Enhanced modelling of sustainable food and nutrition security: the agri-food commodity and nutrient flows and the food supply chains

Deliverable No. D9.4

SUSFANS DELIVERABLES

Gema Carmona-Garcia, Adrian Leip, Franz Weiss (JRC), Peter Witzke (UBO), Monika Verma, George Philippidis, Marijke Kuiper (WEcR)

This deliverable describes the enhanced modelling of agri-food commodity and nutrient flows and representation of the food supply chains and markets in economic models.

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DELIVERABLE SHORT SUMMARY FOR USE IN MEDIA

This deliverable shows enhancements performed in the SUSFANS models with the aim to improve the representation of future dietary changes. If we could induce certain dietary changes, such as a reduction of meat consumption or a reduction of food waste in households, are our tools suitable for estimate the impacts of those changes? Would we be able to calculate changes in nutrient deliveries of those new diets and their impacts on water/air pollution or greenhouse gas emissions? All these questions are extremely relevant in the policy debate, and their answer helps to find the best way to go for the future food system.

Here we focus on two models which have been tailored to support policy design: the agro-economic model CAPRI, which represents the agricultural sector with great detail on agricultural production in the EU countries; we improved the representation of post-farm food processes and food waste, as well as the environmental impacts from household waste water. Secondly the global economic model MAGNET was extended to include consumer food waste responding to price and income changes and to allow for imperfect competition in selected food chains.

The enhancements have made both CAPRI and MAGNET capable of better responding to the questions on nutritional and environmental impacts of diets. It should be noted, however, that in testing some developments proved to be too cumbersome to be included in the main model body compared to the improvement of results. In addition, efforts should still be put on improving data, which is not always available at the proper scale and sometimes is based on estimations and extrapolations.

TEASER FOR SOCIAL MEDIA

Responding to the debate on nutritional and environmental sustainability of future diets SUSFANS aims to develop and assess future dietary options. To do so, we count on a set of existing models which cover the production of agricultural goods and the food market system. However, further detail on specific issues is needed in these models to allow for enhanced specification of dietary scenarios, notably: an improvement of the representation of food losses and waste along the food chain, of post-farm food processing for some food items, of environmental impacts of household waste and on imperfect competition in food markets.

In this paper, we describe these modelling improvements to assess which ones are worth putting efforts on. The exercise has also revealed the need to invest in better data.

ABSTRACT

Deliverable 9.4 describes improvements in the SUSFANS modelling framework which allow to better capture important elements for assessing food and nutrition security and environmental impact of diets. In particular, we focus on CAPRI and on MAGNET models to improve the representation of nutrient flows along the food chain and of food price transmission in markets, respectively.

Improvements in CAPRI include the detailed representation of food waste and losses and the addition of several 'modules' which represent some important post-farm processes which can be relevant for one or both of the dimensions studied in SUSFANS: the nutrition security and the environmental impacts of diets. Among the post-farm processes, we identified several elements which could be relevant, and for each of them we built a 'module', that is an extension of the CAPRI model that we envisage as a prototype which is run independently for the moment, but which could be later on added to the current model according to the results we get.

Among the post-farm elements, we identified the following relevant ones:

1) *Cereal processing:* it represents the milling process and allows to specify nutritional values of the different products obtained from milling, as they could differ from nutrient values of the raw grain, which are the ones reflected now in CAPRI. The cereal processing module applies to cereals used for human consumption. For each type of cereal, we obtain wholegrain flour, white flour and bran. We identify their shares and we specify nutrient contents, with special focus on protein, given its relevance for human nutrition and for environmental pollution. We assume that most of the bran obtained is used for feed. With all these assumptions, estimated the quantities of each milling product produced in each country, their destination, and we recalculated nutrient contents of cereals used for food and cereals used for feed.
2) Slaughterhouses: it models product transformations taking place from the carcass arriving to the slaughterhouse to the products obtained after the rendering process. The output of the module are the products which are actually going to be sold for human consumption, for feed or for industrial uses. A detailed description is done of the different co-products/by-products obtained from the animal and their uses. Nutrient contents are specified to allow for the identification of nutrient flows. We also take greenhouse gas emissions from animals and allocate them to the different animal products and to their different uses.
3) *Post-farm food waste:* current CAPRI configuration includes some rough estimation of food losses in the farm and a 'losses in the market' component which is not precise and does not reflect where exactly waste is generated along the food chain. Efforts have been put here to improve waste representation, by explicitly including losses in the retail and household sector, based on a FAO study (Gustavsson et al., 2011). This changes allow a more precise nutritional assessment and better monitoring nutritional intake.
4) *Household waste water*: it is a simple module where we estimate nitrogen spills to water in domestic sewage systems for each member state and the nitrogen greenhouse gas emissions from sewage water and treatment plants. Emissions are calculated using default IPCC methodology and emission factors, while activity data is taken for statistics and literature. For the estimation of emissions, we specify the access of rural and urban

population to different types of sewage treatment plants, which have different nitrogen recovery rates and different associated emissions.

With the described changes, we address some important processes and all steps in the food chain. Results show that nutritional changes specified in the cereal module can be relevant not for all, but for some of the cereals (wheat, rice), and that current nutrient values used in CAPRI may need to be reviewed.

Regarding the slaughterhouse module, we chose economic allocation as the best method to split environmental burdens among by-products and we calculated the share of emissions removed from meat towards other by-products. Results provide allocation factors that can be incorporated in CAPRI for the distribution of emissions among animal products and uses. In addition, the module provides interesting outcomes in terms of products inside the human consumption pool. In particular, we consider that the shares of pet food and processed food could be interesting to consider in further developments of CAPRI, for a more detailed household module.

Concerning the post-farm food waste improvements, it adds important information for the assessment of the combined effects of diets on nutrition and on the environment. Although more precise data would be desirable, current estimations already constitute an improvement of the model compared to current CAPRI data.

The household waste water module, in turn, is also providing relevant information for the assessment of environmental impacts of human consumption. It is a good first step but, for the assessment of impacts of dietary changes, additional data should be incorporated.

Parallel to the CAPRI developments the macro-economic MAGNET model is enhanced with two modules: (i) consumer food waste and (ii) imperfect competition. Since the available food waste data are mostly incomplete and their accuracy is questioned, food waste data is imputed and used to estimate an income/affluence elasticity of consumer food waste. These waste elasticities, just like consumption elasticities, are found to be high for developing countries and taper off as nations become richer. In other words, as developing country incomes grow closer to high income countries so does their consumer food waste. These income elasticities of waste are then used in the development of a new consumer food waste module in MAGNET.

Computing consumption as the residual after accounting for waste in consumer purchases, while intuitively appealing, adds little to the analyses of how changes in waste affect the supply chain. We thus proceed by a more elaborate representation of waste decisions parallel to consumption decisions. This specification allows a consistent assessment of changes in consumer food waste on both consumption of food and the upstream food system implications. It has however some restrictive assumptions on the waste decision-making. Two alternative approaches are outlined which may overcome these limitations but require data not currently available.

The second module which has been added to MAGNET is imperfect competition both in domestic and foreign markets. Building on existing developments we developed an imperfect competition module which accommodates firm productivity heterogeneity. The newly developed MAGNET module allows to include either the Spence-Dixit-Stigliz-Krugman (SDSK) approach of love of variety and heterogonous firms or the further extension of this model with self-selection by export routes drawing on the work of Melitz. With product varieties produced by heterogeneous firms we need to account for market power and thus abandon the standard assumptions of perfect competition and price transmission for the sectors where varieties and firm heterogeneity is important.

Both SDSK and Melitz improve on the inability of the Armington approach to deal with structural changes in trade patterns at the 'extensive' margin (i.e., output expansion along new export routes following trade liberalisation) in standard CGE and thus MAGNET applications, but only Melitz explicitly models firm self-selection by export routes based on heterogeneous productivity potentials by firms within an industry. The imperfect competition module in MAGNET thus increases the capacity of the model to capture market power in domestic markets as well as development of new trade routes missed by the Armington approach.

A key challenge with either SDSK or Melitz specifications is the calibration of the additional equations which are a key driver of the model results. Apart from the usual difficulties in constructing a consistent global dataset from disparate national sources this kind of information however becomes more sensitive the higher a sector is concentrated and thus the easier it is to trace data back to individual firms. Data on fixed versus variable costs to deduce the mark-up applied by companies is even more sensitive and therefore unlikely to become available in a way suitable to calibrate a global CGE model like MAGNET.

Simplifying assumptions on the fixed cost driving firm heterogeneity, keeping labour and capital from other inputs, allows calibration of the imperfect competition module but may conflict with the need in sustainability assessment to capture substitution between capital and energy. A final note on the connection to diets is in place. Whereas in parallel tasks working on enhancing the ability of the demand side in MAGNET to capture more detail in products (see D9.2) there is no obvious connection to the varieties in the imperfect competition module. Due to the simplifying assumptions in the calibration the additional product varieties in the imperfect competition module to not way in nutritional content. While not through a link with varieties, accounting for imperfect competition does affect price formation and income developments both of which affect consumer purchasing decisions and thus diets. For example, a smaller price decline when accounting for imperfect competition in assessing the impacts of milk quota will, ceteris paribus, also mute the increase dairy product consumption.

1. INTRODUCTION

The main objective of this deliverable is to contribute to an enhanced capacity to model scenarios of food and nutrition security in the EU. Using CAPRI and MAGNET models, we intend to improve the representation of the agricultural commodities and the nutrient flows along the food supply chain, as well as the improvement of the representation of the food markets. Deliverable D9.4 builds on the concepts and data described in D 3.3, here focusing on how these concepts could be included in the CAPRI model. The inclusion of the post-farm nutrient flows in CAPRI will provide a representation of the full food chain and will allow scenario simulations which take into account all stages in the food chain.

The first part of the deliverable describes improvements done in the CAPRI model, in particular the addition of some post-farm elements and the incorporation of food losses and waste along the food chain, all of them aiming to better represent nutrient flows from the production to the consumer and to the environment, improving the capacity of the model to capture some elements of the post-farm food chain that can be relevant for nutrition security and environmental impact of diets. This will allow afterwards to simulate and assess the impacts of alternative future diet scenarios.

The inclusion of the cereal processing module was motivated by the fact that nutritional values of white flour, bran and wholemeal flour differ and we wanted to understand how relevant those changes are in terms of human and animal nutrition. A bit different is the case of the slaughterhouse module, where the reasons to develop it were more related to the fact that high environmental impacts are usually attributed to meat production. We wanted to assess to what extent the situation would change if we distribute those burdens among the livestock by-products. Another key development for the SUSFANS project is the enhancement of the post-farm food waste representation, which will allow the simulation of waste reduction scenarios in a more sustainable future system. And finally, to complete the whole picture of the food chain, the household waste should ideally be included in the scenario assessment, in particular for the accounting of the environmental impacts of the food system.

Parallel to the CAPRI developments the macro-economic MAGNET model is enhanced with two modules: (i) consumer food waste and (ii) imperfect competition which are presented in the second part of the deliverable.

The current set-up of the MAGNET model captures consumer purchases. In the presence of consumer food waste purchases may differ considerably from consumption. Accounting for consumer food waste is highly relevant for both assessing nutrition and sustainability. Nutrition calculations should be based on intake and purchase data. These are however not available in a consistent and global database as required for inclusion in MAGNET. We therefore impute a waste income elasticity allowing a first, although still rough, estimation of wasted and consumed food purchases. Apart from enhancing MAGNET's nutritional assessments, especially in combination with the new nutrition module described in D9.2, tracking changes in consumer food waste also allows an estimate of the associated resources needed to produce the wasted food. This provides both an estimate of the sustainability impact of consumer food waste as well as the scope to reduce pressure on natural resources by tackling waste.

Accounting for imperfect competition enhances MAGNET's ability to track the importance market power on price transmission and trade flows. Building on existing work we include a new module in MAGNET offering a choice between two types of imperfect competition. Both Spence-Dixit-Stigliz-Krugman (SDSK) and Melitz improve on the inability of the Armington approach to deal with structural changes in trade patterns at the 'extensive' margin (i.e., output expansion along new export routes following trade liberalisation) in standard CGE and thus MAGNET applications, but only Melitz explicitly models firm self-selection by export routes based on heterogeneous productivity potentials by firms within an industry. Calibration of either approach is severely hampered by the available data and the necessary short-cuts do not combine well with sustainability nor nutrition assessments.

2. POST-FARM FOOD CHAIN IN CAPRI

2.1. CAPRI model

The Common Agricultural Policy Regionalised Impact Modelling System (CAPRI) is a global agricultural sector model focused on the EU, with a detailed supply module covering EU 28 plus Norway, Turkey and Western Balkans, and a more general market module representing the world agricultural market (Britz and Witzke, 2014). It was designed to evaluate ex-ante impacts of the Common Agricultural Policy and trade policies on production, income, markets, trade and on the environment. CAPRI represents the agricultural production (crops and livestock) up to the farm gate, but at present it does not deal with products obtained after slaughtering.

CAPRI database contains a series of activities, which demand some inputs and produce some outputs (a physical relation is established with the input and output coefficients). For those inputs and outputs, market prices are specified. The activities provide an income which depends on input and output prices and on the activity level. Table 1 shows the type of information contained in CAPRI.

Table 1: Input and output data contained in CAPRI

	Activities	Farm and market balances	Prices	Positions from the EAA
Outputs	Output coefficients	Production, seed and feed use, other internal use, losses, stock changes, exports and imports, human consumption, processing	Unit value prices from the EAA with and without subsidies and taxes	Value of outputs with or without subsidies and taxes linked to production
Inputs	Input coefficients	Purchases, internal deliveries	Unit value prices from the EAA with and without subsidies and taxes	Value of inputs with or without subsidies and taxes link to input use
Income indicators	Revenues, costs, Gross Value Added, premiums			Total revenues, costs, gross value added, subsidies, taxes
Activity levels	Hectares, slaughtered heads or herd sizes			

Secondary products		Marketable production, losses, stock changes, exports and imports, human consumption, processing	Consumer prices	

There are three basic identities linking the different elements of the data base:

1) Total input use (GROF or gross production/gross input use at farm level) can be derived from the input and output coefficients and the activity levels:

$$GROF_{io} = \sum_{j} LEVL_j \cdot IO_j$$

Total production in the farm (GROFio) is equal to the sum for all individual activities j of the input-output coefficients times the activity level of j.

2) Farm and market balances:

$$GROF_{io} - SEDF_{io} - LOSF_{io} - INTF_{io} = NETF_{io}$$

$$NETF + IMPT_{io} = EXPT_{io} + STCM_{io} + FEDM_{io} + LOSM_{io} + SEDM_{io} + HCOM_{io} + INDM_{io} + PRCM_{io} + BIOF_{io}$$

Farm balance positions are: seed use (SEDF) and losses (LOSF) on farm (only reported for cereals) and internal use on farm (INTF, only reported for manure and young animals).

Net trade on farm (NETF) plus imports (IMPT) defines total resources, which must be equal to exports (EXPT), stock changes (STCM), feed use on market (FEDM), losses on market (LOSM), seed use on market (SEDM), human consumption (HCOM), industrial use (INDM), processing (PRCM), and use for biofuel production (BIOF).

3) Value of the EAA in producer prices (EAAP):

$$EAAP_{io} = UVAP_{io} \cdot NETF_{io}$$

It is defined as sold production or purchased input use (NETF) in physical terms multiplied with the unit valued price (UVAP).

The CAPRI model represents food production up to the farm gate, plus product flows in the market (imports/exports, biofuels, and product sold to industry). It does not reflect the whole flows along the food chain. Based on the conceptual framework presented in deliverable D 3.3 (Carmona-Garcia and Leip, 2017), we propose some additions to the model in order to capture a comprehensive view of mass flows in the food system. Figure 1 shows the structure of the CAPRI model, with all the elements of the model and mass flows between them, as well as the proposed post-farm additions.

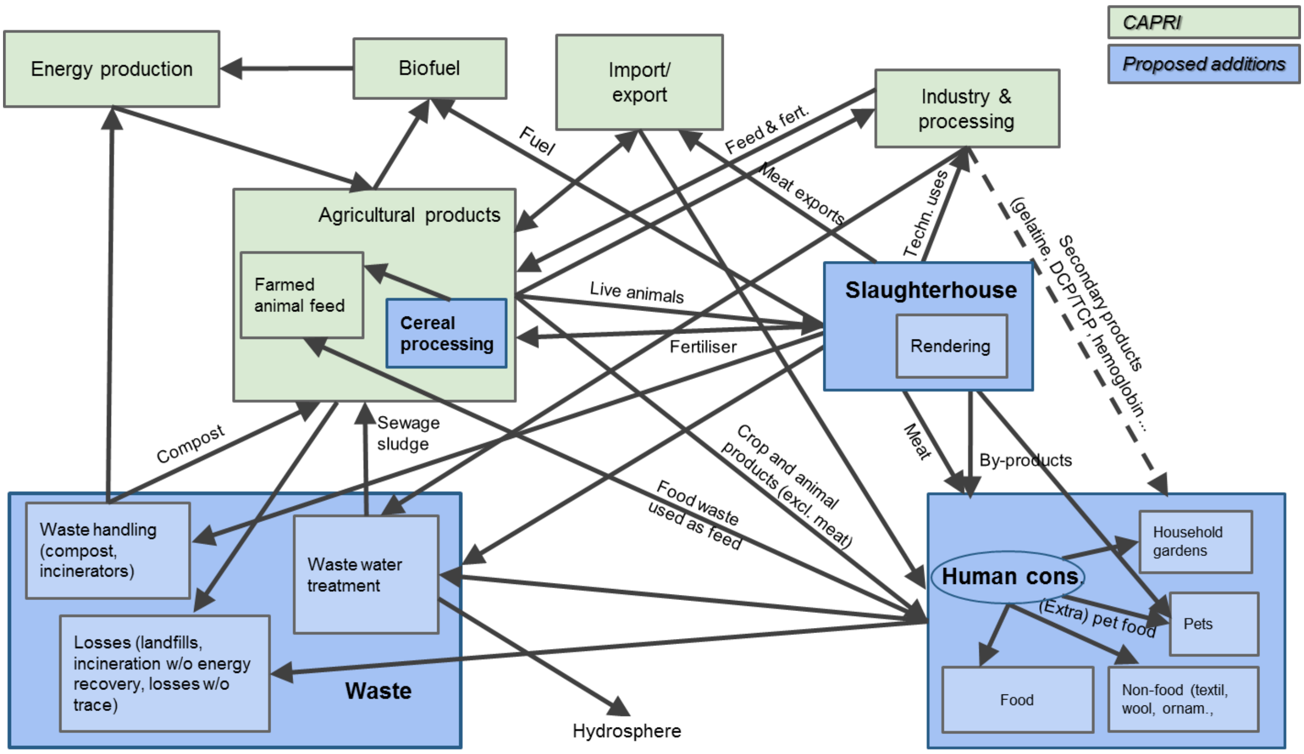


Figure 1: Schematic representation of CAPRI elements (in green) and proposed additions (in blue).

Among these proposed additions, we will focus on the cereal, the slaughterhouse and the household sewage modules and will analyse how the new elements could be incorporated in the model.

2.2. Cereal processing module

A high share of cereals destined to human consumption are processed after harvest, resulting in flour and by-products whose nutritional values differ from the original grain. Additionally, those by-products are sometimes used elsewhere, such as for animal feed. We propose including a cereal processing module at the farm gate, representing the milling process, where the input would be the grain harvested in the farm and the output would include white flour, wholemeal flour and bran.

Currently, a cereal crop production activity results in a certain quantity of gross production. Part is used or lost in the farm, being the difference the net production. This domestic production plus the imports minus the exports is the cereal available for use. This is split in the model into the following: animal feed, seed, industrial use, biofuels, human consumption, losses in the market and stock changes.

$$GROF = SEDF + LOSF + NETF$$

$$NETF + IMPT - EXPT = FEDM + SEDM + INDM + BIOF + HCOM + LOSM + STCM$$

Being: GROF= gross production
SEDF= used in the farm as seed
LOSF= lost in the farm
NETF= net production
IMPT= imports
EXPT= exports
FEDM= sold in the market as feed
SEDM= sold in the market as seed
INDM= sold in the market for industrial processing
BIOF= sold in the market as biofuel
HCOM= sold in the market for human consumption
LOSM= lost in the market
STCM= market stock changes

Our proposal consists on adding details on the production fraction used for human consumption, analysing which part is consumed as white flour or wholemeal flour. The motivation behind this analysis is the fact that the nutritional values of the two types of flour are different, which could have an implication in the design of optimal diets. In addition, the by-products of white flour production (mainly bran) are mainly taken out from the food chain and sold for use in the composition of feed rations. When processing the cereals, different extraction rates are applied for the different types of grains. In a simplified representation of the milling process, from a given type of grain we obtain three new products: white flour, whole meal flour and bran/by-products from milling, where 'white flour' represents the most common extraction rate for each type of grain.

For each cereal used for human consumption, the share used as whole grain and the share of grain processed to obtain white flour have to be defined, assuming that both the whole grain and the refined product are assigned to human consumption and the bran (and shorts, etc.) is used for animal feed or in the food industry. Additionally, we have to define the share of secondary products in terms of mass, as well as their nutrient contents, which will differ from those of the original grain.

Regarding the share of wholemeal flour and white flour by cereal type, we would need ideally statistics by country. However, there is not much official data available. We make an estimation based on literature and on the products reported in the EFSA food consumption database. This database contains the results of surveys from only sixteen member states, and is complete and sufficiently representative only for wheat and rice. For the other products, the number of respondents in some of the surveys is not representative for the member state. Therefore, we use specific values for wheat for the 16 countries providing data, while for the other member states and for the other products we take the EU28 averages.

Table 2: Fraction of grains which are used as whole grain or processed as white flour, for the cereal crops included in CAPRI- EU28 average

CEREALS IN CAPRI	Fraction of wholemeal flour	Fraction of white flour
Soft wheat	0.18	0.82
Durum wheat	0.10	0.90
Rye	0.43	0.57
Barley	0	1
Oats	1	0
Maize	1	0
Paddy rice	0.08	0.92
Other cereals	1	0

- Wheat: both soft wheat and durum wheat are mainly consumed as white flour, with different possible extraction rates, but the most typical is around 66-75%. We will consider 75%, which means that, as a result of processing, we obtain a mass of flour which is 75% of the original weight of the kernel, while the rest is mainly bran.
- Rye follows a roller milling process, similar to wheat, and used mostly for bread making as well. Part of it is processed as whole flour and part as white flour, for which typical extraction rates are lower than for wheat, around 58-68% (Simpson et al., 2012). Human consumption of rye is higher in the Baltic countries, where mostly wholemeal rye is used.
- Barley: only a small share of barley produced is used for human consumption. This part is mostly used as pearled barley. According to the Food and Drugs Administration[1], pearled barley typically represents 60-70% of the original barley kernel, while the rest (30-40%) is the hulls which can be used for animal feed.
- Oats are not usually transformed into flour, but commonly rolled and crushed into oatmeal and used as porridge or in cakes, cookies, etc. Therefore, we do not consider white flour but only whole grain.
- Maize: mostly used for feed, some for industrial uses and only a minor share for human food. Following a dry milling process, products with different particle sized can be obtained, from flaking grits to flour, with different uses. In the same line as oats, it is used as whole grain.

[1] https://www.fda.gov/ohrms/dockets/dailys/04/nov04/113004/04p-0512-cp00001-03-Appendix-01-vol1.pdf

- Rice can be consumed as brown rice (with the bran included) or white rice (with the bran removed). According to the Rice Knowledge Bank[2], typical extraction rate for white rice is 85-90.

The nutritional composition of the different milling products varies and, in particular, we are interested in: energy content, protein content, fat content, fibre content and dry matter. The data used in CAPRI has been taken from the USDA National Nutrient Database for Standard Reference, May 2016 version[3], except for barley pearling by-product, for which nutritional values are taken from Marconi et al (2000). For wholemeal flour, nutritional data should correspond to nutrient contents of grains already present in CAPRI. However, current CAPRI values do not always match values for whole grains found in literature, and therefore a revision is needed.

In the module, we calculate the quantities of white flour, wholemeal flour and bran produced in each country based on the quantities of grain for human consumption already allocated by CAPRI to human consumption. Table 3 presents the results obtained from the calculations in the cereal module, that is the quantity of milling products obtained, based on the quantity of grain.

Table 3: Products obtained from the cereal milling process by country and grain type (thousand tonnes)

		Soft wheat	Durum wheat	Rye	Barley	Oats	Maize	Rice	Other cereals
Belgium and Luxemburg	white	511.57	84.59	9.94	11.02			54.29	
	whole	436.09	5.94	21.95		2.20	29.27	5.25	0.64
	bran	170.52	28.20	6.62	5.93			6.03	
Denmark	white	336.81		24.66	0.53			35.51	
	whole	98.58	96.87	54.47		66.41	24.55		0.07
	bran	112.27		16.44	0.29			3.95	
Germany	white	4247.14	723.68	223.19	10.58			252.29	
	whole	57.20	61.59	493.09		280.63	1474.59	41.89	19.24
	bran	1415.71	241.23	148.79	5.70			28.03	
Greece	white	796.49	567.17	3.55	2.65			51.99	
	whole	233.12	84.03	7.85		6.88	20.10	5.02	9.98
	bran	265.50	189.06	2.37	1.43			5.78	
Spain	white	3327.69	217.50	7.47	2.89			269.42	
	whole	283.21		16.50		11.69	59.65	3.02	
	bran	1109.23	72.50	4.98	1.56			29.94	
France	white	3925.98	628.23	6.05	14.31			366.17	

[2] http://www.knowledgebank.irri.org/step-by-step-production/postharvest/milling

[3] https://ndb.nal.usda.gov/ndb/`

	whole	782.19	147.82	13.38		10.05	285.32	12.58	14.16
	bran	1308.66	209.41	4.04	7.71			40.69	
Ireland	white	142.69	59.33	1.39	1.86			30.65	
	whole	66.84	26.37	3.07		14.89	63.41	3.78	1.88
	bran	47.56	19.78	0.93	1.00			3.41	
Italy	white	4133.88	2717.29	0.57	9.90			274.27	
	whole	170.47		1.26		9.18	395.53	3.08	4.62
	bran	1377.96	905.76	0.38	5.33			30.47	
The Netherlands	white	429.46	83.31	17.26	8.03			66.26	
	whole	1063.42	24.38	38.13		27.12	39.98	11.00	1.63
	bran	143.15	27.77	11.51	4.33			7.36	
Austria	white	423.10	44.17	29.35	2.38			30.77	
	whole	23.51	6.54	64.84		10.38	171.57		12.87
	bran	141.03	14.72	19.57	1.28			3.42	
Portugal	white	637.76	107.37	11.58	6.49			134.73	
	whole	186.66	15.91	25.59		14.20	116.13	13.02	2.95
	bran	212.59	35.79	7.72	3.50			14.97	
Sweden	white	295.42	71.92	27.63	6.12			33.69	
	whole	92.39		61.05		59.49	17.70	22.94	3.94
	bran	98.47	23.97	18.42	3.30			3.74	
Finland	white	235.49	18.14	24.61	5.99			14.39	
	whole	64.31	0.75	54.37		42.50	48.53	5.91	0.73
	bran	78.50	6.05	16.41	3.23			1.60	
United Kingdom	white	3249.82	29.46	6.00	7.58			245.43	
	whole	1522.44	451.71	13.26		281.63	613.57	283.83	14.52
	bran	1083.27	9.82	4.00	4.08			27.27	
Cyprus	white	28.55	23.50	0.02	0.57			4.97	
	whole	8.36	3.48	0.05		0.25	1.30	0.48	2.88
	bran	9.52	7.83	0.01	0.31			0.55	
Czech Republic	white	1033.01	0.68	44.11	2.00			39.49	
	whole			97.44		35.17	43.77	3.82	8.90
	bran	344.34	0.23	29.40	1.07			4.39	
Estonia	white	38.85	6.22	7.49	2.60			4.12	
	whole	11.37	0.92	16.55		2.33	2.32	0.40	3.84
	bran	12.95	2.07	4.99	1.40			0.46	
Hungary	white	982.35	22.04	2.14	2.04			49.96	
	whole			4.72		3.13	339.60		10.93
	bran	327.45	7.35	1.43	1.10			5.55	
Lithuania	white	175.55	1.52	15.19	4.49			6.52	
	whole	51.38	0.23	33.57		5.75	11.95	0.63	6.75
	bran	58.52	0.51	10.13	2.42			0.72	
Latvia	white	103.01	9.02	12.72	8.36			4.14	

	whole	56.10	1.34	28.10		17.07	2.26	0.40	2.50
	bran	34.34	3.01	8.48	4.50			0.46	
Malta	white	10.63	14.97	0.06	0.13			2.36	
	whole	3.11	2.22	0.14		0.52	9.60	0.23	21.28
	bran	3.54	4.99	0.04	0.07			0.26	
Poland	white	2601.97	44.61	267.71	93.10			80.07	
	whole	761.55	6.61	591.45		30.87	26.73	7.74	36.47
	bran	867.32	14.87	178.47	50.13			8.90	
Slovenia	white	111.57	24.95	2.21	1.44			5.94	
	whole	32.66	3.70	4.89		2.19	38.64	0.57	6.15
	bran	37.19	8.32	1.48	0.78			0.66	
Slovakia	white	348.09	6.33	8.53	5.21			24.75	
	whole	101.88	0.94	18.84		3.65	8.14	2.39	24.51
	bran	116.03	2.11	5.69	2.81			2.75	
Croatia	white	309.86	2.61	1.65	0.78			11.03	
	whole	90.69	0.39	3.65		3.15	50.16	1.07	10.40
	bran	103.29	0.87	1.10	0.42			1.23	
Bulgaria	white	680.12	7.82	1.00	9.30			13.80	
	whole	199.06	1.16	2.20		1.74	186.59	1.33	13.55
	bran	226.71	2.61	0.66	5.01			1.53	
Romania	white	2401.00	110.96	2.21	2.62			60.71	
	whole	65.33	16.44	4.88		1.19	653.94		1.34
	bran	800.33	36.99	1.47	1.41			6.75	

We assume that the bran is then used to produce feed through some industrial process and its quantity is already implicitly considered in CAPRI as part of the feed raw material. However, there is a maximum share of bran that can be included in animal diets. For barley middlings, we did not find the maximum share in feed, but the percentage of barley used for human consumption compared to the barley used for feed is very low for all MS (1.8% as an average, maximum 8.2%), and consequently the quantity of bran obtained from barley pearling out of the total product for feed is minimum and we assume that all pearl by-product is used for animal feed. We assume that oats, maize and other cereals are totally consumed as whole grain, therefore no bran is produced as a milling by-by product. For wheat, rye and rice, we set a maximum of bran as by-product of milling which comes back to feed. In the case of rye, it does not seem suitable for ruminants or poultry. ***Table 4*** shows the maximum bran percentage in the feed mix for wheat, rye and rice in feed for the different livestock categories, based on Heuzé and Tran (2015), Heuzé et al. (2015a,b), Luh (1991) and White (1965).

Table 4: Maximum percentage of different type of cereal brans in feed, according to the livestock category

	Wheat bran (%)	Rye bran (%)	Rice bran (%)
Dairy cows	20	0	15
Beef cattle	25	0	30
Calves	10	0	30
Lambs	50	0	30
Ewes	50	0	30
Goats	14	0	--
Pigs	30	20	41
Sows	36	20	41
Broilers	13	0	15
Laying hens	45	0	15

Based on the maximum bran shares, we assign bran to feed production up to the maximum quantity permitted, and all bran quantities over that maximum are considered to be used in the food industry and therefore they remain in the human consumption share.

The nutrient content of grains used as feed also changes if we consider the increase of the bran share in feed due to the incorporation of bran from the milling process. The full grain nutrient values are replaced by new values which take into account the nutrient contents of the bran and the share of bran added to the total grain for feed. As for human consumption, the share of white flour, wholemeal flour and remaining bran (the quantity not added to feed) are used to recalculate nutritional deliveries in CAPRI, compared to the raw grain's values. Table 5 shows the results for crude protein content of grain for whole grain with the new values which take account the composition in terms of milling products. ***Table 6*** compares original values for whole grain to new values obtained for grain used for feed, with the addition of bran. Similarly to protein contents, the delivery of other nutrition parameters is corrected according to the composition of grain products (share of white flour/wholemeal flour for human consumption, bran addition to grain for feed).

Table 5: Crude protein of grain products for human consumption per country: initial value and changes when fraction white/wholemeal flour applied

	Crude protein, initial value (share of total mass)								Change in crude protein in cereals for human consumption, compared to original value of whole grain: *(new-original)/original* (*)							
	Soft wheat	Durum wheat	Rye	Barley	Oats	Maize	Rice	Other cereals	Soft wheat	Durum wheat	Rye	Barley	Oats	Maize	Rice	Other cereals
Belgium and Lux.	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.114	nc	0.160	0.100	0.160	nc	0.061	nc
Denmark	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.107	nc	0.160	0.100	0.160	nc	0.069	nc
Germany	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.100	0.140	0.159	0.100	0.160	nc	nc	nc
Greece	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.129	0.140	0.159	0.100	0.160	nc	0.068	nc
Spain	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.102	0.130	0.156	0.100	0.160	nc	0.070	nc
France	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.105	0.139	0.159	0.100	0.160	nc	0.066	nc
Ireland	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.110	nc	nc	0.100	0.160	nc	nc	nc
Italy	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.121	0.140	0.156	0.100	0.160	nc	0.069	nc
The Netherlands	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.121	0.138	0.159	0.100	0.160	nc	0.069	nc
Austria	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.102	0.140	0.160	0.100	0.160	nc	0.069	nc
Portugal	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.119	0.131	0.160	0.100	0.160	nc	0.070	nc
Sweden	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.107	0.140	nc	0.100	0.160	nc	0.069	nc
Finland	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.112	0.140	nc	0.100	0.160	nc	0.065	nc
United Kingdom	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.110	0.139	0.160	0.100	0.160	nc	0.070	nc
Cyprus	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.107	0.139	nc	0.100	0.160	nc	0.070	nc
Czech Republic	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.100	0.140	nc	0.100	0.160	nc	0.069	nc
Estonia	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.107	0.140	0.160	0.100	0.160	nc	nc	nc
Hungary	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.102	0.140	0.158	0.100	0.160	nc	nc	nc
Lithuania	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.107	0.140	0.160	0.100	0.160	nc	0.070	nc
Latvia	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.111	0.140	0.160	0.100	0.160	nc	0.070	nc
Malta	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.107	0.140	0.160	0.100	0.160	nc	nc	nc

Poland	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.107	0.140	0.160	0.100	0.160	nc	0.070	nc
Slovenia	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.115	0.140	0.160	0.100	0.160	nc	nc	nc
Slovakia	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.107	0.134	0.160	0.100	0.160	nc	nc	nc
Croatia	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.124	0.139	0.160	0.100	0.160	nc	0.068	nc
Bulgaria	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.110	nc	0.159	0.100	0.160	nc	0.067	nc
Romania	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.124	nc	0.159	0.100	0.160	nc	nc	nc

(*) nc= no changes

Table 6: Crude protein of grain products for feed per country: initial value and changes after addition of bran from milling

	Crude protein, initial value (share of total mass)								Change in crude protein in cereals for feed, compared to original value of whole grain: *(new-original)/original (*)*							
	Soft wheat	Durum wheat	Rye	Barley	Oats	Maize	Rice	Other cereals	Soft wheat	Durum wheat	Rye	Barley	Oats	Maize	Rice	Other cereals
Belgium and Lux.	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.082	nc	0.003	0.002	-0.059	nc	0.205	nc
Denmark	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.020	nc	0.003	0.000	-0.059	nc	0.196	cn
Germany	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.109	0.085	0.003	0.000	-0.059	nc	0.201	nc
Greece	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.218	0.067	0.002	0.001	-0.059	nc	0.206	nc
Spain	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.229	0.041	0.002	0.000	-0.059	nc	0.198	nc
France	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.102	0.081	0.003	0.001	-0.059	nc	0.202	nc
Ireland	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.038	nc	-1.000	0.000	-0.059	nc	-1.000	nc
Italy	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.247	0.076	0.003	0.001	-0.059	nc	0.203	nc
The Netherlands	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.027	0.083	0.003	0.001	-0.059	nc	0.202	nc
Austria	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.253	0.082	0.003	0.001	-0.059	nc	0.196	nc
Portugal	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.250	0.066	0.003	0.005	-0.059	nc	0.202	nc
Sweden	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.100	nc	0.003	0.001	-0.059	nc	0.195	nc
Finland	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.260	nc	0.002	0.001	-0.059	nc	0.195	nc
United Kingdom	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.120	0.044	0.003	0.000	-0.059	nc	0.198	nc

Cyprus	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.142	0.068	nc	0.000	-0.059	nc	0.204	nc
Czech Republic	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.167	nc	0.003	0.000	-0.059	nc	0.198	nc
Estonia	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.058	nc	0.003	0.002	-0.059	nc	nc	nc
Hungary	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.232	0.072	0.003	0.001	-0.059	nc	0.203	nc
Lithuania	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.178	nc	0.003	0.002	-0.059	nc	0.199	nc
Latvia	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.174	nc	0.002	0.009	-0.059	nc	0.200	nc
Malta	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.206	nc	0.002	0.000	-0.059	nc	nc	nc
Poland	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.180	nc	0.002	0.006	-0.059	nc	0.200	nc
Slovenia	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.258	nc	0.003	0.003	-0.059	nc	nc	nc
Slovakia	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.277	0.086	0.003	0.004	-0.059	nc	0.200	nc
Croatia	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.216	0.067	0.002	0.001	-0.059	nc	0.207	nc
Bulgaria	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.216	nc	0.002	0.008	-0.059	nc	0.214	nc
Romania	0.130	0.140	0.160	0.120	0.170	0.070	0.070	0.120	0.224	nc	0.003	0.002	-0.059	nc	nc	nc

(*) nc= no changes

Comparing full grain nutrient contents of food cereals with the new values, calculated with the data obtained from the milling module, results vary depending on the cereal and on the member state. While protein content does not change for maize and for other cereals in any country and for durum wheat and rice in some countries, changes can be important for other cereals, like soft wheat (up to 23% less protein content in the Czech Republic and Germany, 22% in Austria, 21% in Spain and Hungary) or rice (up to 13% less protein content in Belgium, 7.6% in Finland). Regarding changes in feed grains, crude protein content suffers relevant changes mainly for wheat (always higher than the original full grain values, from 2% change in Denmark to 28% change in Slovakia) and rice, also increasing (from 19% higher in Sweden or Finland to 21% higher in Bulgaria).

Once we have the nitrogen content of the products obtained in the cereal module, we can also calculate the nitrogen flows passing through the mill: incoming flows are the nitrogen content of the unprocessed grain times the total production used for human consumption, while outgoing flows are the nitrogen content of the products times the quantity produced of each type of milling product. The balance is zero, as all the nitrogen arriving for milling is going out in the form of a new product.

2.3. Slaughterhouse module

After slaughtering, some of the products obtained are consumed fresh, but some others have to go through rendering, a heating process for meat industry waste products through which fats are separated from water and protein residues for the production of edible lards and dried protein residues. In the slaughtering and rendering processes, the main products obtained are used for human consumption, as fresh meat and edible offal or food raw material used for the production of food grade products, and also for leather, through additional processing.

In the CAPRI model, data corresponding to the livestock sector mainly comes from EUROSTAT: herd size statistics, slaughtering statistics, statistics on import and export of live animals, farm and market balance statistics, Economic Accounts for Agriculture (EAA), producer prices and consumer prices. They are supplemented with FAOSTAT and national statistical yearbooks for new member states, Western Balkan countries and Turkey and for trade and food balance sheets.

Livestock activities included in CAPRI are based on the Economic Accounts for Agriculture database and are listed in Table 7.

Table 7: Livestock activities comprised in the CAPRI model

Cattle	Dairy cows Suckler cows Male adult cattle fattening Heifers fattening Heifers raising Fattening of male calves Fattening of female calves Raising of male calves Raising of female calves
Pigs, poultry and other animals	Pig fattening Pig breeding Poultry fattening Laying hens Sheep and goat fattening Sheep and goat for milk Other animals

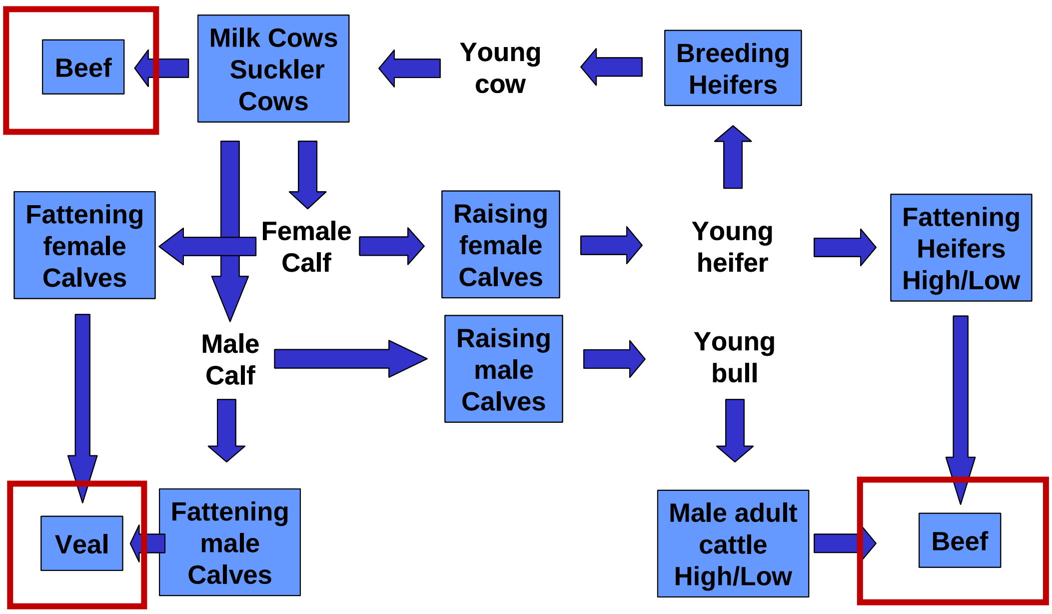
These livestock activities produce a set of outputs, some of which are obtained in the farm, from the live animal (milk, eggs) and some of them in the slaughterhouse. There are also some intermediate products which do not reach the market but are re-introduced in the production system in the form of fertiliser, for example. Table *8* lists marketable and intermediate products from livestock production included in CAPRI:

Table 8: Outputs obtained from livestock activities in the CAPRI model

Marketable products from animal production	Milk from cows Beef/veal Pork meat Sheep and goat meat Sheep and goat milk Eggs Poultry meat Other marketable animal products
Intermediate products from animal production	Milk from cows for feeding Milk from sheep and goat cows for feeding Young cows Young bulls Young heifers Young male calves

	Young female calves
	Piglets
	Lambs
	Chicken
	Nitrogen from manure
	Phosphate from manure
	Potassium from manure

Intermediate products are not marketable products, but outputs of some livestock activity which continue in the production process as input for other livestock activities. Young animals, for example, turn into input when they are not slaughtered but stay in the fattening/breeding process the following year. The most complex case is for cattle. Figure 2 shows the connection between cattle activities comprised in the model; in red squares, fresh meat produced in the slaughterhouses:



Source: CAPRI Modelling System

Figure 2: Cattle activity chain in the CAPRI model

Animals used for milk production are considered to produce meat only when their milk production period is over. The same will happen with hens: their primary objective is egg production but, at the end of the production period, they will be slaughtered and their meat will be sold in the market.

In addition to meat, there exist other marketable products obtained from the animal slaughtering which are not in CAPRI. These products include some edible co-products, which are food-grade products used for human consumption after processing and used in the food industry or for medical applications, and some by-products not intended for human consumption but also sold in the market and used for other purposes.

Table 9 shows the livestock categories entering the slaughterhouse, the associated meat products already included in the CAPRI database and the co-products which are not included in the model so far:

Table 9: Livestock activities and their output (already in CAPRI and proposed)

ACTIVITIES	SLAUGHTERHOUSE PRODUCTS (already in CAPRI)	SLAUGHTERHOUSE CO/BY-PRODUCTS (not in CAPRI)
Dairy cow Suckler cow Fattening bulls Fattening heifers	Beef	Food grade organs and intestines Food grade fat Food grade bones Food grade blood Cat. 3 skin/hide Other marketable cat. 3 products Cat. 2/1
Fattening calves	Veal	Food grade organs and intestines Food grade fat Food grade bones Cat. 3 skin/hide Other marketable cat. 3 products Cat. 2/1
Fattening pigs Sows	Pork	Food grade organs and intestines Food grade fat Food grade rind Food grade bones Food grade blood Other marketable cat. 3 products Cat. 2/1
Fattening poultry Laying hens	Poultry meat	Food grade organs and intestines Cat. 3 feathers Other marketable cat. 3 products Cat. 2/1
Fattening and milking sheep and goat	Sheep and goat meat	Food grade organs and intestines Cat. 2/1

Category 3 products are suitable for animal feed. Some of them go directly to pet food industry and most of them go through a rendering process, after which they are used for pet food, fertiliser production, biofuels or other industrial applications. Category 2/1 can go to landfill, incineration (with or without energy recovery) or they can go through a rendering process after which they can be used as biofuels, to cement industry or incineration for energy production, and (only for category 2, when processed separately) other industrial uses and fertiliser production.

According to EC (2005), 47 million tonnes of animals are slaughtered in the EU for meat production every year, from which 17 million tonnes, minus hides, skins and bones for gelatine production, are handled by the animal by-product industry. Around 14-15 million tonnes are processed by renderers and fat melters, and the by-product fraction is increasing along time. The European Fat Processors and Renderers Association (EFPRA) and EUROSTAT data indicate, for year 2014, a production of 7.5 million tons of beef, 22.0 million tons of pork, 13.0 million tons of poultry meat, 700 thousand tons of sheep meat and 50 million tons of goat meat in the whole EU. The same year, EFPRA accounted for 17.2 million tons of by-product raw material processed, resulting in 2.7 million tons of animal fat and 3.9 million tons of animal proteins.

About half of the tallow and animal fat produced are used by oleo-chemical industry as raw materials for soaps, cosmetics, pharmaceuticals, detergents, industrial products such as paint, car tyres…, while food-grade oils and fats produced by fat melters are used in the food industry. Until BSE crisis, a high proportion of the solid end-products of rendering (eg. proteins) were important ingredients of animal feed, but in 1994 the EU banned the use of mammalian protein for feeding ruminants (Decision 94/381/EC). This ban was expanded in 2001 to the feeding of all PAP to all farmed animals being prohibited (Regulation 999/2001), restricting their feeding use to pet food and fur animals. From 2013 (Regulation 56/2013), PAP from non-ruminants were also allowed for fish feed. These bans also lead to an increase of solid material being disposed of to landfill and by incinerations. From the latter, energy can be recovered, and can also be used as fertiliser for non-grazing land.

Figure 3 below makes a summary of the main products and by-products obtained from livestock slaughtering, classified into food-grade products, category 3 and category 2/1 by-products. Red arrows indicate an intermediate processing/rendering process, and blue arrows the final destination in the market.

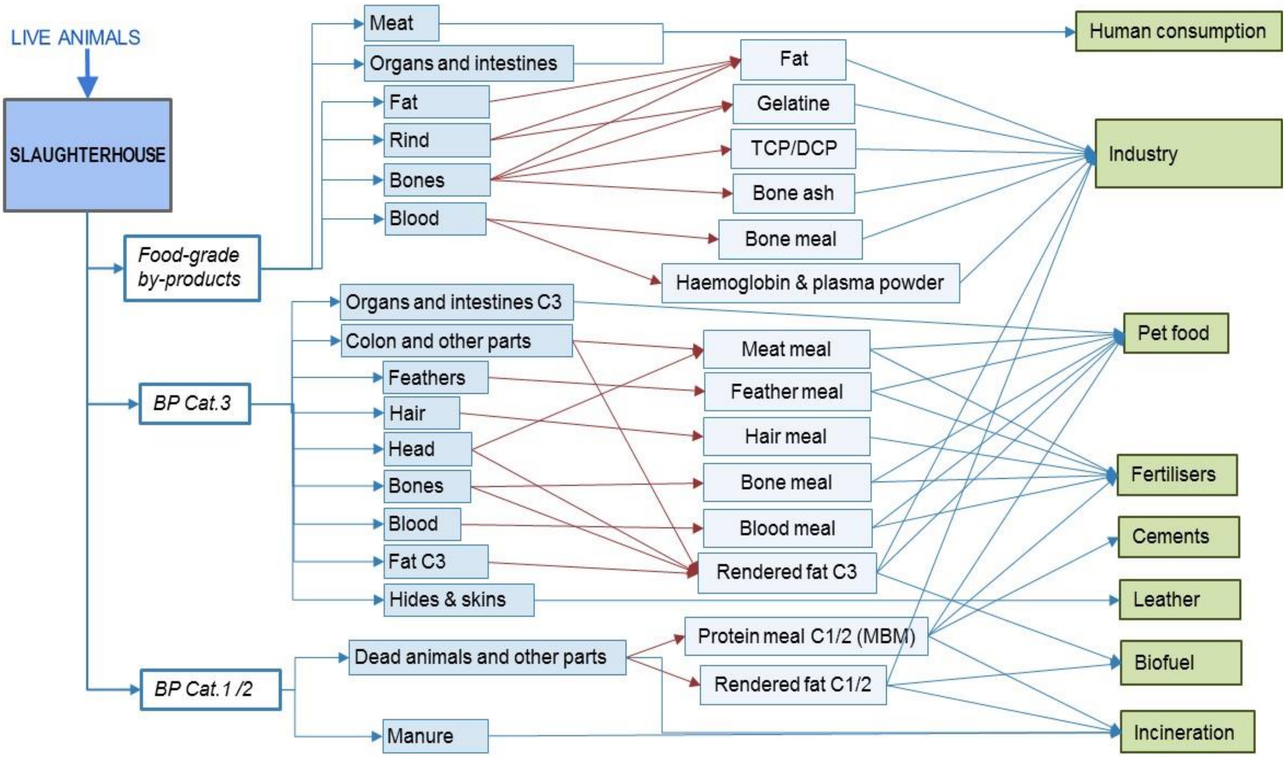


Figure 3: Products and by-products obtained from livestock slaughtering, their processing outputs and their final destination.

Food-grade products include fresh meat, organs and intestines which can be consumed directly, and some edible co-products: animal fat, pork rind, bones and blood. These are processed to obtain fat, gelatine, dicalcium and tricalcium phosphate, bone ash, bone meal, haemoglobin and plasma powder, which are used mainly in the food industry, and also in the pharmaceutical industry.

Category 3 products are suitable for animal feed, although there are some legal limitations. Organs and intestines can be directly used for pet food. Colon and other parts and pig heads can be rendered to obtain meat meal and fat. Feathers, pig hair and fat produce feather meal, hair meal and rendered fat, respectively. Bones are processed to obtain bone meal and fat. Processed protein meals are used for pet food (or also feed for fur animals and for fish, in aquaculture) and for the production of fertilisers, while rendered fat is used in pet food, as biofuel or for industrial uses to produce soaps and cosmetics, etc. Hides and skins from cattle go to the leather industry.

Finally, category 1 and 2 products can be incinerated (with or without energy recovery) or processed to obtain protein meal ('meat and bone meal, MBM') and fat. These can be incinerated and used as biofuel. If processed separately, category 2 MBM can be used for pet food, for fertilisers or in the cement industry, and category 2 fat can serve to industrial uses.

At present, CAPRI calculates the live animals arriving to the slaughterhouse and the quantity of meat produced, but by-products are not part of the model. For each livestock category, we define which by-products are obtained from the slaughtering, their share in terms of live weight at slaughtering, the share of rendering products obtained from each unit of slaughtering products, if they are further processed, and the destinations of the final products.

Livestock categories are those already specified in CAPRI (see Table 9 above). Heifers and calves are either used for meat production (fattening heifers/calves) or for becoming adults (raising heifers/calves). Therefore, raising heifers and raising calves are not producing any meat. Other livestock categories non primarily intended for meat production (but used for reproduction, milk or egg production) are slaughtered at some point and produce some meat.

For every livestock type, we have to specify the typical final live weight before slaughtering, which will be needed for the calculation of the mass of products and by-products obtained in the slaughterhouse. Apart from fresh meat, the rest of slaughterhouse products are not in CAPRI. The share of the different products depends on the livestock category. A proposed set of products and by-products is listed in Table 10.

Table 10: Products and by-products obtained from slaughtering.

Products and by-products
Fresh meat
Food-grade organs and intestines
Food-grade fat
Food-grade rind
Food-grade bones
Food-grade blood
C3 organs and intestines
C3 colon and other parts
C3 feathers
C3 hair
C3 head
C3 bones
C3 blood
C3 fat
Hides and skins
Dead animals and other parts
Manure

Each livestock category produces a quantity of (by)products, which is specified as a function of its final live weight, that is, we define the weight of (by)product compared to a unit of the animal final live weight. Table 11 shows the values for this parameter, adapted from Luske and Blonk (2009).

Table 11: Share of products and by-products related to the final live weight of the animal.

Products and by-products	**Livestock category**				
	Pig/sow	Cow/bull	Calf/heifer	Sheep and goat	Poultry
Pork	0.552	0	0	0	0
Beef	0	0.458	0.493	0	0
Lamb meat	0	0	0	0.45	0
Poultry meat	0	0	0	0	0.629
Food-grade organs and intestines	0.036	0.031	0.052	0.1	0.083
Food-grade fat	0.032	0.068	0.035	0	0
Food-grade rind	0.027	0	0	0	0
Food-grade bones	0.111	0.083	0.077	0	0
Food-grade blood	0.018	0.028	0	0	0
C3 organs and intestines	0.035	0.01	0	0	0.059
C3 colon and other parts	0.054	0.021	0	0	0.117

C3 feathers	0	0	0	0	0.059
C3 hair	0.009	0	0	0	0
C3 head	0.016	0	0	0	0
C3 bones	0.028	0	0.031	0	0
C3 blood	0.023	0	0	0	0.039
C3 fat	0.013	0	0	0	0
Hides and skins	0	0.073	0.073	0	0
Dead animals and other parts	0.046	0.135	0.143	0.45	0.02
Manure	0	0.094	0.096	0	0

Some clarifications about these coefficients may be needed: hides and skins are only obtained from cattle. For pigs, the skin is considered under 'rind' and for lamb it is not used us such but processed within category 1/2 products, given that the production is low and it is not economically feasible to use them. Regarding the head, only pig head is used after slaughtering.

For a specific slaughterhouse product, the total mass produced depends on the final live weight per livestock category and on the number of slaughtered heads, already calculated in CAPRI.

$Q_j = \sum_i FractionBP_{ij} * LW_i * SLG_i$

Where Q_j = quantity of slaughter (by)product j (in mass unit).

$FracBP_{ij}$= weight of slaughter product j which is produced per unit of final live weight of the livestock category i.

LW_i= final live weight of livestock category i.

SLG_i= number of slaughtered heads of livestock category i.

For example, total food grade fat produced in one region ~~would be~~is:

$Q_{FGFAT} = 0.032 * (LW_{PIG}*SLG_{PIG} + LW_{SOW}*SLG_{SOW}) + 0.068 * (LW_{DCOW}*SLG_{DCOW} + LW_{SCOW}*SLG_{SCOW} + LW_{BULF}*SLG_{BULF} + LW_{HEIF}*SLG_{HEIF}) + 0.035 *(LW_{CAMM}*SLG_{CAMM} + LW_{CAMF}*SLG_{CAMF})$

We then define the a set of 'final products', which is composed of the final products going to the market and could be fresh, directly after slaughtering, or the result after a rendering process. Table 12 shows the list of final products obtained from the slaughtering and rendering processes.

Table 12: Final products ready for consumption, from slaughtering or rendering

Rendering/final products
Food-grade rendered fat
Gelatine
TCP/DCP
Bone ash
Food-grade bone meal
Haemoglobin and plasma powder
C3 meat meal (multi-species)
C3 pork meal
C3 poultry meat meal
C3 feather meal
C3 hair meal
C3 bone meal
C3 blood meal
C3 rendered fat
Leather (grain and split)
C1&2 protein meal
C1&2 rendered fat

The quantity of product obtained from the rendering process depends on the animal type. From each slaughtering product j, a quantity of rendering product k will be produced, which is equal to a fraction of the mass. is not used.

Table 13 shows the mass of final product obtained as a share of the weight of the slaughtering product from which it is produced.

Some slaughter products are not included in this table because they do not go through a rendering process, but consumed directly as fresh product or not consumed at all (waste). We consider that fresh meat, food grade organs and intestines are consumed directly after slaughtering, while manure from the dead animal is not used.

Table 13: Share of rendering products related to the weight of the slaughtering product from which it is obtained, for each livestock category.

RENDERING PRODUCTS	SLAUGHTER PRODUCTS- Pig and sow												
	Food-grade fat	Food-grade rind	Food-grade bones	Food-grade blood	C3 colon + other parts	C3 feathers	C3 hair	C3 head	C3 bones	C3 blood	C3 fat	Hides and skins	Dead animals + other parts
Food-grade rendered fat	0.6	0.3	0.13										
Gelatine		0.2	0.047										
TCP/DCP			0.137										
Bone ash			0.066										
Food-grade bone meal			0.2										
Haemoglobin and plasma powder				0.205									
C3 meat meal (multi-species)					0.104			0.093					
C3 pork meal					0.047			0.042					
C3 poultry meat meal													
C3 feather meal													
C3 hair meal							0.3						
C3 bone meal									0.473				
C3 blood meal										0.18			
C3 rendered fat					0.12			0.467	0.093		0.6		
Leather (grain and split)													
C1&2 protein meal													0.239
C1&2 rendered fat													0.12
	SLAUGHTER PRODUCTS- Cow and bull												

RENDERING PRODUCTS	Food-grade fat	Food-grade rind	Food-grade bones	Food-grade blood	C3 colon + other parts	C3 feathers	C3 hair	C3 head	C3 bones	C3 blood	C3 fat	Hides and skins	Dead animals + other parts
Food-grade rendered fat	0.600		0.130										
Gelatine			0.047										
TCP/DCP			0.138										
Bone ash			0.066										
Food-grade bone meal			0.200										
Haemoglobin and plasma powder				0.202									
C3 meat meal (multi-species)					0.150								
C3 pork meal													
C3 poultry meat meal													
C3 feather meal													
C3 hair meal													
C3 bone meal													
C3 blood meal													
C3 rendered fat					0.120								
Leather (grain and split)												0.250286	
C1&2 protein meal													0.241
C1&2 rendered fat													0.119

RENDERING PRODUCTS	SLAUGHTER PRODUCTS- Calves												
	Food-grade fat	Food-grade rind	Food-grade bones	Food-grade blood	C3 colon + other parts	C3 feathers	C3 hair	C3 head	C3 bones	C3 blood	C3 fat	Hides and skins	Dead animals + other parts
Food-grade rendered fat	0.600		0.130										
Gelatine			0.047										
TCP/DCP			0.138										
Bone ash			0.066										
Food-grade bone meal			0.200										
Haemoglobin and plasma powder													
C3 meat meal (multi-species)													
C3 pork meal													
C3 poultry meat meal													
C3 feather meal													
C3 hair meal													
C3 bone meal									0.470				
C3 blood meal													
C3 rendered fat									0.090				
Leather (grain and split)												0.35	
C1&2 protein meal													0.241
C1&2 rendered fat													0.119

RENDERING PRODUCTS	**SLAUGHTER PRODUCTS- Sheep and goat**												
	Food-grade fat	Food-grade rind	Food-grade bones	Food-grade blood	C3 colon + other parts	C3 feathers	C3 hair	C3 head	C3 bones	C3 blood	C3 fat	Hides and skins	Dead animals + other parts
Food-grade rendered fat													
Gelatine													
TCP/DCP													
Bone ash													
Food-grade bone meal													
Haemoglobin and plasma powder													
C3 meat meal (multi-species)													
C3 pork meal													
C3 poultry meat meal													
C3 feather meal													
C3 hair meal													
C3 bone meal													
C3 blood meal													
C3 rendered fat													
Leather (grain and split)													
C1&2 protein meal													0.240
C1&2 rendered fat													0.090

RENDERING PRODUCTS	SLAUGHTER PRODUCTS- Poultry												
	Food-grade fat	Food-grade rind	Food-grade bones	Food-grade blood	C3 colon + other parts	C3 feathers	C3 hair	C3 head	C3 bones	C3 blood	C3 fat	Hides and skins	Dead animals + other parts
Food-grade rendered fat													
Gelatine													
TCP/DCP													
Bone ash													
Food-grade bone meal													
Haemoglobin and plasma powder													
C3 meat meal (multi-species)					0.082								
C3 pork meal													
C3 poultry meat meal					0.109								
C3 feather meal						0.333							
C3 hair meal													
C3 bone meal													
C3 blood meal										0.175			
C3 rendered fat					0.158								
Leather (grain and split)													
C1&2 protein meal													0.190
C1&2 rendered fat													0.160

Each slaughter product will lead to a mass of final product which is a function of the final live weight of the animal, the fraction of slaughter product compared to the whole animal and the fraction of rendering product compared to the unit mass of slaughter product.

Finally, the last step in the chain that we have to define is the destination of the final products. Table 14 shows the possible destinations of the products.

Table 14: Possible destinations for animal final products.

Market destination
Human consumption
Food industry
Pet food
Fertilisers
Cement industry
Leather industry
Biofuel
Incineration

A share of the final product (slaughter or rendering product) will be assigned to a specific use. Table 15 shows these fractions:

Table 15: Share of final products which is used in each market destination

FINAL PRODUCTS	Final destination							
	Human consumption	Industry	Pet food	Fertiliser	Cement	Leather industry	Biofuel	Incineration
Fresh meat	1							
Food-grade organs and intestines	1							
Food-grade rendered fat		1						
Gelatine		1						
TCP/DCP		1						
Bone ash		1						
Food-grade bone meal		1						
Haemoglobin and plasma powder		1						
C3 meat meal (multi-species)			1					
C3 pork meal			0.63	0.37				
C3 poultry meat meal			1					
C3 feather meal			1					
C3 hair meal			0.75	0.25				
C3 bone meal				1.00				

C3 blood meal			0.50	0.50				
C3 rendered fat			0.67	0.33				
Leather (grain and split)		0.32	0.52				0.16	
C1&2 protein meal						1		
C1&2 rendered fat			0.01	0.12	0.18			0.69
Food-grade rendered fat		0.01					0.70	0.29
Manure								1

The quantity of a product k used for a certain purpose would be calculated as a function of the final live weight of the animal, the fraction of the animal becoming each type of slaughter and rendering product and the fraction of those final product that are assigned for each defined use. These uses, in turn, are grouped according to the market balance positions, that is, the destination in the market: human consumption, food industry and pet food are grouped into the products consumed in households (HCOM); products used in the fertiliser, cement and leather industries are all grouped in the industrial uses (INDM), biofuels destination is energy production (BIOF), while incinerated products are considered losses (LOSM).

Among final products, some are used for animal feed. For those, nutritional values were obtained from feedipedia[4], an animal feed resources information system developed by a joint initiative of INRA, CIRAD, AFZ and FAO. Table 16 shows, for the final products whose destination can be feed, the main parameters relevant for feed formulation.

Table 16: Nutrient contents of animal by-products used as feed

	DM (%)	CP (%DM)	GE (mJ/kgDM)	Lysine (%protein)	Ash (%DM)	Crude fibre (%DM)
Meat and bone meal	95.8	54.9	17.7	5.0	30.5	--
Blood meal	93.8	94.1	24.1	8.7	3.0	0.5
Bone meal	95.4	0.0	1.6	4.7	84.5	0.9
Feather meal	92.1	85.7	23.5	2.1	5.5	0.9
Poultry meal	92.3	60.2	24.4	4.4	10.6	--

[4] https://www.feedipedia.org/

Fertilisers obtained from the slaughtering products will be used for agricultural production. For their modelling in CAPRI, we have to introduce their nutrient values. Comparing different data sources, including some leaflets for commercial products and some scientific articles (FAO (2002), Card et al. (2015), Jones S. (2011), Ingels C. (2011), Benton Jones (2012), SONAC (n.d.)) we found slight differences depending on the exact product, but those differences are not significant. We take the following values (from SONAC):

Table 17: Nutrient contents of organic fertilisers produced from animal processed protein meals

Protein meals	Nutrient contents			
	N	P	K	Ca
Meat and bone meal	8	6.5	0.2	14
Meat meal	8	3.7	0.9	7
Blood meal	14	0.5	0.3	0.3
Bone meal	6	10	0.2	22
Feather meal	13	0.2	0.1	0.4
Hair meal	14	0.2	0.1	0.2

Nitrogen flows in the slaughterhouse module can be calculated based on the nitrogen or protein content of each product and by-product. For the conversion of protein into N content, we apply the Kjeldahl factor.

- N input flows are calculated as the N content of the live animal arriving to the slaughterhouse, based on existing CAPRI values.

- N output is calculated based on the quantities of products obtained and their respective nitrogen content, for which we used the following data sources: N content of fresh meat is already in CAPRI. N content of products are mainly obtained from Scislowski et al. (2012), except for gelatin (from GMIA, 2012), haemoglobin (Martinez-Llorens et al., 2008) and manure (data from ECOCHEM[5]. For feather meal, hair meal and blood meal, values are taken from Table 16 and Table 17.

In the slaughterhouse module, we also estimate greenhouse gas emissions from waste water. To do so, we use the default methodology and default coefficients from IPCC (2006).

[5] http://www.ecochem.com/t_manure_fert.html

Both methane and nitrous oxide emissions are calculated as a function of the mass of slaughtered product and, respectively, the organically degradable material and N content of the water.

$$CH_4 Emissions = (TOW - s)\ EF - R$$

Where:

TOW=total organically degradable material in wastewater (kg COD). This is based on the quantity of product, calculated in CAPRI, and the wastewater generated for which we take IPCC default.

EF= emission factor for each treatment/discharge pathway or system (kg CH4/kg COD). We take default values for anaerobic lagoons, which are the most common systems in slaughterhouses, according to IPCC (2006).

S= organic component removed as sludge (kg COD)

R= amount of CH4 recovered (kg CH4)

We dismiss S and R, assuming that there is not removal of organic matter.

$$N_2O\ Emissions = N_{effluent} \cdot EF_{effluent} \cdot {}^{44}/_{28}$$

Where:

$N_{effluent}$= nitrogen in the effluent discharged (kg N), which is estimated based on Haan et al. (2006) and the product quantity calculated by CAPRI.

$EF_{effluent}$= emission factor for N_2O emissions from discharged to wastewater (kg N_2O-N/kg N), for which we take IPCC default.

Table 18 shows the results of the calculation of GHG emissions from wastewater produced in the slaughterhouse.

Table 18: Methane and nitrous oxide emissions from slaughterhouse effluents

	CH_4 emissions (kg CH_4/year)	NO emissions (kg N_2O/year)
Belgium and Luxemburg	20.05	0.010
Denmark	24.25	0.012
Germany	85.52	0.043
Greece	5.45	0.003
Spain	62.52	0.030
France	66.87	0.032
Ireland	13.26	0.007

Italy	47.20	0.023
The Netherlands	28.59	0.013
Austria	10.38	0.005
Portugal	9.60	0.005
Sweden	6.21	0.003
Finland	4.60	0.002
United Kingdom	40.65	0.020
Cyprus	1.08	0.001
Czech Republic	7.68	0.004
Estonia	0.87	0.000
Hungary	9.75	0.005
Lithuania	2.46	0.001
Latvia	1.10	0.001
Malta	0.18	0.000
Poland	40.28	0.020
Slovenia	1.89	0.001
Slovakia	2.39	0.001
Croatia	3.08	0.002
Bulgaria	2.60	0.001
Romania	12.60	0.006

In addition to losses through wastewater ($N_{effluent}$), during the slaughtering and mostly during the rendering process. These losses are calculated as the difference between incoming N flows (in the form of live animals) and outgoing N flows (in the form of products, by-products and N in sewage systems). Those losses vary in the different member states between 4 and 6% of total N outputs.

Finally, we propose an approach for the allocation of environmental burdens among products and by-products from livestock production. The cradle-to-farm gate environmental burdens, such as greenhouse gas emissions, are currently entirely associated with the produced fresh meat. However, burdens should be distributed among all products.

The estimation of allocation ratios for distribution of environmental burdens is not a straightforward task, and different criteria can be used for it, sometimes leading to very different shares. In the EU, allocation of upstream burdens should respect the ISO 14044 and the PEF guidelines. According to PEF, if allocation is needed, the ideal way is partitioning the burdens in a way that reflects the underlying physical relationships between inputs, outputs, products and functions delivered. However, this is usually not easy, and other type of relationship (like mass, energy use or economic allocation) has to be used. Gac et al. (2014) make an overview of the co-products obtained in the meat processing process for different animal species, analysing their end use (waste or co-product) and compare different allocation strategies. Desjardins et al. (2012), Scislowski et al. (2012) and Ramirez Mosquera (2012) analyse different options for the allocation of environmental burdens (mass and economic allocation) for slaughterhouse co-products for different species. Rechman (2013) makes a LCA of pork production, based on a wide literature review which shows that economic allocation is the most commonly used. Blonk and Luske (2008) present the allocation at the slaughterhouse in pork and veal, using economic allocation factors. Cattle Model Working Group final report also choses economic allocation, in this case for beef production, the same as Mila-i-Canals et al. (2002) for the leather production. Ramirez Mosquera (2012) also presents economic allocation criteria for cattle, sheep and pig, providing some useful data on economic values of the different products in the UK.

If we allocate burdens according to their economic value, not all the products obtained in the slaughterhouse will get a share of them. Category 1 and 2 by-products have no associated commercial value and are therefore waste with no allocated environmental burden. This is despite the fact that some (economic) benefit might be gained from the production of energy or fertilisers. However, as the default destination is to be burnt with no economic purpose (EC 2002, 2009), we consider this as marginal. Furthermore, information on the economic revenue of these uses and their share on total cat 1/2 by-products is not available. Among category 3 products, some will not have commercial value and, like for categories 1 and 2, they will have no allocation by default. Skins and hides going to leather industry, by contrast, have an economic value and will participate in the burden allocation. Part of category 3 products can also go to pet food industry, having an economic value and being subject to the allocation of burdens, as well. Overall, we consider the following destinations of by-products as relevant:

- Pet food (from category 3, but also from carcass)
- Leather
- Wool and other textile products
- Fertiliser (compost from cat 3, but also from industry, retailer and household wastes)
- Energy (for cat 1 and 2 not for allocation of upstream burdens, but rather generating GHG credits)
- Products for industrial purposes

For the economic allocation of environmental burdens among the different livestock products and co-products, -we should ideally use the mass production and 3-year average prices. However, not much data is available on prices, therefore we allocate emissions based on prices found in literature for by-products at the exit of the slaughterhouse (Luske and Blonk, 2009). Further processing and prices for final market products are not considered for the allocation of burdens.

The allocation factor (AF) for a specific type of product *j* is calculated as:

$$AF_j = \frac{P_j * MF_j}{\sum_j (P_j * MF_j)}$$

Where AF_j = allocation factor of product j

MF_j = mass fraction (share of the specific product/co-product compared to the total weight of the animal at the slaughterhouse).

P_j = market price of product j

j = a, b,… n all marketable products coming from the slaughtered animal

Once we know the environmental burden for the meat production (that is what CAPRI calculates so far), if we want to distribute it among the different co-products, we basically need the mass fraction of the product. Due to a lack of country-specific data, we can take default allocation factors from literature (Luske and Blonk, 2009). Based on default mass and price of each type of by-product, the allocation could be based on the following percentages:

Table 19: Products and by-products from livestock slaughtering, their mass fraction (as a percentage of the animal live weight), price and economic allocation factor. Based on Luske and Blonk (2009).

	Mass fraction (%)[1]					Price per kg (€/kg) of co and by-products derived from their value as an ingredients					Allocation factor (percentage of total €*kg)				
	Pig	**Beef**	**Veal**	**Broiler**	**Lamb**	**Pig**	**Beef**	**Veal**	**Broiler**	**Lamb**	**Pig**	**Beef**	**Veal**	**Broiler**	**Lamb**
Fresh meat	55%	46%	49%	63%	45%	1,9	3,0	4,0	1,5	2,0	87,5%	90,7%	93,9%	89,1%	93,8%
Food grade fat	3%	7%	3%	0%	0%	0,5	0,5	0,5	0,5	0,0	1,3%	2,3%	0,7%	0,0%	0,0%
Food grade rind	3%	0%	0%	0%	0%	1,0	0,0	0,0	0,0	0,0	2,6%	0,0%	0,0%	0,0%	0,0%
Food grade bones	11%	8%	8%	0%	0%	0,2	0,2	0,2	0,0	0,0	2,3%	1,3%	0,9%	0,0%	0,0%
Food grade organs and intestines	4%	3%	5%	8%	10%	0,8	0,6	0,6	0,8	0,6	2,8%	1,2%	1,4%	6,0%	6,3%

Food grade blood	2%	3%	0%	0%	0%	0,3	0,3	0,3	0,3	0,3	0,4%	0,5%	0,0%	0,0%	0,0%
Cat. 3 skin/hide	0%	7%	7%	0%	0%	0,1	0,8	0,8	0,1	0,1	0,0%	3,7%	2,7%	0,0%	0,0%
Cat. 3 feathers	0%	0%	0%	6%	0%	0,1	0,1	0,1	0,1	0,1	0,0%	0,0%	0,0%	0,6%	0,0%
Other marketable cat. 3 products[2]	18%	3%	3%	22%	0%	0,2	0,2	0,2	0,2	0,0	3,2%	0,4%	0,3%	4,3%	0,0%
Cat. 2/1	5%	23%	24%	2%	45%	0,0	0,0	0,0	0,0	0,0	0,0%	0,0%	0,0%	0,0%	0,0%
Total	*100%*	*100%*	*100%*	*100%*	*100%*						*100%*	*100%*	*100%*	*100%*	*100%*

[1]*These are mass fractions estimated for a default live weight at the slaughterhouse of 110, 480, 260, 2 and 40 kg for pigs, beef, veal, broilers and lambs, respectively.*

[2]*Other marketable category 3 products may include organs and intestines, colon, bones, head, fat, blood, hair and manure usable for energy or fertilizer production or other technical uses, pet foods and other applications different from human consumption*

Based on these allocation factors, environmental impacts, such as greenhouse gas emissions, currently assigned only to fresh meat would be distributed among all valuable products coming from slaughtering. Based on this methodology, we have modelled the allocation of greenhouse gas emissions of each livestock activity to the different slaughterhouse products which have a commercial value.

In the slaughterhouse module, we calculated the allocation of greenhouse gas emissions to the different products and by-products obtained, firstly based on economic criteria and then following a mass allocation type for comparison. We have grouped those products and by-products according to their use: human consumption, industrial uses, biofuel and waste. Table 20 presents an illustrative example of these results, showing economic and mass allocation of total global warming potential of agricultural GHG in Denmark, in absolute values (kg CO_2-eq/head) and in percentage of total emissions in all uses.

Table 20: Comparison economic vs. mass allocation of total GWP of all agricultural GHG in Denmark, 2008.

		ECONOMIC ALLOCATION			MASS ALLOCATION		
		Human consump.	Industrial uses	Biofuels	Human consump.	Industrial uses	Biofuels
Total values (kg CO_2-eq/head)	Cow	3010.2	26.2	0.07	2948.7	86.0	1.79
	Calf	1047.1	11.4	0.05	1007.3	50.5	0.69
	Sheep and goat	168.2			168.2		
	Pig	384.08	0.75	0.23	376.88	6.33	1.85
	Broiler	4.39	0.01	0.00	4.32	0.06	0.02

Percentage (% all uses)	Cow	99.14	0.86	0.00	97.11	2.83	0.06
	Calf	98.92	1.07	0.01	95.17	4.77	0.06
	Sheep and goat	100.00			100.00		
	Pig	99.74	0.20	0.06	97.88	1.64	0.48
	Broiler	99.84	0.11	0.05	98.37	1.27	0.35

According to allocation results for all countries and livestock categories, the mass allocation removes between 0 and 4.8 % of total emissions from human consumption, compared to what calculated originally by CAPRI. With the economic allocation option, this range is smaller, varying from 0 to 1.1%. We prefer economic allocation, as it seems more logical to attribute the highest shares of impacts to those products which have the highest value in the market, and it is also in line with CAPRI LCA module. Given the small share of greenhouse gas emissions assign to uses other than human consumption, we propose to use in CAPRI simple correction factors which would transfer a small part of the environmental burdens currently assigned to meat to other uses.

2.4. Post-farm food waste modelling

The current share of food waste out of the total quantities produced for human consumption is approximately one third, and that is why avoiding and recycling waste along the food chain have been pointed as key elements of a future sustainable food system (Godfray et al., 2010; Gustavsson et al., 2011). Waste is hardly represented in CAPRI, which just contains farm losses, happening before the farm gate, and 'losses in the market', a imprecise concept which comprises different types of losses taking place between the farm gate and the consumer, while losses in the households are not accounted. The produced quantities enter the farm and market balances; production minus seed use, internal use on farm and losses on farm equals the net trade on farm, which establishes the link with the market. The sum of net trade of farm plus imports must be equal to exports plus stock changes, feed use on the market, losses on the market, seed use on the market, industrial use, processing, human consumption and biofuel production. Most of the data is taken from sources available at European level. Farm and market balances, economic indicators, crop areas and herd sizes come mainly from EUROSTAT, complemented with FAOSTAT Trade and Food Balance Sheets.

FAOSTAT contains some data on food losses from the farm gate to the household (storage and transport). Another data source is the EU project

FUSIONS[6], which made a comprehensive study of food wastage, estimating food losses in the EU for all the stages in the food chain, from production to households based on a combination of national waste statistics and findings from research studies. Although the information was collected at national level, not all the countries had reliable data for all stages, and the result of the study was an estimation of wastes for the EU-28 and for year 2012. For household wastes, results also show the destination of such wastes: collection by municipalities, sewage system and home composting. Another EU project, AGROCYCLE[7], provides data on food waste, for a set of representative vegetables, fruits, cereals and livestock products in the EU, for the production, processing and consumption phases.

The representation of food waste is important in order to simulate food waste reduction scenarios. To be able to explicitly deal with a reduction in waste, the CAPRI database and baseline procedure was modified in various ways. The key source for loss rates in the food system was Gustavsson et al (2011), that is also used in MAGNET and GLOBIOM models. However, as database handling differs in these systems, the following only applies to CAPRI.

Gustavsson et al. (2011) provides loss rates for the retail and household sector, which have been explicitly entered in the database and result data cube (column "LOSCsh"). Moreover the losses in the distribution sector ("LOSM" and as a share "LOSMsh") and the industrial use of raw milk (INDM and INDMsh) have been considered when computing per capita consumption (column "INHA") from the consumption quantities on markets (column "HCOM" in the European database, column "HCON" = HCOM+LOSM+INDM).
Per capita consumption is not simply HCOM or HCON divided by population, but it is computed before generating the national database and considered during calibration of the market model. Per capita consumption is now estimated as food intake after losses, which is considered more useful for nutritional assessments. It should also be mentioned that this food intake is now conceptually the same in market model outputs and in the national-scale database.

Given the additional efforts to monitor nutritional intake, the aggregate calorie intake is now also monitored, permitting a firm control of nutrient

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[6] https://www.eu-fusions.org/
[7] http://www.agrocycle.eu/

developments for European countries but not ensuring that projections are reasonable for other world regions. Some control has been achieved through additional weights in the objective function for the market model calibration. However, additional hard constraints have not been implemented to avoid feasibility problems during the market model calibration, such that a fine tuned baseline in terms of the nutritional outlook for word regions is a time consuming and unsatisfactory trial and error process. Nonetheless some efforts have been made to avoid implausible results for single regions that were often observed in past CAPRI baselines and thereby also ensure some moderate standardization across MAGNET, GLOBIOM and CAPRI.

After these preparations in the database, baseline and reporting, the simulation of a diet shift could be supplemented with an explicit cut in the waste rates in the household and retail sector. To prevent an increase of consumption (because more purchased goods would be eaten rather than wasted), a supplementary consumption shift has been implemented that reduces purchases, keeping all the rest unchanged, in line with the reduced loss rates.

No efforts have been made to estimate the cost to bring about such a reduction in waste rates. Instead, the analysis was limited to market results, including nutritional status, as well as environmental indicators such as greenhouse gas emissions effects.

2.5. Household sewage module

From the 'human consumption' pool defined in Carmona-Garcia and Leip (2017), we concentrate here on the households, specifically on nutrient flows through the sewage system. Protein arriving to households is calculated from CAPRI, summing up crude protein contents of all products used for human consumption. We estimate nitrogen flows to water based on statistics of population, distinguishing between urban and rural population, and of sewerage systems per inhabitant. Data on population access to the different types of sewage systems is taken from van Drecht et al. (2009).

We consider three types of sewerage systems: with mechanical treatment, with biological treatment and with advanced treatment. Each of them has a different N removal rate. ***Table 21*** shows, by member state, nitrogen consumption in households, additional nitrogen from industry, non-consumed protein added to sewage water and nitrogen discharged to rivers with sewage water.

Table 21: Nitrogen consumption and nitrogen discharged in household sewage water, per member state (tonnes of N)

	Human N consumption	Additional N from industry	Non consumed N protein added to wastewater	N in sewage water discharged to rivers
Belgium and Luxemburg	73427.1	1170.0	18356.8	67679.1
Denmark	35845.3	6047.4	8961.3	20212.5
Germany	428810.5	91731.6	107202.6	144687.8
Greece	110311.8	733.0	27577.9	104769.6
Spain	270564.9	5448.4	67641.2	207784.7
France	342265.5	16839.9	85566.4	230045.1
Ireland	30462.0	104.8	7615.5	29431.1
Italy	425634.1	17387.2	106408.5	316760.1
The Netherlands	91636.8	16911.5	22909.2	33668.5
Austria	39907.1	7777.0	9976.8	15611.8
Portugal	71296.7	171.3	17824.2	67223.0
Sweden	51509.8	8664.5	12877.4	29075.0
Finland	25867.4	4607.6	6466.8	14696.2
United Kingdom	326798.0	5239.9	81699.5	263952.1
Czech Republic	53631.3	7153.1	13407.8	28620.3
Estonia	6092.6	570.1	1523.2	3679.4
Hungary	54539.4	612.2	13634.9	47444.0
Lithuania	15230.7	226.1	3807.7	14131.4
Latvia	11150.4	978.5	2787.6	6967.9
Malta	3241.8		810.4	3322.8
Poland	198819.6	9967.2	49704.9	143930.8
Slovenia	11005.0	106.1	2751.2	10122.1
Slovakia	23692.3		5923.1	19771.0
Croatia	19458.6		4864.6	18412.7
Bulgaria	40785.3		10196.3	38618.6
Romania	144277.4		36069.4	136815.6

Nitrogen spill to wastewater ranges from 1% (Germany) to 12% of nitrogen consumption (Slovenia), highly related to the share of the population connected to sewage systems, specially to high efficiency systems.

Nitrogen contained in sewage water is subject to emissions. In addition to N coming from households, we consider an additional fraction of industrial wastewater which is added to the sewage system. We calculate N_2O emissions from the effluent based on IPCC (2006) methodology, using IPCC default emission factors. IPCC guidelines differentiate two types of N_2O emissions from wastewater: direct emissions from nitrification and denitrification in treatment plants and indirect emissions from the effluent after disposal (containing N from households and additional N from industries). In general, direct emissions from sewage plants are much smaller than indirect ones, and may only be relevant when there is a high share of advanced treatment plants.

Indirect N_2O emissions are calculated using equation 6.7 from IPCC (2006), volume 5, chapter 6:

$$N_2O\ Emissions = N_{EFFLUENT} \cdot EF_{EFFLUENT} \cdot 44/28$$

Where:

> $N_2O\ Emissions$ = kg N_2O emitted per year
>
> $N_{EFFLUENT}$ = nitrogen contained in the effluent discharged to aquatic environments (kg N/yr)
>
> $EF_{EFFLUENT}$ = emission factor for N_2O emissions from N discharged to wastewater (kg N_2O-N/kg N). We take IPCC default = 0.005.
>
> The factor 44/28 is the conversion of kg N_2O-N into kg N_2O.

Activity data is the N spill calculated above, based on statistics of population and accessibility to different types of sewage systems with their associated capacity to remove nitrogen with sludge.

Regarding direct emissions from advanced treatment plants, they are calculated following equation 6.9 from IPCC (2006), volume 5, chapter 6:

$$N_2O_{PLANTS} = P \cdot T_{PLANT} \cdot F_{IND-COM} \cdot EF_{PLANT}$$

Where:

> N_2O_{PLANTS} = total N_2O emissions from plants in inventory year, kg N_2O-N/yr.
>
> P = population
>
> T_{PLANT} = degree of utilisation of modern, centralised treatment plants (%)
>
> $F_{IND-COM}$ = factor for industrial and commercial co-discharged protein
>
> EF_{PLANT} = emission factor, 3.2 g N_2O-N/person/yr.

Table 22 shows the estimated emissions from sewage water discharged and from advanced treatment plants.

Table 22: Nitrous oxide emissions from sewage water and from sewage advanced treatment by member state

	N_2O-N emissions from sewage water (tonnes N_2O/yr)	N_2O-N emissions from advanced treatment (kg N_2O/yr)
Belgium and Luxemburg	531.76	0.0021
Denmark	158.81	0.0112
Germany	1136.83	0.2213
Greece	823.19	0.0009
Spain	1632.59	0.0103
France	1807.50	0.0367
Ireland	231.24	0.0002
Italy	2488.83	0.0295
The Netherlands	264.54	0.0369
Austria	122.66	0.0198
Portugal	528.18	0.0003
Sweden	228.45	0.0188
Finland	115.47	0.0116
United Kingdom	2073.91	0.0118
Czech Republic	224.87	0.0173
Estonia	28.91	0.0016
Hungary	372.77	0.0014
Lithuania	111.03	0.0007
Latvia	54.75	0.0026
Malta	26.11	
Poland	1130.88	0.0244
Slovenia	79.53	0.0002
Slovakia	155.34	
Croatia	144.67	
Bulgaria	303.43	
Romania	1074.98	

Additionally, we calculate N_2 emissions based on Choubert et al (2005). We consider that the total conversion to N_2 is proportional to the fraction treated with advanced systems, for which 90% efficiency is assumed. For the other systems, a conversion factor of 20% is assumed. Table 13***: Share of rendering products related to the weight of the slaughtering product from which it is obtained, for each livestock category.*** presents the estimated quantities of nitrogen spilled to rivers through sewage water from households.

If we compare N_2O emissions to N consumption, we find a range between 2.6 (Germany) and 8.0 (Ireland, Malta) kg of N_2O emissions per tonne of N consumed.

3. LINKING HOUSEHOLD FOOD WASTE TO CHANGING INCOMES

Globally about one-third of food produced for human consumption is lost or wasted (FAO, 2011). In developing countries food loss and waste (FLW) mainly occurs in the postharvest and processing stages because of financial, managerial and technical restraints (FAO, 2011). In developed countries FLW is mainly observed at the consumer and retail stage. Higher average incomes in rich countries can make food appear relatively inexpensive and therefore affordable enough to be wasted. An increase in income is also associated with a change in the composition of the diet, generally towards more fresh products (Buchner et al., 2012). This shift in diets towards more perishable food products such as fruit and vegetables, is also responsible for higher consumer waste in monetary units. Food is also wasted owing to improper understanding of package/best-by dates and inadequate planning in the household (FAO, 2011). Aesthetic quality standards also induce FLW, as food is thrown away that does not have the right size or shape.

Despite all these aforementioned factors affecting FLW, the most commonly used estimates of FLW (FAO 2011) are obtained by applying waste factors to each step in the food supply chain (FSC) using the Food Balance Sheets (FBS) data. In terms of future projections of FLW in MAGNET (and other applied models), this means that by using these FAO numbers only FLW during food production is accounted for. Here we describe an approach to consider alternative factors that affect FLW, More specifically we introduce evolution of consumer food waste linked to evolving incomes in MAGNET.

3.1. Introducing consumer waste decisions in MAGNET

Since the available food waste data are mostly incomplete and their accuracy is questioned, food waste data is imputed and used to estimate an income/affluence elasticity of consumer food waste (see Verma et al. 2016 for details). These waste elasticities, just like consumption elasticities, are found to be high for developing countries and taper off as nations become richer. In other words, as developing country incomes grow closer to high income countries so does their consumer food waste.

A new variable denoting consumer demand for food waste (qpw) is introduced in the MAGNET model, with its own income elasticities (ε_i^{yw}) to capture the relationship between income developments and amount wasted. This along with actual consumption (qpc) then determines total food purchases (qp).

$$qp_i = sw_i qpw_i + sc_i qpc_i$$

where the sw_i and sc_i are the waste and consumption shares in purchase of good i. For readability the region index, capturing different waste shares linked to variations in income level, is suppressed.

Figure 1a and b show a graphical comparison of the new approach alongside the old approach. MAGNET follows the standard GTAP nested demand system where regional income (i.e. income obtained from payments to land, labour, capital and natural resources plus income from taxes) are allocated to the savings, government and private expenditures. Total private expenditures are then allocated over different commodities (qp) using a CDE demand system.

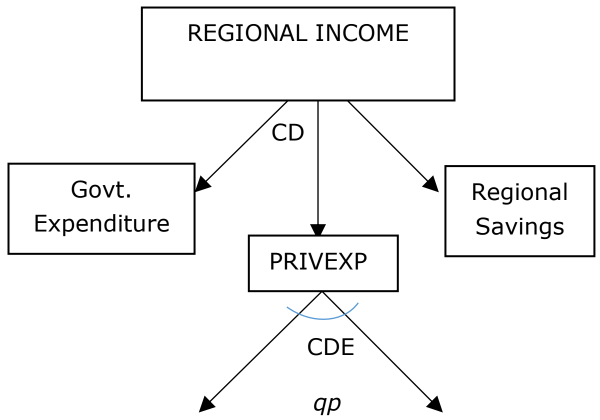

Figure 1a: Standard MAGNET specification of the demand system

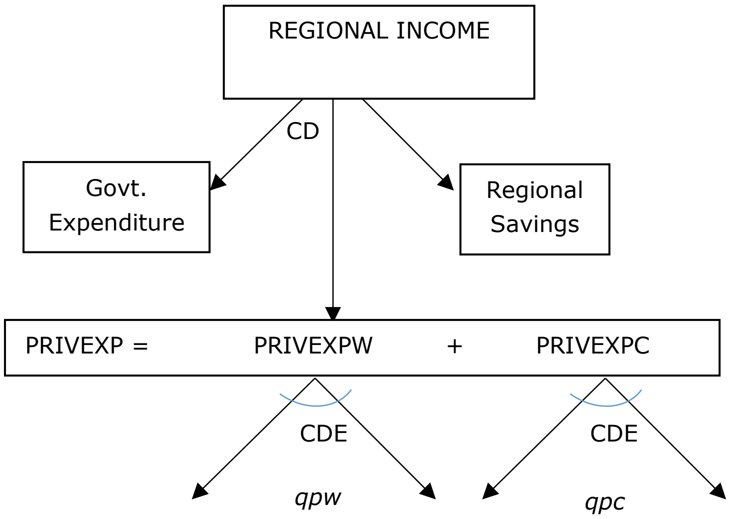

Figure 1b: Alternative specification of the demand system with consumer food waste

The alternative specification to allow for consumer food waste is depicted in figure 1b. An additional nest is added splitting the total private expenditures over wasted (PRIVEXPW) and consumed (PRIVEXPC) expenditures. While respecting the budget constraint, i.e. expenditures on wasted and consumed commodities sum to the total available income for private expenditures, both waste and consumption are driven by income and commodity price developments (determined endogenously in the MAGNET model) using a CDE demand system. Thus if the income per capita is increasing, the expenditures on wasted commodities will increase as well and consumption of commodities will increase less than in the standard MAGNET specification of the demand system.

Furthermore, using a CDE specification for waste demand implies that, similar to regular consumption demand, a commodity price increases will decrease its the waste demand. Thus amounts wasted may vary by commodity if prices develop differently – commodities growing more costly be wasted less. At the same time the relationship between income and total waste (PRIVEXPW) needs to be respected, creating an interdependency between different commodities: if some are wasted less because they are becoming relatively expensive others will be wasted more, else the link between waste and income would be violated.

3.2. Including food waste in MAGNET

The graphical illustration in figure 1 outlines the inclusion of waste in a simplified manner. Although obtaining an estimate of consumer food waste is useful in itself and especially in the context of changing diets, as discussed at the end of this chapter, ambitions for this module are higher. The ability to track food waste immediately raises the question of implications of reducing food waste. The food system implications of such a reduction area highly dependent on the manner in which the food waste is modelled.

Based on figure 1 the first option coming to mind is computing consumption as the residual after accounting for waste. Despite its intuitive appeal such a set-up has limited use in assessing reductions in waste. With consumption defined residually any reductions in waste will increase consumption expenditures, leaving total expenditures untouched. There will be some shifting towards non-food, with food waste being computed over food items while consumption expenditures cover both food and non-food purchases. But with food consumption also increasing when waste is reduced the upstream impacts on the supply chain and production will be muted.

More importantly, however, an increase in food consumption when waste is reduced does not appear likely in the context of high-income countries where waste levels are highest and exploring options for reductions most relevant. In a high-income setting food expenditures are a small share of total consumption expenditures (9 percent of total private expenditures according to the MAGNET database, against 37 percent in low income countries). While available income may be limiting food purchases for very poor households even in rich societies, these nuances are not captured by the aggregate representation of consumption in MAGNET. An automatic increase in food consumption when waste declines is therefore not plausible in a high-income setting.

To move away from consumption being a residual we start by defining quantities purchased (QP), wasted (QPW) and consumed (QPC) with an obvious accounting relationship for each food commodity c[8]:

[8] A more generic set-up could be used defining waste for all commodities. For non-food commodities quantities of food waste are zero and the equation collapses to the standard set-up with expenditures equaling consumption. Such a generic specification allows capturing non-food waste for other commodities in case this would be relevant.

$$QP_c = QPW_{fc} + QPC_c$$

Differentiating this equation with respect to income and some manipulation yields a new expression for income elasticities of food purchases, i.e. the strength of the response of food expenditures to increases in income:

$$\frac{\partial QP_c}{\partial Y}\frac{Y}{QP_c} = \frac{\partial QPC_c}{\partial Y}\frac{Y}{QPC_c}\left(\frac{QPC_c}{QP_c}\right) + \frac{\partial QPW_c}{\partial Y}\frac{Y}{QPW_c}\left(\frac{QPW_c}{QP_c}\right)$$

Equation above gives a relationship linking the three elasticities of income. The term on left hand can be interpreted as income elasticity of food purchases. The right hand side is a weighted sum of income elasticity of consumption and income elasticity of waste; the weights being the shares of commodity c consumed and wasted respectively. In MAGNET model code this corresponds to:

EY(i,s) = SCCW(i,s)*EYW(i,s)) + (1-SCCW(i,s)* EYC(i,s));

where EY is the CDE income elasticity (as present in the standard model), SCCW the share of commodities wasted, EYW the income elasticity of wasted commodities and EYC the income elasticity of consumed commodities. Unfortunately we cannot infer calorie wasted by commodity from our current available data sources, and thus have to assume that income elasticity of waste is uniform across all commodities. The waste elasticity being defined commodity specific additional data allowing a commodity specific response of waste can be incorporated in MAGNET.

Having waste and consumption specific income elasticities we can replace the standard CDE demand function with two separate CDE demand functions for wasted and consumed quantities. Note we only make the income response waste or consumption specific. The price elasticities, i.e. the response to relative price changes, is the same for both waste and consumption. Thus if a food commodity becomes more expensive it will both be wasted and consumed less.

Compared to past assessments of waste reductions with MAGNET the new approach has several advantages. The approach used in the past did not distinguish wasted from consumed purchases and employed a preference shift reducing private expenditures and thus consumption of food. The new module offers a more nuanced framework where changes in consumption are not predefined.

While this implementation of consumer food waste functions perfectly well for assessing food system implications of rising incomes or waste reductions, like land demand or food consumed, it does impose a CDE structure on food waste demand which may not be appropriate but needed for maintaining the general equilibrium consistency of the model.

We can move away from the CDE specification of food waste if the alternative specification respects the budget constraint of private expenditures. One option is to track the value of calories wasted and introduce a dedicated variable tracking its income consequences. If food waste changes, for example through an effort to reduce waste, the private savings are captured by a dedicated variable. The (empirical) challenge then is to determine the destination of these savings, which could be spend on all or only non-food purchases, or flow to private savings.

An alternative option is to leave the demand system intact, i.e. keep waste implicit in total household purchases and maintain a single CDE system defining total private purchases (consumed and wasted). When computing nutrition indicators (and diet restrictions) the share of food waste in total purchases can be accounted for using the estimated relationship between income and consumer food waste. Deviations from the income-waste relationship, for example efforts to reduce waste, can then be handled by modifying (a_waste) the existing link between private purchases (QP) and domestic (QPD) and imported (QPI) food commodities (c):

$$QP_c = a\_waste*(QPD_c+QPI_c).$$

A waste reduction is then treated as a form of technical progress where less production (QPD+QPI) is needed to satisfy consumer demand (QP = QPC + QPW). While this approach will reduce food consumed it does not provide control over the allocation of the income freed by reducing waste which will be allocated according the standard utility function underlying the CDE. The waste sifter can be moved exogenously, to explore the food system implications of waste reduction for consumers and producers. If additional information is available on the cost of achieving this reduction, and who pays for this (consumers, producers, government), the shifter can be made dependent on time or money spent.

3.3. SUSFANS case study country waste estimates

Applying the link between income and waste we can use total private expenditures per capita from the MAGNET database to derive base year consumer food waste estimates for the EU member states[9].

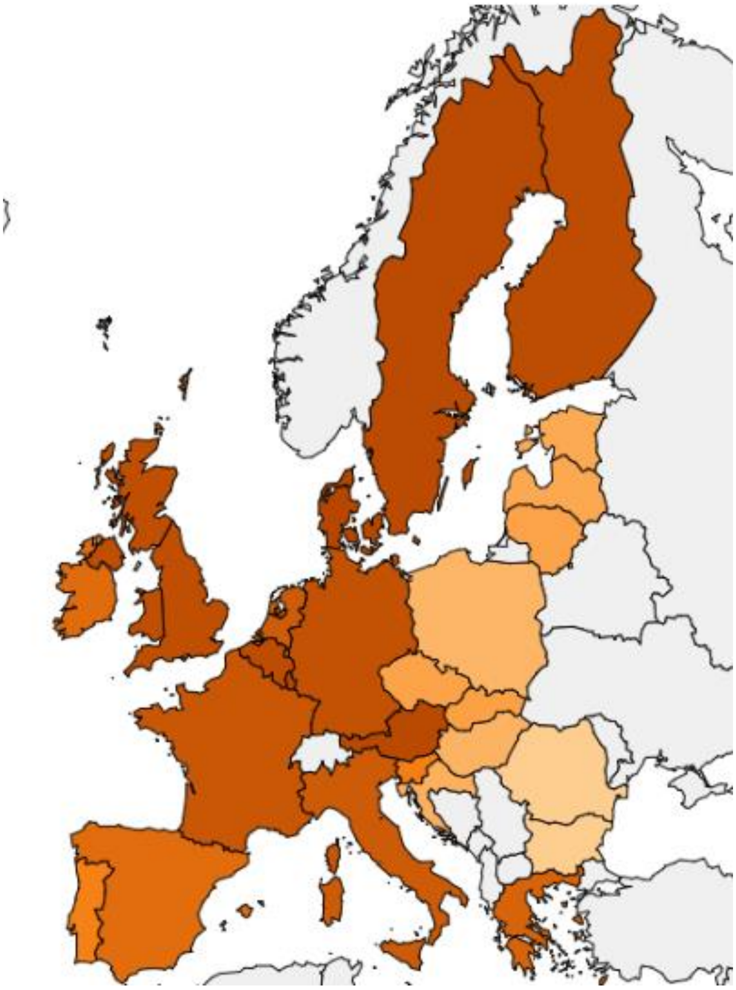

Figure 2: Consumer food waste (Kcal/cap/day) in EU countries in 2011
Source: Author's elaborations using own estimates and the MAGNET database

[9] The disaggregated MAGNET database, derived from the GTAP database (Narayanan, Aguiar, and McDougall 2015), holds data for all 28 EU member states. For computational reasons in the MAGNET model simulations a more aggregate representation of the EU may be used, at least distinguishing the four focus countries.

The EU average estimate is average 1127 Kcal/cap/day wasted in 2011 (the MAGNET base year). In the four focus countries the corresponding numbers (in increasing order) are 799 for the Czech Republic, 1179 for Italy, 1197 for France and 1293 Kcal/cap/day for Denmark. The much lower estimated amount of waste for Czech Republic compared to the other focus countries is due to its much lower per capita available income as measured by total private expenditures (10,488 USD/capita versus 20,761 USD/capita for the EU as a whole). Figure 2 visualizes the differences in estimated waste for the EU member states, with darker colours signalling more consumer food waste.

The 1127 Kcal/cap/day estimated for the EU is substantially higher than the estimated average global consumer food waste in 2011 of 536Kcal/cap/day. The latter number is much higher than the average consumer food waste reported in Kummu et al. (2012)[10]. As per their study, over the period 2005-2007, 214 Kcal/day/cap were wasted globally by consumers alone. Kummu et al. use the already adjusted food availability data but still account for the production losses while estimating food waste. This results in a potentially downward biased estimate of 214 Kcal/day/cap.[11]

3.4. Consumer food waste and SFNS assessments

The newly developed income driven consumer waste module for MAGNET enhances the scope for assessing future sustainable and healthy European diets in two important ways.

First of all, accounting for consumer waste allows for a correction of the nutrition assessment with the GENuS nutrition module developed in parallel and described in D9.2. The GENuS nutrition data are derived from the FAO Food Balance Sheets and therefore suffer from the same limitation of not capturing consumer food waste outlined at the start of this chapter. Estimates from the consumer waste module can serve to adjust the GENuS nutrition availability data towards intake of nutrients. This combination of MAGNET modules will thus improve the nutrition estimates from MAGNET, and especially so in cases where no additional intake data are available,

[10] Kummu et al. draw on FAO 2011 to provide Kcal estimates and can therefore in essence be seen as an extension of the FAO analysis.

[11] See Verma et al 2016 for a detailed comparison

For the SUSFANS focus countries detailed consumer intake data are used to feed the SHARP model. In the course of task 9.5 a link between MAGNET and SHARP is to be developed, sending price, consumption and income changes to SHARP while receiving detailed nutrition and diet information from SHARP. The latter implies that for the SUSFANS focus countries MAGNET can include more precise nutrition intake data form the SHARP database. These nutritional intake data are expected to be lower than the GENuS nutrition availability data[12]. The differences between these two sources can be attributed to consumer food waste and offers the possibility for the focus countries to improve the calibration of the food waste estimation with country-specific parameters.

Secondly, accounting for consumer food waste when imposing diets defined on an intake basis by SHARP[13] enhances the food system assessments. The imposition of for example a calorie restriction will translate into a reduction in consumer demand in MAGNET. With the consumer food waste module activated, however, we can connect the calorie target from SHARP to consumed products (PRIVEXPC in figure 1b) instead of targeting total private purchases (PRIVEXP in figure 1a). The upstream impact on supply chains and production of the diet change will thus be moderated by the wasted quantities. More importantly this moderation is not set in stone as in current approaches using a fixed waste percentage. If incomes change due to the food system implications of the diet change consumer food waste will respond as well and affect how the SHARP targets are reached.

[12] Part of these differences will be due to different product definitions and procedures in constructing the different datasets. Correcting for these differences requiring in-depth knowledge of all data processing steps is beyond the scope of the current work.

[13] As part of task 9.2 the new nutrition module has been set up to allow for imposition of constraints on nutritional values of consumption demand to explore food system implications of changing diets. See D9.2 for more details.

4. ALLOWING FOR IMPERFECT COMPETITION IN MAGNET

Homogeneous goods' models are consistent with the neo-classical theory of international trade, but are not equipped to deal with intra-industry trade. A response to this problem, and one widely employed in the CGE literature, is use of the Armington assumption, which allows for two-way trade flows in otherwise homogeneous products (Armington, 1969). This approach links product differentiation with exogenous considerations related to region of origin. For example, agricultural products with disparate physical attributes relating to differences in climate or soil, or because different varieties (e.g. soft and hard wheat) are aggregated into a single commodity (e.g. wheat). Similarly, in manufacturing goods, a stigma (positive or negative) may be attached to a particular product based on its region of origin. For example, in car manufacturing, 'buy German' may be considered as higher quality, whilst a Chinese substitute may be considered as lower quality. This regional connotation is only effective at the border where total imports are sourced from different regions in the world. An Armington elasticity determines the ease with which import flows switch between countries - the higher the elasticity the more homogeneous products from different regions are and the more responsive imports become to prices. For purchasing decisions of sectors, consumers and government imports are treated as homogenous, i.e. the country of origin does not play a role when consumers decide between domestic and imported commodities.

The emergence of the New Trade Theories in the 1960s recognised that product differentiation exists between firms as well as between regions. If firms produce differentiated products, then they may exercise market power which necessitates imperfectly competitive market structure. In the CGE trade literature, a number of seminal papers led by Spence (1976), Dixit and Stiglitz (1977) and Krugman (1979) (henceforth known as the SDSK model) characterise market power and utility effects. Swaminathan and Hertel (1996) incorporated these theoretical developments into a large scale multi-region model (GTAP). More recently, Akgul et al. (2016) have extended the SDSK approach of Swaminathan and Hertel (1996) in GTAP with further modelling developments to accommodate firm productivity heterogeneity and self-selection by export routes, based on the work of Melitz (2003).

The imperfect competition module in MAGNET builds on these developments providing an option to include either the SDSK and Melitz approaches to capture firm heterogeneity and market power.

4.1. Imperfect competition in a CGE model

CGE models like MAGNET normally operate with constant returns to scale technologies with each sector producing a single homogenous commodity[14]. Furthermore assuming that markets are perfectly competitive producers have no influence on market prices. The result is a zero profit condition[15] where value of production equals the cost of production. With a constant returns to scale technology, homogeneous products and no market power there is no need to keep track of the number of producers nor their specific products. Thus production can be represented by one single producer for each sector.

Introducing imperfect competition is done by abandoning the assumption of homogeneous products in favour of product variety. Swaminathan and Hertel (1996) incorporated these theoretical developments into a large scale multi-region model (GTAP), which forms the basis of much of the following discussion.

To characterise differentiated commodity demands, it is assumed that consumers as a group do not have a bias for any one given 'variety', but rather seek to consume as many varieties as possible ('love of variety' behaviour). Thus, aggregate consumer utility is a monotonically increasing function of increases in the number of varieties (the so-called *variety effect*). The elasticity of substitution of the utility function is a constant which does not change with the number of varieties. Thus, all pairwise combinations of varieties have identical substitution elasticities and consumer preferences are said to be *symmetric*.

[14] MAGNET allows for the production of by-products where sectors produce more than one product (for example vegetable oil and oilcake), but these are produced in fixed ratios and are treated as a single product in the production decisions.

[15] Zero profit in the economic sense meaning that sale proceeds are divided over all inputs used in production. The payments to endowments (labour, capital, land) can be seen as the profit accruing to the owners of these endowments.

On the production side, the availability of varieties along the varietal spectrum is based on the emergence of new firms in the industry, where a 'one-to-one' relationship between the number of firms and varieties is assumed. Moreover, to characterize the behaviour of all firms within an industry, one assumes 'symmetry' which implies that all firms face the same cost, technology and demand conditions. This assumption allows the modeller to treat each 'representative' firm as a micro-scaled version of the industry which in turn allows the use of industry data (consistent with GTAP data). To operate in the industry, the 'representative' firm must incur fixed overhead costs. In their GTAP application, Swaminathan and Hertel (1996) motivate these as value added factor costs (i.e., labour and capital) which arise from both the research and development and marketing activities necessary to bring a 'unique' product variety to the market.

Profit is the difference between total revenues and total costs, where the latter is subdivided between the aforementioned fixed costs and variable costs. Changes in industry total fixed costs are a direct function of the number of varieties in the industry, whilst total variable costs are made up of all intermediate input costs and that proportion of value added costs not employed in the fixed overhead costs of production.

Each imperfectly competitive industry exhibits increasing returns to scale technology (IRS) at the firm level. The problem with imposing increasing returns to scale technologies is that one loses the linear homogeneity property (under constant returns to scale production functions) which is required for consistent aggregation in the nesting structure. To overcome this problem, the literature (Krugman, 1979, Harris, 1984; Harrison *et al*., 1995; Swaminathan and Hertel, 1996) employs an alternative treatment of IRS. More specifically, average variable costs (AVC) are assumed to exhibit constant returns to scale, such that average variable costs and marginal costs (MC) change at the same rate. On the other hand, the fall in average total costs associated with an increasing returns industry is realised as total fixed costs are spread over more units of production with increases in 'representative' firm output.

Thus, under conditions of profit maximization, the mark-up of sales price over marginal cost (MC = AVC) can be derived:[16]

$$\frac{P}{MC} = \frac{\sigma}{(\sigma - 1)}$$

where σ represents the elasticity of substitution between varieties.[17] Thus, assuming that price equals average total cost, a mark-up of 1.1 implies that the price is 10% higher than the marginal cost (equal to average variable cost under constant returns to scale assumption). Assuming zero long run economic profits (i.e. firms will enter the market if a profit can be made), it is possible to determine both the number of firms operating within the industry and, subject to the market clearing condition for total industry output, the output of each representative firm.[18]

More recently, Akgul et al. (2016) have embedded within the SDSK approach of Swaminathan and Hertel (1996) in GTAP further modelling developments to accommodate firm productivity heterogeneity and self-selection by export routes, based on the work of Melitz (2003). As in the SDSK approach, there is a continuum of firms each offering a single variety, although upon entry into the industry, this model determines whether firms have the capacity to operate in domestic markets only, or also in export markets, based on productivity thresholds.

[16] Assuming that price equals average total cost, a mark-up of 0.3 implies that marginal cost and average fixed costs are 70% and 30% of the output price respectively.

[17] It is not clear why the CGE literature favours the use of the elasticity of substitution parameter to calibrate industry mark-ups (which remain at a fixed ratio). In theoretical terms, this mark-up is properly calculated as a function of the demand elasticity, of which the Armington substitution is only one component part.

[18] With knowledge of industry output (Z) and the number of firms (N), one can deduce output per firm (Q) simply by Z = QxN.

4.2. Imperfect competition module in MAGNET

The representation of imperfect competition in MAGNET follows the treatment of Meltiz type imperfect competition in Akgul et al. (2016).[19] Keeping the traditional 'love-of-variety' model, one assumes that consumer utility derived from consuming across a continuum of varieties of *i* in region *s* ($Q_{i,s}$), is a CES aggregate of all available varieties sourced from region *r* collapsing the standard two–layered Armington nested structure is collapsed into a single nest.[20] In common with the SDSK representation, the 'love-of-variety' effect is such that varietal proliferations unambiguously increase this CES utility and decrease the per unit cost of utility.

As in the SDSK approach it is also implicitly assumed that there is a one-to-one relationship between the number of 'symmetric' (i.e., equal cost structures) firms and available varieties in the industry. Furthermore, each firm exercises market power over sales of their variety of the Melitz good in region *s*, and as such will charge an optimal mark-up σ_i / (σ_i -1) over their marginal cost of production $C_{i,r,s}$. The average price charged by the firm with average productivity ($\psi_{i,r,s}$), is given by the mark-up expression:

$$\tilde{P}_{i,r} = \frac{C_{i,r}}{\tilde{\psi}_{i,r}} \frac{\sigma_i}{\sigma_i - 1}$$

As in the SDSK representation, variable costs of production exhibit constant returns to scale technology such that changes in average variable costs are equal to changes in marginal costs, whilst internal scale economies occur as fixed costs are spread over a larger number of units of production.

The Melitz model categorises fixed costs into two concepts. The first, consistent with the Swaminathan and Hertel (1996) monopolistic competition model, is that of industry-wide research and development (R&D) and product marketing setup costs which allow firms to sell their unique variety of 'i' in their 'home' region *r*. These costs are equal to the per unit fixed input cost ($W_{i,r,r}$) multiplied

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[19] The reader is encouraged to consult this (open access) paper, from which a large proportion of the modelling in MAGNET is taken. A more elaborate description of all steps in deriving the equations and on activation of the imperfect competition module is included in the MAGNET documentation of this module.

[20] In the MAGNET model, it is assumed that the elasticity of substitution in the upper (ESUBD) and lower (ESUBM) portions of the nest are equal, which effectively collapses into a single nested structure described here. See also the discussion on nesting domestic and imported varieties below.

by the number of units of fixed setup costs ($H_{i,r}$). Thus, industry profit ($\Pi_{i,r}$) is given as:

$$\Pi_{i,r} = \sum_{s} N_{i,r,s}\tilde{\Pi}_{i,r,s} - N_{i,r}^{p}W_{i,r,r}H_{i,r}$$

which is the sum of the profits of the average firm operating in destination market *s* (r=s; r≠s) multiplied by the number of active firms, less the fixed set up costs associated with the number of potential firms ($N^{p}_{i,r}$) that operate in industry *i* in region *r*.

The second category of fixed costs is destination-specific 'fixed trading costs'. These costs relate to the costs of packaging, shipping and product labelling specific to each destination market *s*. This cost concept also covers the possible fixed costs incurred from necessary product line adjustments associated with the regulations in the destination market (r=s; r≠s) and even lobbying costs necessary to secure contracts to operate in certain markets These costs are defined as the per unit fixed input cost ($W_{i,r,s}$) multiplied by the number of units of fixed trading costs ($F_{i,r,s}$). Consequently, the profit condition for an average firm to operate in a destination market *s* (r=s; r≠s) is given as:

$$\Pi_{i,r,s}(\tilde{\psi}_{i,r,s}) = \frac{P_{i,r,s}(\tilde{\psi}_{i,r,s})}{T_{i,r,s}}Q_{i,r,s}(\tilde{\psi}_{i,r,s}) - \frac{C_{i,r,s}}{\psi_{i,r,s}}Q_{i,r,s}(\tilde{\psi}_{i,r,s}) - W_{i,r,s}F_{i,r,s}$$

Note that firm profit is a positive function of the productivity level ($\psi_{i,r,s}$) and an inverse function of average variable costs of production ($C_{i,r,s}$), trade and transportation taxes ($T_{i,r,s}$) and fixed trading costs. In the model code, this profit function does not appear explicitly, but rather is employed as an identity to determine the firm's productivity $\psi_{r,s}$ in serving any of the *s* markets.

Consider that there is a range of possible productivities which can be drawn from a Pareto distribution whose cumulative distribution is $G(\psi) = 1 - (b/\psi)^{a_i}$, where b_i is the minimum productivity (associated with the least productive producer in each country/region) and a_i is the Pareto shape parameter (this is further discussed further below). There will be a firm operating by route *r* to *s* with minimum productivity $\psi^*_{i,r,s} > b_i$ for which operating profits are exactly equal to fixed costs. Any firm with productivity below this threshold, $\psi^*_{i,r,s}$, will not operate in this market.

In Akgul et al. (2016), it is shown that average productivity thresholds move in proportion to minimum productivity thresholds.

They also observe that productivity changes are a function of variable costs and output prices. In addition, the 'market access' effect shows that as firms have access to new markets, the cost per sale by destination route s falls resulting in falling productivity thresholds (i.e., the necessary productivity to enable firms to compete in destination market *s*).

Under the conditions of the mark-up, the profit expression and the market clearing restriction that industry output (qo) be equal to average firm output (qof) multiplied by the number of firms in the industry ($N_{i,r}$), represented in linear terms (in MAGNET) as

$$qo_{i,r} = qof_{i,r} - n_{i,r}$$

it is possible to determine the entry and exit of firms from the industry.

Finally, of the potential number of firms in the industry, only those firms whose productivity threshold satisfies the requirement $\psi_{i,r,s} > \psi^{*}_{i,r,s}$ may operate in market *s*. More formally, if 1 - $G(\psi^{*}_{i,r,s})$ is the proportion of firms on the cumulative distribution that are active in market *s*, then it can be shown that:

$$N_{i,r,s} = N_{i,r}\left[\psi^{*}_{i,r,s}\right]^{-a_i}$$

Totally differentiating in MAGNET this reduces to

$$n_{i,r,s} = n_{i,r} - a_i \psi^{*}_{i,r,s}.$$

The key ethos behind the inclusion of imperfect competition in MAGNET is to employ its existing flexible modular structure to implement a 'layered' approach, where developments in the Melitz model can be superimposed directly over the SDSK model. In this way, the user can easily compare the additional trade impacts arising from the different model specifications (and in turn, compare with the standard 'Armington' approach). In addition, the flexibility of the approach should extend to allow the users to flexibly choose different market structure classifications (sectors) by different GTAP regions. These modularity requirements necessitated significant modifications of the GTAP-based work of Swaminathan and Hertel (1996) and Akgul (2016) on which the code builds.

In both GTAP applications a *non-nested* approach is employed for purchases of monopolistically competitive differentiated products (homogeneous products keep the two-nested Armington structure – see below). More specifically, for each agent (i.e., firms, households, and government) imported varieties of 'i' (r≠s) compete directly with the domestic variant (r=s) within a single nest (see Figure 3). The rationale is that domestic and foreign firms/varieties compete directly which enlarges the size of the market and therefore the gains from trade from specialization (i.e. imperfect competition and branding is global) (Francois et al., 1995).[21]

Unfortunately, implementing such an assumption increases the dimensions of the model. By way of example, intermediate demands are now indexed over four dimensions, where firms in region 'i', from region 'r', purchase good 'j' from region 's' (r = or ≠ s). Similarly, final demands are now indexed over three dimensions. Depending on the number of regions contemplated within the study, the scale of the MAGNET model could increase dramatically.

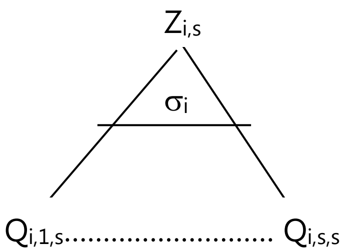

Figure 3: A non-nested Armington structure

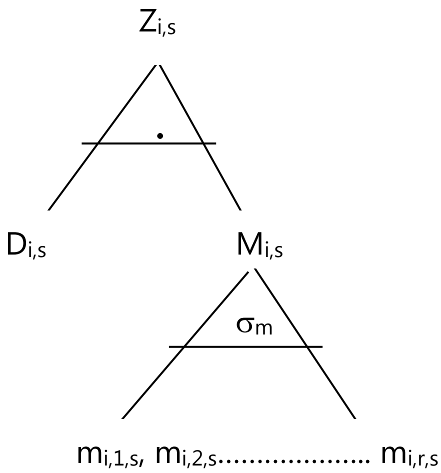

Figure 4: A nested Armington structure

[21] Comparing the nested and non-nested specifications, Francois et al., (1995) find that the latter yields larger welfare effects.

The MAGNET model, with numerous available modelling enhancements, is already a highly sophisticated CGE representation. To avoid exacerbating further the computational burden, and despite the intuitive appeal of the non-nested approach, for pragmatic reasons, the standard (GTAP) nested Armington structure is preserved both for purchases of homogeneous and monopolistically competitive goods. Thus, a lower Armington nest disaggregates imports by region of origin ($m_{i,r,s}$) employing σ_m substitution possibilities, whilst the upper nest characterizes domestic ($D_{i,s}$) versus 'composite import' ($M_{i,s}$) purchase patterns subject to σ_d substitution possibilities (see Figure 4).

In order to more closely approximate the non-nested modelling structure, a quasi-non-nested approach is adopted, where the same elasticity of substitution parameter value is employed in the lower and upper levels of the nest (see parameterization section), whilst the utility effects arising from the consumption of changes in the number of available domestic and foreign varieties are weighted, based on expenditure shares.

An additional major consideration is the need to reconcile the imperfectly competitive module with the flexible nesting structures which are available to MAGNET. This allows the user to characterise different production technologies (i.e., standard GTAP or customised MAGNET production nests) for different imperfectly competitive industries. In modelling terms, this requires numerous additional set definitions to classify sectors by both nest structure type and market structure type. As a caveat, it should be noted that whatever nest structure is favoured, to permit the calibration of fixed costs exclusively from the primary value added inputs, all nests and sub-nests of primary factors must be separable from all other inputs in the production nest. For example, under this assumption, a capital-energy nest structure, often characteristic of many applications, is not permitted. [22]

Finally, to gain additional insight into trade policy, further additions are made to the welfare decomposition code to characterise the money metric equivalent changes in variety effects, scale effects, endogenous productivity effects and

[22] On the basis of characterising R&D and marketing costs, one could contemplate including services within the same nest grouping as primary factors. It should be noted that the imperfectly competitive module works better when the substitution elasticities for primary factors are relatively larger (smaller price effects). This dampens the changes in costs, which in turn reduces the circle of scale effects, variety effects and productivity effects in the imperfectly competitive industry.

fixed bilateral route cost effects (Swaminathan and Hertel, 1995; Akgul et al., 2016). Assuming differentiated product demands, trade growth permits new firms to enter markets giving rise to varietal proliferations. Thus, the variety effect is the money metric equivalent of the utility changes to final and intermediate demands by 'love-of-variety' consumers resulting from endogenous changes in varieties/firms.

The scale effect is the money metric measure of efficiency changes (in terms of fixed costs) resulting from increasing returns to scale technologies as the scale of output per representative firm in the industry rises. For example, increases in existing trade opportunities on the intensive margin, or new trade opportunities on the extensive margin may arise owing to varietal proliferations, which permits firms to expand the scale of their production. If industry fixed costs are spread over a greater output, then average fixed costs fall. This implies a fall in average total costs, whilst under a fixed mark-up, a fall in the sales price of the industry.

The productivity effect captures the net effect from reallocation of resources from less productive firms to more productive firms within the industry. This reflects the changing composition of demand by different sales routes s, where certain firms in domestic market *r* have expanding market shares by sales route(s) *s* ($r=s$ or $r\neq s$), whilst others face dwindling market shares in sales route(s) *s* ($r=s$ or $r\neq s$).

Finally, the fixed trading cost effect measures the ratio of potential firms in the industry which engage in sales by bilateral routes. Fixed costs payments by those firms which are not able to participate along sales routes s, represents a welfare loss to the industry.

4.3. Calibration and parameterisation

In parameterising the Melitz model, the two crucial parameters are the shape parameter (a_i) and the elasticity of substitution in region *s* between competing varieties of *i* sourced from *r* (σ_i). These parameters are instrumental for calibrating the industry mark-up and the value of 'fixed entry costs' and 'fixed trading costs' by sales destination *s*.

With knowledge of industry costs (VOA) from the MAGNET database, one is able to calibrate total industry variable and fixed costs based on knowledge of the markup. For example, a mark-up 1.1 implies that total variable costs are 90.91% of total costs and total fixed costs are the residual. Based on the assumption that fixed costs are entirely constituted by value added costs (see discussion above), a choice of low substitution elasticity will lead to a higher mark-up.[23] Depending on the regional variations in the value added and intermediate inputs cost structure for the industry under consideration, this could result in calibrated industry fixed costs exceeding available total primary value added costs. One must therefore either resort to a lower substitution elasticity, or loosen the assumption to accommodate a greater range of substitution elasticities across regions.[24]

In the Melitz representation, the fixed cost component is subdivided into setup costs (same as the SDSK interpretation), whilst the remainder is fixed trading costs ($N_{i,r,s}W_{i,r}F_{i,r,s}$), which is a function of the elasticity of substitution and the shape parameter. More specifically, the calibration of fixed trading costs (Akgul *et al.*, 2016) is given as:

$$N_{i,r,s}W_{i,r}F_{i,r,s} = \frac{N_{i,r,s}\tilde{P}_{i,r,s}\tilde{Q}_{i,r,s}}{T_{i,r,s}} \frac{a_i - (\sigma_i - 1)}{\sigma_i a_i}$$

An examination of this expression reveals that to ensure non-negative fixed trading costs, the condition $a_i > (\sigma_i\text{-}1)$ must hold. In the case of both parameters, the values must be chosen carefully. There are currently no rigorous (i.e., econometric) estimates for parameter a. Estimating the Pareto distribution parameters *a* and *b* is beyond the scope of this study although a promising avenue of research is addressed in Spearot (2016).

A closer examination of the shape parameter shows that it plays an important role in characterising the relative degree of firm heterogeneity between different competitors within the imperfectly competitive industry.[25]

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[23] The lower is the value of σ_i, the more differentiated are the varieties of 'I', such that each firm's market power over its' own variety increases, resulting in a higher price mark-up.

[24] For example, one could reasonably contemplate extending the definition of R&D, marketing and distributional costs based on primary value added to costs, to also include ' services' intermediate input costs.

[25] In the Spence-Dixit-Stiglitz-Krugman representation, it is assumed that firms operate on all sales routes.

Melitz (2003) posits that firms in region 'r' operating along a given route 's' (r=s; r≠s), draw productivity $\psi_{i,r,s}$ from a cumulative probability distribution function;

$$G(\Psi) = 1 - \left(\frac{\Psi^{*}_{i,r,s}}{\Psi_{i,r,s}} \right)^{a}$$

where $G(\psi)$ is the cumulative probability (≤ 1) of achieving a given productivity level ($\psi_{i,r,s}$), and $\psi_{i,r,s}^{*}$ is the minimum threshold productivity which firms need to achieve to be able to operate on a given market 's'. As the shape parameter (a) increases in size, the cumulative probability that firms will achieve any given productivity level also increases.

In graphical terms (Figure 5), a plot of the cumulative distribution function of firm productivity shows that as the shape parameter grows it becomes more like a step function (a=5), which implies that relative productivities across firms in the industry are more uniform (i.e., firms are more homogeneous in terms of relative competitiveness).

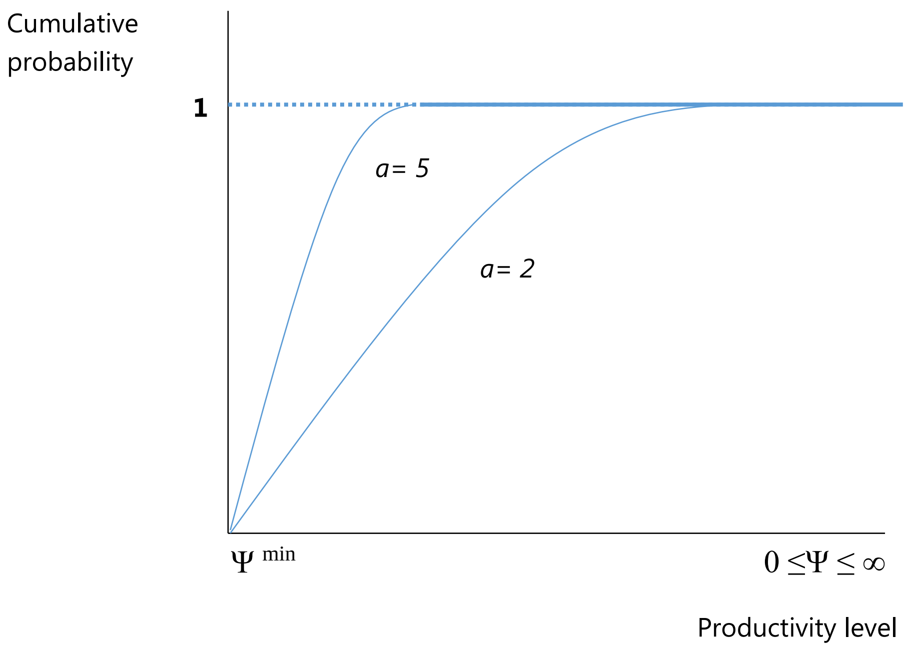

Figure 5: Cumulative probability density function of firm productivity

In an industry characterised by more uniform productivities across firms, reference to Melitz mark-up expression above shows that the price charged by firms (incumbents and new firms) converges more, the equation determining the number of firms shows that with a higher shape parameter value increases the responsiveness of firm participation by sales routes ($N_{i,r,s}$) to changes in productivity, where (*ceteris paribus*) rising minimum/average productivities result in many firms ceasing to operate on specific markets. By extension, with a smaller shape parameter, rising minimum/average productivities result in relatively fewer firms leaving the market, since these are already very efficient firms. In other words, a lower shape parameter implies that the more efficient firms represent a larger share of industry sales by destination market.

To underline this point further, rearranging distribution function above such that if 1 - $G(\psi^*_{i,r,s})$ is the proportion of active firms on the cumulative distribution that are active in market *s*, then under the conditions of a higher shape parameter, with rises in $\psi_{i,r,s}^*$, then 1 - $G(\psi^*_{i,r,s})$ falls much more quickly (i.e., the fall in the number of firms is much more pronounced). In the absence of any empirically robust estimates of firm heterogeneity by imperfectly competitive industry, a shape parameter value may chosen such that fixed trading costs ($N_{i,r,s}.W_{i,r,s}.F_{i,r,s}$) are calibrated as a fixed percentage of total industry fixed costs (subject to the parametric restrictions discussed above).

4.4. Imperfect competition and SFNS assessments

Both SDSK and Melitz improve on the inability of the Armington approach to deal with structural changes in trade patterns at the 'extensive' margin (i.e., output expansion along new export routes following trade liberalisation) in standard CGE applications, but only Melitz explicitly models firm self-selection by export routes based on heterogeneous productivity potentials by firms within an industry. The imperfect competition module in MAGNET thus increases the capacity of the model to capture market power in domestic markets as well as development of new trade routes missed by the Armington approach[26].

[26] This inability of the Armington approach is due to the small share problem. The Armington equations are calibrated on the base data. If these contain zero (or very small) trade flows for certain bilateral flows they will remain small or zero throughout the simulations. In a way the model loses sight of these potential new trade routes which are captured in the Melitz specification.

Employing the modularity of MAGNET the imperfect competition module has been applied to an analysis of the milk quota abolition alongside a standard perfect competition version of the model (Philippidis and Waschik, 2016). Consistent with previous studies, assuming perfect competition shows that falling raw milk prices resulting from quota removal bestow a competitive advantage to EU dairy exporters in the medium term. The imperfect competition variation in addition predicts a 'shakeout' in the EU dairy industry as production is concentrated into fewer larger scale firms, with remaining firms exhibiting greater third-country export orientation. The resulting varietal proliferation on extra-EU trade routes generates even greater export market penetration and welfare gains to the EU. Both versions of the model result in broadly similar price, output and bilateral trade trends. Accounting for market power, however, reduces the degree of direct price transmission such that raw milk price reductions under quota abolition are smaller with imperfect competition. Whilst the difference may not be large, Soregaroli et al. (2011) note that even small price differences may have important effects on farmers operating at the margin. This is particularly pertinent at a time when EU dairy farmers are struggling with low milk prices.

A key challenge with either SDSK or Melitz specifications is the calibration of the additional equations which are a key driver of the model results. For example, lack of data underlies the assumption that fixed costs consist of labour and capital. Ideally a global dataset identifying the number of firms and their market share would be used to calibrate the model. Apart from the usual difficulties in constructing a consistent global dataset from disparate national sources this kind of information however becomes more sensitive the higher a sector is concentrated and thus the easier it is to trace data back to individual firms. Data on fixed versus variable costs to deduce the mark-up applied by companies is even more sensitive and therefore unlikely to become available in a way suitable to calibrate global CGE model like MAGNET.

In terms of future research, further development of Spearot's (2016) econometric estimation of the shape parameter of the Pareto distribution of heterogeneous firms could be extended to regions as well as industries. On the other hand, recent trade research (Head et al., 2014; Freund and Pierola, 2015) even suggests the exploration of alternative distributions, arguing that Pareto may be an inadequate fit to real world business data, particularly in cases where a large number of firms account for a small proportion of sales.

In the context of sustainable food and nutrition assessments the requirement following from the fixed cost assumption that labour and capital are kept separate from other inputs like energy should be noted. In climate and sustainability assessments MAGNET regularly employs a production structure derived from the GTAP-E model (Burniaux and Truong, 2002) with an elaborate capital-energy nesting structure to capture changes energy use in environmental analyses. Sectors with such a structure cannot have an imperfect competition structure. In contrast to GTAP-E MAGNET allows flexible nested CES production structures which vary across sectors thus allowing imperfect competition for some sectors where others maintain the elaborate capital-energy specification for sustainability assessments.

A final note on the connection to diets is in place. Whereas in parallel tasks working on enhancing the ability of the demand side in MAGNET to capture more detail in products there is no obvious connection to the varieties in the imperfect competition module. The main concern with increasing product detail at the demand side is to increase MAGNET's ability to track variations in nutritional content. These variations are ultimately, although at times very indirect through multiple processing stages, linked to the primary product content. In both SDSK and Melitz imperfect competition calibration procedures firms (which map one-to-one with varieties) vary only in terms of fixed costs composed of labour and capital while the variable cost structure is identical. This implies that the primary product content of the product varieties in imperfect competition is identical as well. Lacking better data for calibrating the imperfect competition module the additional product varieties it adds to MAGNET do not provide additional variation in nutritional indicators. Furthermore by maintaining a two-layered (Figure 4) Armington structure in MAGNET as opposed to distinguishing commodities by region of origin (Figure 3) as in the GTAP-based applications implies that differences in nutritional content across regions is also not immediately obvious from consumer purchasing decisions, but can still be derived by combining the total demand for imports and its allocation over regions.

While not through a link with varieties accounting for imperfect competition does affect price formation and income developments both of which affect consumer purchasing decisions and thus diets. For example, a smaller price decline when accounting for imperfect competition in assessing the impacts of milk quota will, ceteris paribus, also mute the increase dairy product consumption.

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