calibration of a modular system is challenging, as a re-configuration by adding or replacing modules will likely impact the allocative response of the model or can even require a re-calibration. There are now also automated approaches to calibrate linear and mixed integer programs (Britz, 2020) which are for instance applied in FARMDYN.

Modularization mainly aims at, first, easier adjustments to different use cases, such as covering regional policies, and second, at model extensions, for instance, by integrating new indicators. According to the principle of information hiding, a module is defined by its task, such as determining feeding amounts at given herd sizes and component prices, but not by how the task is achieved or coded in detail. Accordingly, the module's definition includes the list of well specified inputs required from other modules and core model, and the minimum set of well specified outputs to be generated for others. This requires a clear and technically detailed documentation (symbol name, units, dimensions etc.) of the variables supposed to be defined endogenously by a module and of all variables exposed to other modules and the core model. According to the low coupling principle (Stevens et al., 1974), modules should interact only through these defined interfaces. Thus, a module should bundle as many functionalities pertaining to its task as possible (high cohesion). This includes not only the equations that a module contributes to the overall model, but also its parameterization and reporting.

Accordingly, a module of a generic BEFM should be broken in three code blocks: (1) its data preparation – to separate data from model code and avoid time consuming data preparation for each model run, (2) its equations which feed into the overall MP model statement, and (3) its reporting part. Its equations and related variables are at its core by providing the link to equations and variables of other modules. The equations also mirror how the task is performed in detail and therefore constitute its unique core. But a module might feature multiple implementations for data preparation to work with differently structured databases, and for reporting, for example, to provide rough overviews or detailed debugging reports, or to output different formats, such as spreadsheets or interactive web-pages.

With regard to the required data, a distinction between native and contributed modules is useful here (Fig. 2). By definition, a native module (the hexagons labelled: 'Module' in Fig. 2) can be always fully parameterized from the general model database, while a contributed equation module offering additional functionalities (the purple block of hexagons in Fig. 2) might require additional data which it must provide by own code for data preparation. The same holds for the reporting step.

Ideally, the general model database could serve any case-study using native modules only. Yet, EU wide databases such as FADN cannot provide the farm management detail required for a technologically rich generic BEFM. As a compromise, contributed modules should provide sensible default values in case the required information cannot be obtained from the data-processing steps (the purple database symbol labelled: '0' in Fig. 2). A case-study application can then code its own data driver to use a specific database which replaces default values.

In summary, the most crucial aspects for design and integration of modules in such a setting are the clear definition of obligatory inputs and outputs (interfaces) and ensuring that the equations in the module can be executed by providing default values for all parameters. This also implies that the technical documentation of core model and modules, and the development of protocols for contributor should receive particular attention from the very beginning if model development and maintenance is to be distributed across multiple teams with high staff turnover rates.

This already underlines that modularity comes along with challenges for the computational implementation. The example models above comprise tens or hundreds of thousands of code lines of which larger sections relate to data processing and reporting. The restricted language features of an AML like GAMS, used for all four models reviewed, ease learning but challenge code development and maintenance for such large-scale projects, especially if multiple developers are involved. Particular cases, where different variables and parameters are named similarly but refer to different contents (namespace conflicts), are difficult to handle in programming languages that do not allow for the distinction of namespaces. This requires additional synchronization efforts, for instance by establishing protocols for coding and model database (e.g. Janssen et al., 2009b) within the user community and by emphasizing the need for good code documentation.

Modularity also needs to reflect user-model interaction. Three of the models reviewed in detail (CAPRI- FT, IFM-CAP, FARMDYN) feature a GUI, all realized in GGIG, to facilitate, for instance, choosing the included modules or the database to use. An important question is to which extent a specific model configuration (farm branches, activities covered, specific policy implementation etc.) is driven by the database or defined by user interactions. Second, to what extent should the user be able to provide (or overwrite) data via the GUI, otherwise read from the model data-base, such as running specific prices, yields or values of policy measures. Third, should the GUI also cover such functionalities for contributed modules? If yes, how is this technically achieved and institutionally organized?

3.3. Software engineering

Past modelling work and related programming was often centralized in the hand of one core developer. This is impossible for developing a

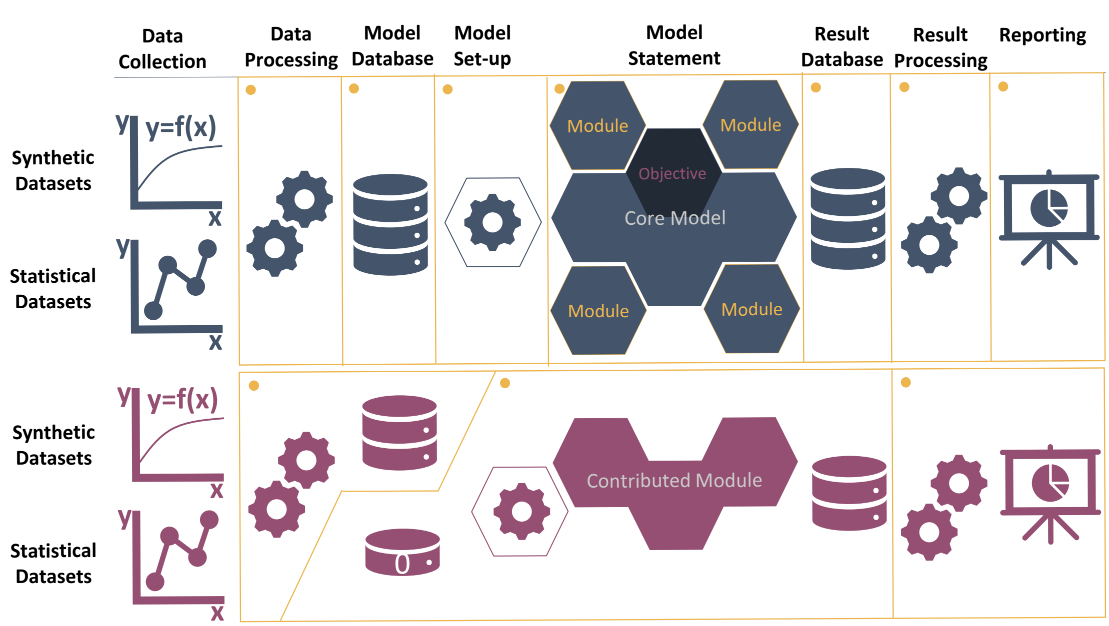

Fig. 2. Modular Setup of Core Model and Contributed Modules.

generic and modular BEFM where parallel efforts of many developers are needed instead. The typically project-driven development with potentially parallel projects changing and expanding code provides further challenges. A revision or version control system (VC) supports such collaborative work by keeping track of changes and to inform team members about them. Specifically, a VC allows tracking local (client) modification, branching off versions and reintegrate parallel code development. Systems such as Git[10] even support versioning local modifications without interfering with the master code. Besides FSSIM, all surveyed models reported using SVN[11] as VC system. But the ability of a VC is often not yet sufficiently exploited due to missing knowledge and skills by modellers who fear to destroy others' code work. An effective use of a VC, hence, needs investments in training, infrastructure, tools, and coaching.

In addition, clear standards and a separation for code-engineering as discussed above (interfaces, modules, structure, unit tests), code-programming (readable and trackable code, naming convention, revision control) and code-testing (compilation and execution test, unit tests) are essential to avoid intransparent and unreadable programming codes. This allows for traceable revisions, reduces learning costs, and supports an efficient communication between developers. Related standards must be agreed upon by the community. Particular focus should be on systematic testing, by providing test input data sets and expected outputs for each sub-module, known as unit testing. Testing is demanding in a modular and generic set-up as it needs to reflect different configurations of the BEFM and data sets. Detecting compile and run-time errors as well as unforeseen changes in outcome indicators requires therefore a larger suite of test cases.

The ultimate goal is to provide code which is intuitive and easy to read, surrounded by helpful comments, and is organized in small logical units, which can be independently tested. A challenge is that AML languages, like GAMS, have no object-oriented and function-based code logic. However, software like GGIG (Britz, 2014) can organize the code in small logical tasks and run them in a sequence. This design is an important step to a continuous integration (CI) approach, as an established practice of automating the integration of code changes from multiple developers. CI software, such as Jenkins,[12] automatizes the process of installation, compilation, execution, and analysis of test results. This allows to detect errors in coding and to indicate related code revisions on an automated basis. However, if the model is complex and the execution time high, a continuous integration for each code update might not be feasible. Instead, release cycles with a wider time window might be useful. The release can be deployed and maintained independently from the core development. To summarize; version control, testing strategies and continues integration are important aspects of quality management and at the same time document changes accordingly.

3.4. Developer and user community

As observed by Janssen and van Ittersum (2007) and Reidsma et al. (2018), the development of a BEFM is often carried out by individual teams and usually remains use case-specific, thus impairing the possibility to re-use existing tools and to exploit the potentials of shared maintenance and development within a larger user community. The reviewed four models are to some extent an exception as they are already used by multiple teams and were applied for a wide range of use cases. Still, the current number of users is rather limited, compared to modelling systems used in other economic domains, like general and partial equilibrium analysis. We review here some success stories of economic template models with a larger network of users to identify some of their characteristics that were conducive for their widespread use and could help to steer the development of a generic BEFM.

An outstanding example is the Global Trade Analysis Project (GTAP) Standard Model (Hertel, 1997), a global multi-regional Computable General Equilibrium (CGE) model. Its success roots mainly in providing a global database which comprises both benchmark data and behavioural parameters fitting to the economic simulation model. Its widespread use is fostered by yearly paid for on-line and class-room courses on methodology, code implementation and model application. The GTAP consortium supports networking further with its yearly conference, where awards are granted for various types of contributions, and, since recently, its peer-reviewed journal. GTAP is managed by a consortium which comprises also major sponsors, mainly international organizations and governments which have an interest in database and model maintenance for policy impact assessments. Further funds are generated by licensing fees of the database (not the model). However, contributors of national data receive the full database for free. Compared to a BEFM with a focus on Europe (or at least moderate zone production systems), the potential GTAP user community is much larger as the model is global and covers all sectors of the economy. The GTAP center which maintains the database is also the main development point for the core model and its variants.

Interestingly, modularity was a lower concern of the GTAP community as the various model variants produced over the years, e.g., with a focus on bio-fuels and land use, multiple households or international migration, are not directly compatible to each other. MAGNET (Woltjer et al., 2014) and CGEBOX (Britz and van der Mensbrugghe, 2018) are modular CGEs drawing on the GTAP database und family of models. Modularity in this type of models faces similar challenges as in farm scale models since all equations have to be solved simultaneously, and not as in bio-physical models recursively in space and time.

CAPRI, of which the FT layer was presented above, is now maintained for more than 20 years. First major development steps, including database updates, were funded by three large EU projects. Since then, the network around CAPRI has assigned responsibility for model parts (modules) to developers in different institutions in a kind of quid pro quo contract. Support via the iMAP platform (M'barek et al., 2012) is another crucial factor to let CAPRI survive. Regular annual meetings and trainings introduce newcomers to the model and allow developers to present new features. The template structure of CAPRI eased its application to a growing EU while expanding in parallel its database proved challenging due to partly missing official statistics. CAPRI is to some degree modular, for instance, its global market and the supply side models can be used independently.

The IFPRI Standard CGE provides an example of a model template not linked directly to data work. Its success roots in well commented GAMS code, a standardized and well-defined layout for its input data in the shape of a Social Accounting Matrix (SAM), detailed manuals covering algebraic model formulation, exercises as well as standard scenarios for testing of model behaviour (Löfgren et al., 2002). All these factors, also found for the other two examples, can contribute to the success of a model template, as well as providing data such as in case of GTAP and CAPRI.

It is clear that the organisation of a community is essential to establish an operational BEFM. The organisation should enable developers and users to accumulate domain knowledge in building parameterizing and applying the BEFM. To achieve this, the community needs to define the thematic domain of the community, common standards as software engineering rules and actions of the community (see Fig. 3). At the same time the organisation should be flexible enough to adjust the thematic field to meet interests of new participants without moving too far away from the initial agenda. It could be conceivable that the native modules (see Fig. 2) in which all potential participants might have a common interest, defines the thematic domain of the community, and hence the areas where standards and actions are setup. The surveyed bio-economic models and their developer teams are hosted

[10] https://git-scm.com

[11] https://subversion.apache.org/

[12] https://www.jenkins.io

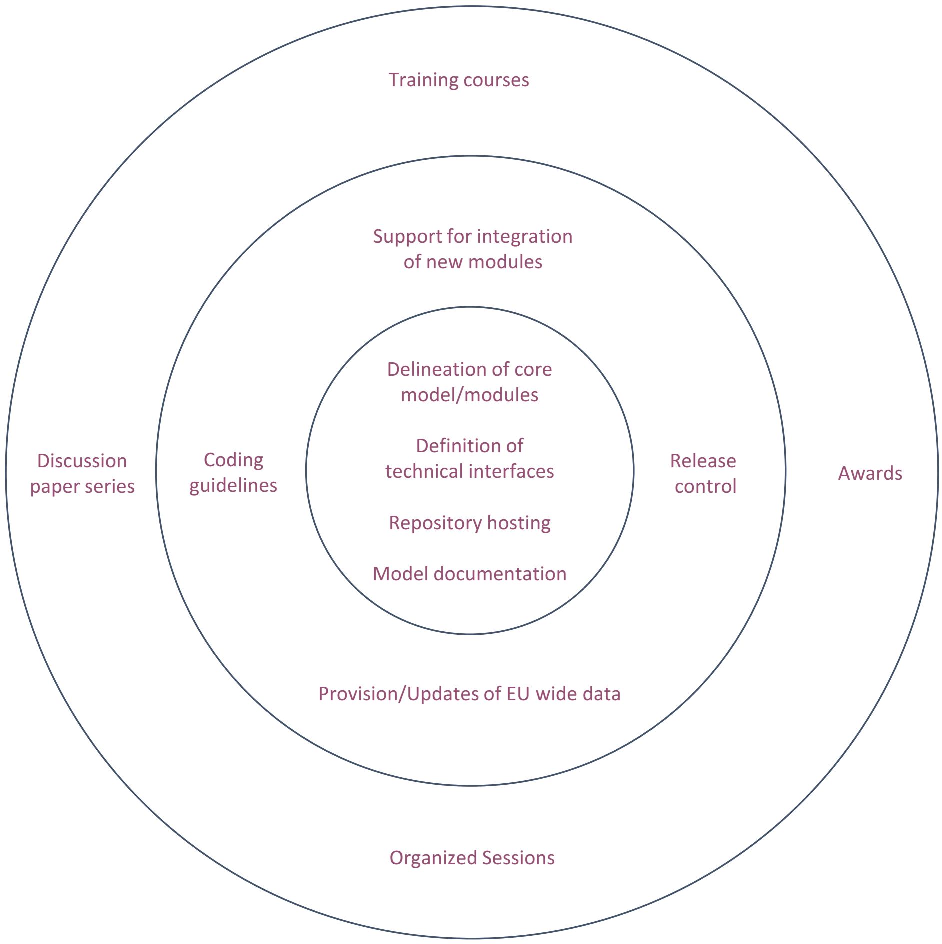

Fig. 3. A Hierarchy of Actions to Build a Network of Model Users and Developers.

mainly in public research institutions, i.e., governmental research institutions, European organizations or universities. This outlines the pool of potential and initial participants for a BEFM community. It covers researchers or developers of public research institutions, who use the tools and the knowledge for providing reports to the government. Such institutions might also provide in-kind support in the form of server facilities, web-hosting and other infrastructures. Another group of participants use the community to advance their academic qualification and/or to get involved in projects in this field. They are important as a source for innovation and for educating new staff. Given the differences in backgrounds, the network needs to accept different levels of participation. There might be a core group, maybe temporarily elected, who participate regularly, whereas others follow the activities but do not have an active role. As all actions are provided at a voluntary basis, as they share the same interest or passion, it is a kind of community-learning or community of practice approach, in contrast to a hierarchal organized committee or cooperation. In pursuing the goal to provide a core BEFM, members engage in joint activities and discussions, help each other, and share information. Given that most developments are financed by public funds, the community should be open, but possibly expect the provision of certain inputs, like solutions of actual problems in the code and in the concepts, sharing knowledge via platforms, creating new modules, publishing papers, or organizing meetings and conferences.

3.5. *Ensuring usability, longevity and related funding*

The network around a model reflects its usability, with easy application to new case-studies being a key factor. This asks for provision of default values for core modules, links to EU wide databases such as FADN, and clearly defined requirements for case study specific information. An up-to-date documentation including a user-guide, potentially accompanied by training videos, reduces learning costs for newcomers. Coding standards detail how the modular design is supported by namespacing, documentation guidelines, etc., to reduce coding costs and foster shared maintenance. The reviewed models offer a GUI to select data and model features and perform runs. IFM-CAP, CAPRI-FT and FARMDYN draw on the same GUI Generator (GGIG, Britz, 2014) which comprises a report generator, but additional reporting facilities and exports of results in different formats increase usability further.

All these activities require substantial resources, not factored into projects focusing on model application. General funding mechanisms remain a limitation: they favour developing new tools over existing ones, if existing ones are not regularly updated and maintained and/or too complex to be used or not suitable to be adjusted to the question at hand. Maintenance relies often on small teams at academic institutions facing high staff turn-over linked to project-based hiring. Hosting model teams at government institutions can ensure more continuous funding and a more stable team, such as in case of the iMAP at JRC which comprises CAPRI and IFM-CAP. However, full open access and open source is essential to benefit the entire scientific community. Otherwise, developments paid by public funds generate (later) private rents from restricted access. Open access fosters a growing network of users which might develop specific modules or focus on model application. Besides attracting dedicated funds for maintenance, the network of model developers and users can agree to devote a certain share of each project either in kind or in cash to quality management and maintenance. This requires a legal entity managing the common resources and to ensure that all users contribute. Open-source and open-access can provoke free-riding problems as no user can be forced under that licence model to contribute to model maintenance. The networking activities are summarized in Fig. 3 where those in the inner circle are immediately required for the basic setup of the model itself, while the outer circles comprise those needed for fostering a growing network. The mentioned GTAP network, for instance, provides all of these services to the user community, including training courses, the possibility to publish ongoing work during annual conferences, and awards. In the case of CAPRI, the network takes responsibility for the two inner circles, plus annual training courses for new users.

4. Conclusions

Following up on reviews by Janssen and van Ittersum (2007) and Reidsma et al. (2018) which advocated the development of a generic and modular BEFM to be developed and maintained by a larger community, we develop conceptual guidelines for the content and design features of such a modelling tool and review potential candidate models. This study complements existing reviews by proposing a pragmatic operationalization of the terms 'generic', 'modular', and 'network driven' and by reviewing four established models for CAP impact assessment in this respect. The four BEFMs (CAPRI- FT, FARMDYN, FSSIM, IFM-CAP) differ in detail and data requirements but have in common that they are all applied repeatedly over a longer time, comply to varying extents with modular design principles, are generic in the sense that a wide range of use case can be covered, and have an established user and developer community. Important elements of modularity in this context are encapsulation of details, low coupling, and high cohesion, i.e., restricting module interdependencies, and delineation of modules with separate aspects of the modelled farming system, such as decision drivers, farm management, investments, indicators, or policy measures. In these respects, separation of code and data is followed quite stringently by all four reviewed models, but further elements such as exchanging blocks of equations to better represent the requirements of alternative case studies detail are not yet very common. We suggest a design pattern with clearly defined interfaces between the different modules and a core model, such that modules are interchangeable e.g., with regard to policy and technology. The call for a generic model also requires the objective function to be exchangeable (profits, risk, multi-criteria) and a separation into different farm branches is desirable. Clearly, some default implementation of modules (equations and parameters) must be provided and ideally, drivers to EU wide database such as FADN provided, to reduce data collection needs in case study application.

The development of such a generic and modular BEFM will probably draw on (a potentially restructured version of) an existing model, integrating aspects of others. It requires a clear strategy for further maintenance as many tools never made it beyond the first development phase and a one-off application. This strategy must cover guidelines for model extensions by new modules, and actions to expand the user network such as providing a clear documentation, ideally in the form of training videos/courses or organized sessions at conferences. A release strategy and distributing early coding efforts across multiple teams with a clear distribution of responsibilities can foster its survival. To facilitate putting in practice this strategy, which may potentially lead to a successful development of a generic and modular BEFM, the collaboration among the modellers needs to be initiated and sustained (ideally led by a dedicated coordinator) to exploit the existing human capital in the field. Further, this needs to be supported by demand for the model application from the policy makers' side to give purpose to the whole project and to make it financially sustainable.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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