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RESEARCH ARTICLE

Economic supply chain modelling of industrial insect production in the Netherlands

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Abstract

Defatted larvae meal (dLM), specifically from black soldier flies, could help overcome the animal protein gap. As insect production is an emerging sector, current economic research is scarce and very diverse. Thus, the aim of this research was to develop a simulation model that enables the analysis of full industrial scale costs of producing dLM and to provide insight in the distribution of these costs in the insect supply chain. The deterministic supply chain model is built on three modules, technical, transition and economic module, which all follow a previously defined supply chain structure and allow to extract quantity and price information for intermediate or final products. The model was parameterized and checked for plausibility in multiple consultation rounds with the INSECTFEED consortium and business partners. Additionally, model behaviour was checked with scenario, sensitivity, and break-even price analyses. In the default situation 5.57 tDM raw substrate and 26.7 million neonates are required to produce 1 tDM dLM for a price of €5,116/tDM. Most costs are added in the raw substrate delivery (€1,952/tDM) and production and collection (€821/tDM) step. Important cost factors are the raw substrate (€1,939/tDM) and building and inventory (€1,459/tDM). Parameters with high relative response rate towards the price of dLM are the feed conversion rate, dry matter percentage of larvae, raw substrate price, larvae density, labour wage and growth rate. To reach break-even prices for substituting fish meal with alive grown larvae (AGL) (€1,318/tDM AGL), improving production parameters is not sufficient. Just changing prices of raw substrate to –€78/tDM or frass to €1,175/tDM would enable a profitable operation. However, these are not deemed as realistic in mass production. Although there is some insecurity in data, the model results are the most realistic representation of industrial scale production amounts and costs.

Keywords

black soldier flies – *Hermetia illucens* – economics of insect production – supply chain modelling

1 Introduction

The continuously growing world population, in combination with the rising incomes, lead to an ever-increasing demand for high quality protein, either directly consumed instead of meat and dairy products, or as high quality protein source in animal feed (OECD-FAO, 2020). Therefore, it is important to find other protein sources that can increase the total high quality protein production at competitive prices (Gkarane *et al.*, 2020; OECD-FAO, 2020). Since the first "insects to feed the world" conference in 2014, the attention is drawn

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to insect protein as one potential solution. More specifically, black soldier flies (BSF) are seen as one of the most promising species due to its high protein content, rich amino acid profile, short growing period, lack of diseases, and variety of possible rearing substrates (Joosten *et al.*, 2020; Huis, 2022; Lu *et al.*, 2022). Per kilogram protein, insect production facilities require less soil surface and water compared to traditional protein sources like soybean meal. Furthermore, insect production can facilitate a circular economy when low-value side streams, such as catering waste or manure are used for rearing (Bosch *et al.*, 2019). Bioactive compounds like Chitin or Lauric acid in insects could improve animal health and reduce antibiotic use (Gasco *et al.*, 2018; Dörper *et al.*, 2020; Saatkamp *et al.*, 2022). Moreover, providing live larvae as feed could improve animal welfare by enabling natural behaviours (Star *et al.*, 2020). Thus, economic opportunities of insects as feed are potentially reduced feed costs, improved nutrient efficiency (Biasato *et al.*, 2017; Schiavone *et al.*, 2017), or higher valued end products (Biasato *et al.*, 2017; Schiavone *et al.*, 2017; Saatkamp *et al.*, 2022).

Commercial insect production is still an emerging sector, with no standard production procedures or business models in place (J. Kooistra, personal communications). Thus, literature on prices is very diverse and reports selling prices between €1,816 and €18,190 and operational costs between €1,451 and €3,777 per ton BSF products (Ites *et al.*, 2020; Pleissner and Smetana, 2020; Niyonsaba *et al.*, 2021). However, besides operational costs, also fixed costs for building and inventory should be respected to get a full overview. Moreover, wet mass (WM) costs and dry mass (DM) costs are used interchangeably in various studies and confuse the reader.

Spykman *et al.* (2021) reported costs between €5.18 and €6.54 per kg crude BSF protein and showed the importance of a modular approach to simulate insect production. Various production stages are needed in different capacities depending on the raw substrates used for feeding the insects. Although very helpful, the focus was rather on the environmental impact than on total production costs. Thus, for example labour costs were not included in the study. Moreover, results were based on lab scale experiments and showed a bit overestimated in personal communication with larger-scale equipment suppliers. There still is a big lack of consistent knowledge about costs involved with BSF production.

Besides that, costs are only given for a specific end products which can be, in increasing processing intensity, alive grown larvae (AGL), dried whole larvae, whole larvae meal or defatted larvae meal (dLM) (Niyonsaba *et al.*, 2021). By nature, the production costs of these products increase with higher processing intensity. Next to the final products, some companies, which only focus on one part of the supply chain and thus on marketable intermediate products, are emerging. For example, Freezm and Insectocycle are focused on the production and distribution of eggs or neonates. Egg production can benefit from scale effects if it is centralized, but additional transportation, storage, and margin as transition costs are expected between two different companies. Contrary, Suckling *et al.* (2021) and Pahmeyer *et al.* (2022) show decentral rearing case studies which reduce transportation costs for the raw substrates. However, the studies start with 5-day old larvae and are very specific such that it cannot be directly compared with other centralized business models.

To the authors knowledge, there is currently no economic model available that captures the entire supply chain, including the value of all marketable intermediate products and the final product at the same time. Moreover, yet no model follows the full-cost approach, allows for transition costs, and separates cost factors, like labour or energy, for the different production steps. Only if the supply chain is transparently modelled with all input parameters and production steps, it is possible to compare different business models and to find the most influential bio-economic parameters.

We describe a generic model that is able to estimate the amount of inputs and costs in different steps of dLM production and is ready to be used for detailed comparisons of business models after quick adaption of settings and input parameters. We have parameterized the model for Dutch circumstances and the black soldier fly species.

2 Methodological design

To fulfil the aim of a transparent supply chain model that allows to compare different business models and to find the most influential bio-economic parameters, in this section we describe the methodological design of our study. Hence, we first describe the supply chain structure that was used as a template for the model. Afterwards, we provide a qualitative overview of the simulation model. This is followed by an in-depth mathematical description of the model in sub-section "Mathematical model description", which can be skipped by those not interested in the details of the model. Next,

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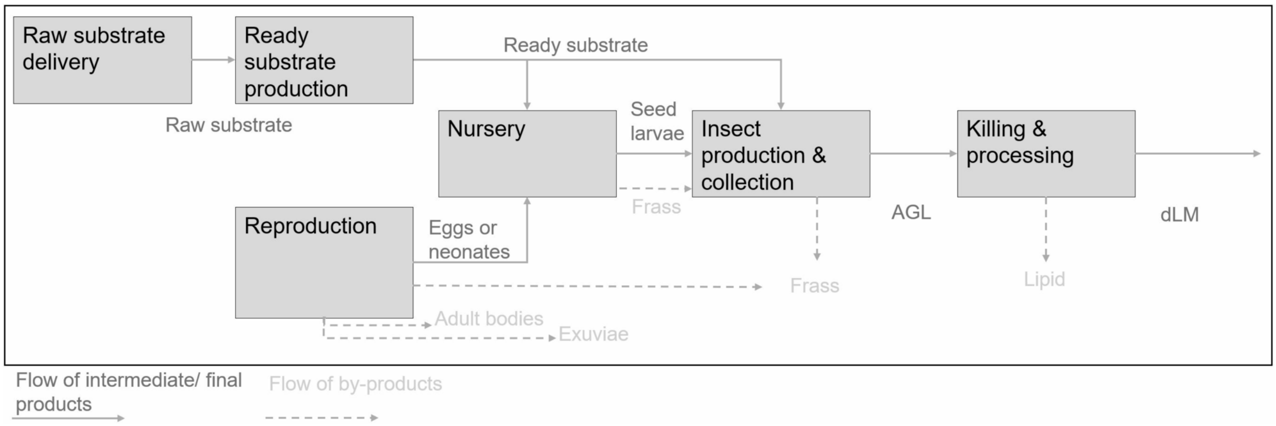

FIGURE 1 dLM production supply chain production steps.

in the model construction and parameterization sub-section we describe the construction procedure, data gathering, and determination of the input parameters. Finally, the model behaviour sub-section outlines the analysis methods and scenarios used.

Supply chain structure

Given the above, Figure 1 shows the template structure of the dLM meal production supply chain which was derived from publications of Saatkamp *et al.* (2022) and Veldkamp *et al.* (2022). Six main production steps were identified that each yield a product (e.g. neonates) or transform intermediate outputs (e.g. seed larvae) in new products (e.g. alive larvae).

The supply chain starts with two main streams. The first stream begins with the delivery of raw substrate (RSD) which are processed by the ready substrate production (RSP) into a mixture with the right texture, moisture, and nutritiousness to feed the larvae. The second stream is the reproduction (Rep) which encompasses all life stages of the flies (larvae, adults, and eggs) to provide enough eggs or newly hatched neonates to the consecutive step. The adult bodies, exuviae (remains of exoskeleton), and frass are by-products of the reproduction.

The consecutive step is the nursery (Nur) in which neonates are reared to seed larvae within 5 days under optimal climatic conditions.

As the size of the seed larvae is too small to separate them from the frass (S. Salari, personal communication), the mixture of seed larvae and frass is handed over to the insect production & collection step (P&C). The mixture is topped up with fresh substrate, reared for another 6 days under optimal climatic conditions, and separated into frass and AGL. Afterwards, the frass is sanitized and the AGL are handed over to the killing & processing step (K&P).

There are various methods available to kill and process larvae (Ojha *et al.*, 2021; Sindermann *et al.*, 2021) into different products like dried whole larvae, larvae meal, or dLM. As the most promising processed product seems to be dLM due to its more stable nutritiousness (Huis, 2022), it was decided to focus on that production. The insect lipid is a valuable by-product of the defatting process.

A challenge in modelling the supply chain is that it is possible that several actors with different scales, operate the same production step. At the same time, an actor can specialize in one production step or operate several production steps simultaneously.

Qualitative model description

Having described the structure of the supply chain, this sub-section gives a qualitative overview of our model that was developed in MS Excel. Furthermore, we show how we handled the challenge of different actors in the supply chain.

To be able to simulate different levels of vertical integration and sizes of actors, the model structure (Figure 2) was divided into three main modules, a technical module, an economic module and a transition module.

The technical module simulates masses and the number of animals or batches which are transferred in the total chain. One main task is to harmonize all quantity requirements and supplies by selecting an appropriate number of actors with a predefined scale. Therefore, all production steps, described in sub-section "Supply chain structure", were implemented as separate sub-modules which are characterised by the capacity that can be handled by one actor conducting this production step. The total mass produced in the supply chain is determined by the P&C sub-module. The other sub-modules automatically adjust the number of actors in such way that all requirements are fulfilled from the

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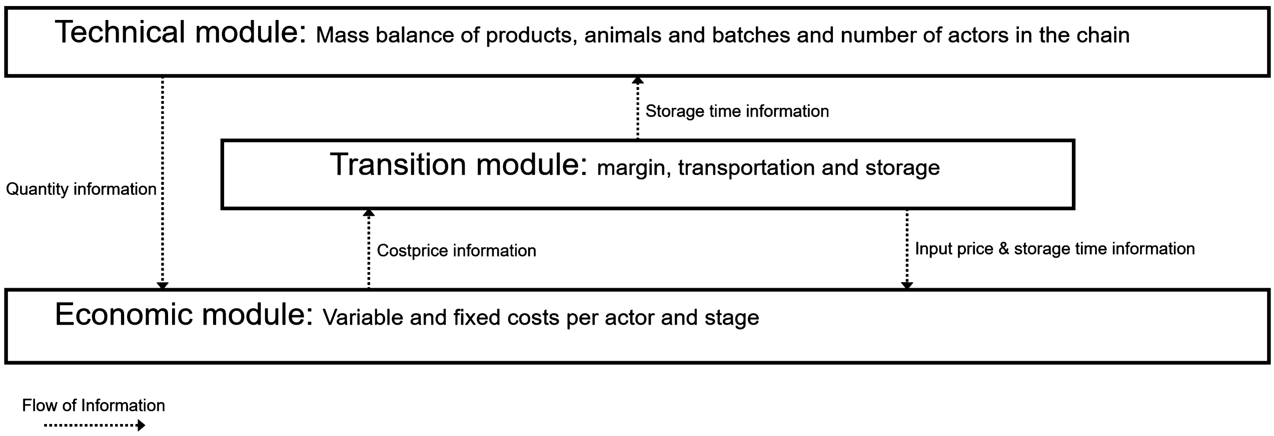

FIGURE 2 Three layered model structure: Information flow between the technical, transition and economic module of the insect production supply chain model.

previous supply chain steps and all supplies are processed by following supply chain steps. P&C was chosen as the core of the model because this step adds the highest costs to the production and uses the most production space. The transformations in the production steps are modelled with the help of feed conversion rates (FCR), mortalities, time requirements, predefined efficiencies or losses of machinery, and target DM contents. It showed as important to keep track of DM and WM content simultaneously, because conversion rates and pricing are mostly based on DM basis, but capacities of equipment and transportation rely on total WM.

The economic module estimates the costs that are involved with producing intermediate or final products. Equal to the technical module, the economic module consists of several sub-modules reflecting the different production steps. Opposed to the sub-modules of the technical module, the focus of the economic sub-modules is always one actor. The economic sub-modules receive quantity information from the technical module, which is divided by the total number of actors in the chain to obtain actor-specific values. Furthermore, the economic sub-modules follow the full-cost approach, which means that besides variable/direct costs also fixed costs are considered by use of depreciation periods and interest rates (Drury, 2008). In case of valuable by-products like Frass or Oil, allocated variable overhead costs and fixed costs are reduced by the assumed by-product revenues. Therefore, the sub-modules not only keep track of required labour, energy, water, other consumables, and input prices, but also calculate investments in equipment and land and process by-product prices. In a first step, for each production step, net added production costs (nAPC), which are the added production costs minus the by-product revenues, are calculated. Secondly, the nAPC are used to calculate the net total production costs (nTPC) up to the specific production stage. Finally, the economic sub-modules result in cost price (CP) information for all intermediate and final outputs.

The CP information is first directed to the transition module, processed, and then forwarded as an input price information for a subsequent economic sub-module. The transition module adds supply chain dependent transportation costs and margins to the cost prices. Specifically, in case of different actors conducting two consecutive production steps, the module assumes 100 km transportation for the intermediate products and a 5% margin on the cost price. Having added potential transition costs, net total costs (nTC) up to a specific stage and a market price (p) for intermediate/final products can be calculated based on nTPC and CP. Another main task of the transition module is to predict storage times of the intermediate/final products. These are used by the economic module to calculate storage costs and by the technical module to calculate storage losses. As the storage times are dependent on the structure of the supply chain, this means that also storage costs and storage losses can be different if several production steps are carried out by the same actor or not.

Mathematical model description

While sub-section "Qualitative model description" gave a qualitative overview of the simulation model, this sub-section provides in-depth insights into the calculations in the three main modules: technical module, economic module, and transition module.

Starting with the technical module, Figure 3 gives a detailed insight by filling the grey technical sub-modules. All sub-modules are defined by a transformation process (T) that relies on a set of transformation parameters, one or more capacities (C) that have to be

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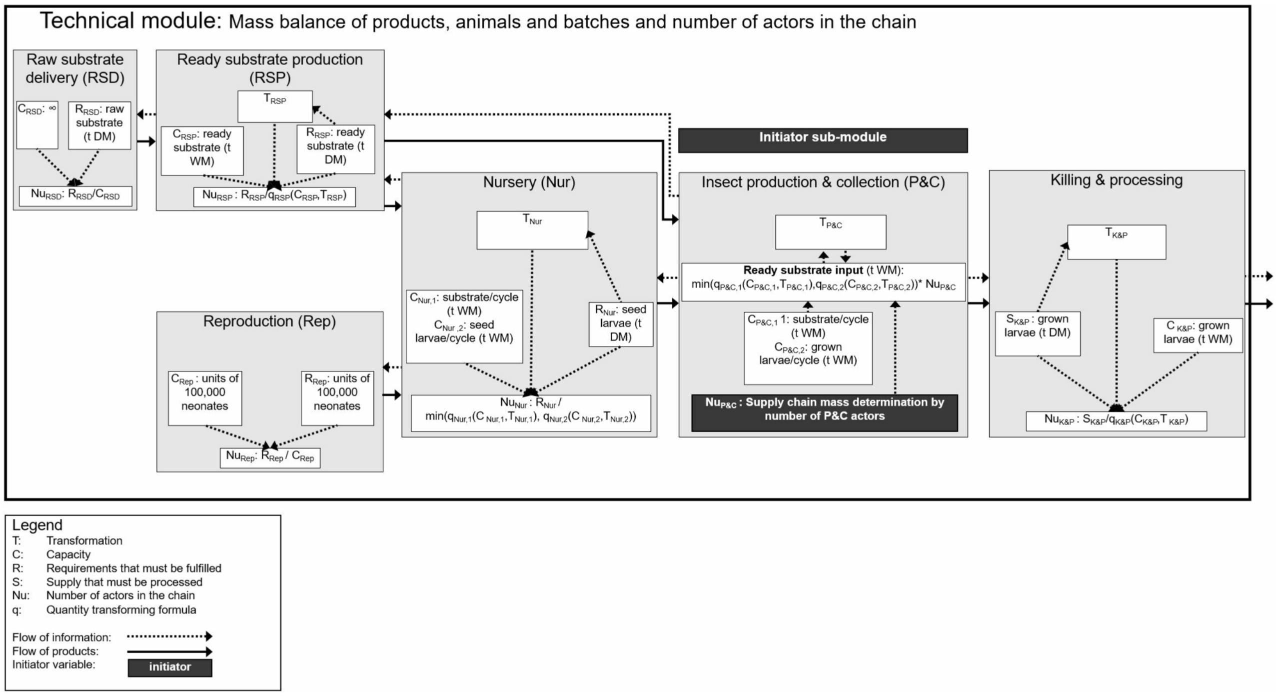

FIGURE 3 Initiation of the supply chain production and flow of products and information in the technical module.

met, and a number of actors (Nu) in the chain with a specific production size.

The initiator sub-module P&C indirectly determines all masses in the supply chain by issuing quantity requirements (R) chain upwards and supplies (S), that have to be processed, chain downwards. Thus, the dotted information arrows, which depict the information flow within the model, do not always follow the transportation of goods (solid arrows), but originate in the insect production & collection step.

In detail, the dark black marked variable, $Nu_{\text{P\&C}}$, initiates the whole supply chain production by determining the number of actors doing insect P&C.

$$I^{\text{ready substrate}}_{\text{WM,P\&C}} = \min\big(q_{\text{P\&C},1}(C_{\text{P\&C},1}, T_{\text{P\&C},1}), q_{\text{P\&C},2}(C_{\text{P\&C},2}, T_{\text{P\&C},2})\big) * Nu_{\text{P\&C}} \quad (1)$$

As expressed in Equation (1), the two capacities $C_{\text{P\&C},1}$ (substrate/cycle) and $C_{\text{P\&C},2}$ (AGL/cycle) are transformed by quantity transforming formulas $q_{\text{P\&C},1}()$ and $q_{\text{P\&C},2}()$ into theoretical ready substate amounts that can be handled with the underlying transformation parameters. The minimum of these two, is multiplied with $Nu_{\text{P\&C}}$ to calculate $I^{\text{ready substrate}}_{\text{WM,P\&C}}$: the WM based ready substrate input at P&C step in the whole supply chain.

Multiplying $I^{\text{ready substrate}}_{\text{WM,P\&C}}$ with the appropriate dry matter percentage (DM%) results in the requirement for DM based raw substrate (R_{RSP}) originated from P&C. Transforming $I^{\text{ready substrate}}_{\text{WM,P\&C}}$ with appropriate DM%, larvae weights, FCR and mortalities results in requirements for seed larvae (R_{Nur}) and supply of AGL ($S_{K\&P}$). The default value of $Nu_{\text{P\&C}}$ is 1 which means that one actor is conducting P&C.

$$Nu_{\text{Nur}} = R_{\text{Nur}} / \min\big(q_{\text{Nur},1}(C_{\text{Nur},1}, T_{\text{Nur},1}), q_{\text{Nur},2}(C_{\text{Nur},2}, T_{\text{Nur},2})\big) \quad (2)$$

As can be seen in Equation (2), with the example of the nursery step, for the others steps, besides P&C, the number of actors in the chain is determined by the ratio of requirements (or supplies) and the transformed capacities. If more than one capacity constraint is applicable, a minimum function is used to find the binding capacity.

Figure 4 represents a detailed view of the transformations with the example of K&P ($T_{\text{K\&P}}$). The transformation process itself, depicted efficiencies or losses of machinery, and target DM contents are developed on the base of a confident industry example.

The main input of K&P in the total supply chain are alive grown larvae and the main output is defatted larvae meal. In between, 6 further sub-steps from storage up to drying of the defatted meal were identified. While

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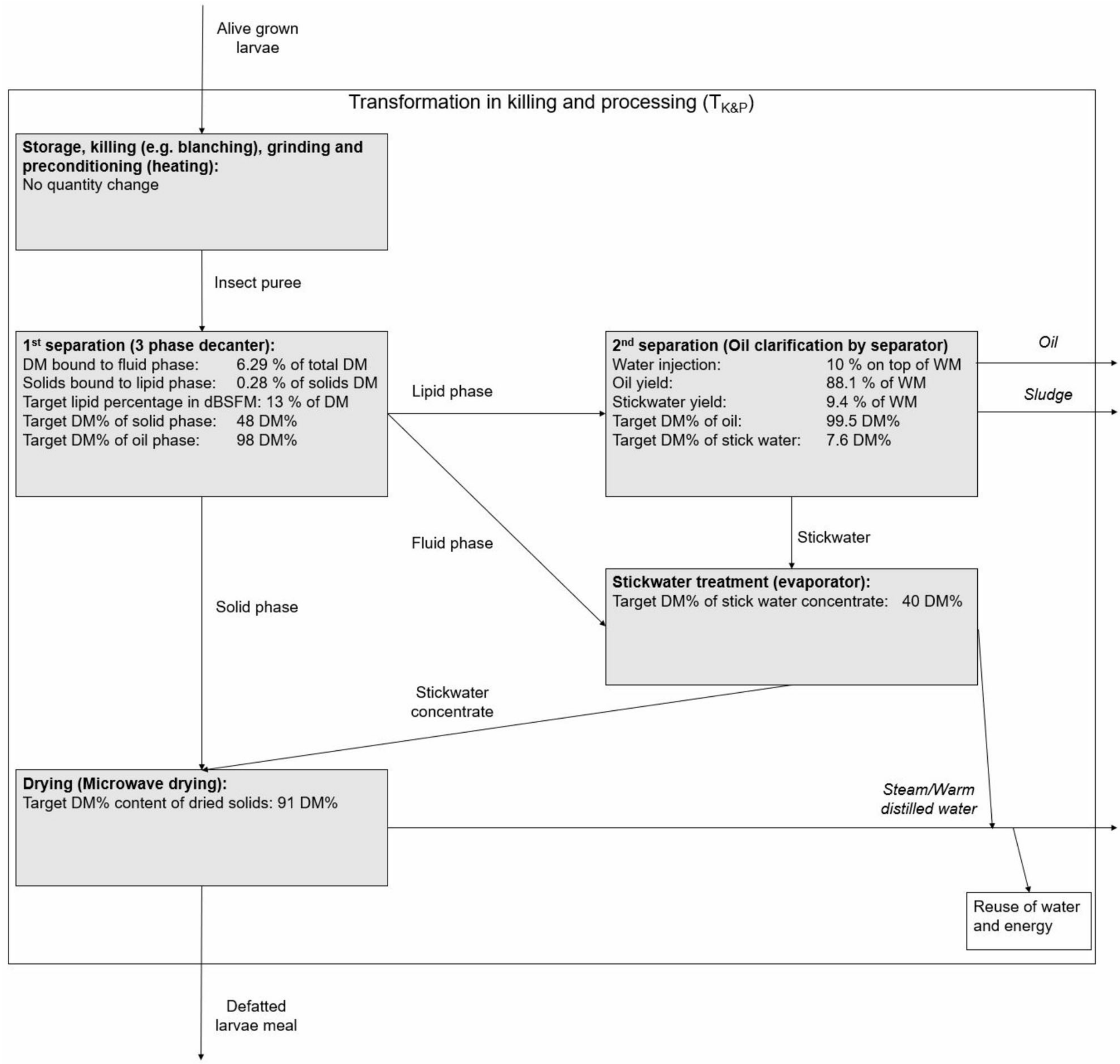

FIGURE 4 Example of more in depth transformation process: killing & processing.

storage, killing, grinding, and preconditioning induce no quantity change, the 1st separation divides the insect puree in three separate phases based on different densities: solid phase, fluid phase, and lipid phase. The lipid phase is injected with warm water and then clarified in a 2nd separation into oil, sludge, and stickwater. The fluid phase from the 1st separation and stickwater from 2nd separation are condensed in a multilevel flash evaporation up to 40 DM% and then brought back to the stream of solids. In the end, the sensitive products, solids and stickwater concentrate, which both cannot be circulated in an evaporator, are solely dried.

Information about total amounts of AGL, evaporated water, oil yield, or dLM yield are transferred to the economic module to calculate costs. Insights into the other transformation processes can be found in Supplementary Figure S1.

The incoming quantity information from the technical module has to be processed by the economic module.

$$x^{ac,i}_{main\ output} = x^{sc,i}_{main\ output}/Nu^{i} \tag{3}$$

More specifically, as the focus of the economic sub-modules is always one actor (ac) and one production step (i), the sub-modules get mass information like total amount (x) of main output in the supply chain (sc) and divide this by the number of actors to calculate the out-

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put that is produced by one actor.

$$
\begin{aligned}
&\mathrm{APC}^{ac,i} \\
&= \sum_{j=1}^{n}\left(x^{ac,i,j}_{raw\ substrate} * p^{j}_{raw\ substrate}\right) \\
&\quad + x^{ac,i}_{insect\ breeding\ feed} * p_{insect\ breeding\ feed} \\
&\quad + x^{ac,i}_{labour} * p_{labour} \\
&\quad + x^{ac,i}_{electricity} * p_{electricity} \\
&\quad + x^{ac,i}_{gas} * p_{gas} \\
&\quad + x^{ac,i}_{input\ water} * p_{input\ water} + x^{ac,i}_{waste\ water} * p_{waste\ water} \\
&\quad + x^{ac,i}_{cleaning\ water} \\
&\quad * 0.00125\ t\ detergent/t\ cleaning\ water * p_{detergent} \\
&\quad + \sum_{s=1}^{m}\left(x^{ac,i,s}_{storable\ product} * d^{s}_{storable\ product}\right. \\
&\quad \left. * t^{i,s}_{storable\ product} * p^{s}_{storage}\right) \\
&\quad + \left(x^{ac,i}_{animal} * p_{animal} + \frac{1}{2} * x^{ac,i}_{feed} * p_{feed}\right) \\
&\quad * t^{i}_{animal}/365 * r \\
&\quad + \left(x^{ac,i}_{building\ space} * p_{building\ space}\right) \\
&\quad * \left(dep_{building} + maint_{building} + r\right) \\
&\quad + \sum_{eq=1}^{e}\left(I^{ac,i,eq}_{equipment}\right) \\
&\quad * \left(dep_{eqipment} + maint_{equipment} + r\right) \\
&\quad - \sum_{b=1}^{q}\left(x^{ac,i,b}_{by-product} * p^{b}_{by-product}\right)
\end{aligned} \tag{4}
$$

Equation (4) shows the generic calculation method of net added production costs for all production steps. For most input parameters, costs are calculated by multiplying the amounts from the technical part with an input price. Some inputs, like insect breeding feed, do only occur in one step and amounts are zero in the other steps. Other products, like raw substrates ($j = 1 \ldots n$), storable products ($s = 1 \ldots m$), equipment ($eq = 1 \ldots e$) or valuable by-products ($b = 1 \ldots q$), do occur in various forms and are cumulated.

Furthermore, not all cost factors are only a multiplication of amount and price. As storage costs are priced per volume and time, the amount of storable products per year is multiplied by their density (d) and average storage time (t).

The calculation of forgone interest for animals in stock is based on the amount of animals and feed, but also the average live time of the animals within a year and the applied interest rate (r) have to be considered. Especially for the feedstuff, an in-time delivery is assumed, such that in average only half of the total feed requirement is bound in the animals.

Fixed costs are allocated by multiplying the investments (I) with appropriate depreciation rates (dep) and maintenance rates ($maint$). As it is assumed that the facility is newly build, the full investment amount is also multiplied with an interest rate.

The last exception are the valuable by-products which are subtracted from the costs instead of added.

$$
\begin{aligned}
&\mathrm{nTPC}^{ac,i} \\
&\quad = \sum_{w=1}^{l}\left(x^{ac,i,w}_{intermediate\ input\ product} * p^{w}_{intermediate\ input\ product}\right) \\
&\qquad + \mathrm{nAPC}^{ac,i}
\end{aligned} \tag{5}
$$

To get the net total production costs of one actor up to a certain step, the costs for intermediate input products ($w = 1 \ldots l$) from previous supply chain steps have to be added to the added production costs. Only for the raw substrate supplier and the reproduction (preformulated feed assumed), which have no intermediate inputs, *nAPC* is equal to *nTPC*.

$$
\mathrm{CP}^{i}_{main\ output} = \mathrm{nTPC}^{ac,i}/x^{ac,i}_{main\ output} \tag{6}
$$

Finally, the cost prices of the respective main outputs are calculated by diving the total production costs by the amount of main output.

As mentioned in sub-section "Qualitative model description", the cost price information is handed over to the transition module, which has the task of converting the cost prices ($\mathrm{CP}^{i}_{main\ output}$) into market prices ($p^{i}_{main\ output}$) which are used as input prices ($p^{w}_{intermediate\ input\ product}$) for the economic sub-modules of later production steps.

$$
\begin{aligned}
&p^{i}_{main\ output} \\
&\quad = \mathrm{CP}^{i}_{main\ output} * (1 + M) \\
&\qquad + \mathrm{WM}^{i}/PU^{i} \\
&\qquad * Dis^{i} \\
&\qquad * \left\{
\begin{array}{c|l}
Dis^{i} \le 50\ \mathrm{km} & p^{<50}_{transp} \\
50\ \mathrm{km} < Dis^{i} \le 100\ \mathrm{km} & \left(p^{<50}_{transp} * 50 + p^{50<x<100}_{transp}\right. \\
 & \quad \left. *(Dis^{i} - 50)\right)/Dis^{i} \\
100 \le Dis^{i} & \left(p^{<50}_{transp} * 50 + p^{50<x<100}_{transp}\right. \\
 & \quad *(100 - 50) + p^{100<}_{transp} \\
 & \quad \left. *(Dis^{i} - 100)\right)/Dis^{i}
\end{array}
\right. \\
&\quad = p^{w}_{intermediate\ input\ product}
\end{aligned} \tag{7}
$$

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TABLE 1 Selected average storage days

Storage days	Same actor		Different actor	
	Current step	Next step	Current step	Next step
RSD → RSP	0	7	7	7
RSP → Nur & P&C	0	0	7	7
Rep → Nur	0	0	2	2
Nur → P&C	0	0	2	2
P&C → K&P	0	0	2	2
K&P →	0		7	

TABLE 2 Raw substrate description and composition that is used for the default scenario

	Composition of raw substrate mix (% of DM)	Raw substrate price (€/tWM)	DM content (%)
Spent grain	15	110.6	28
Potato peels	55	74.8	22
Wheat bran	30	295.46	86.9
Source	INSECTFEED Consortium	Duynie Feed (2022)	Bühler Group Insect Technology

Therefore, the transition module adds a supply chain structure dependent margin (M) on the costprice by multiplying CP with $(1+M)$. The transportation is added based on the ratio of WM per pricing unit (PU), an average transportation distance (Dis), and a staggered price for transportation. While the pricing unit is mostly 1 tDM, only neonates are transferred to the nursery by units of 100,000 individuals.

The other main task of the transition module is to determine supply chain structure dependent storage times ($t^{i,s}_{storable\ product}$). One product needs to be stored at the exit of the current production step and at entry of the next production step. Table 1 shows the selected average storage days in case two consecutive steps are operated by the same actor or by different actors. For example, if RSD and RSP is done by one actor, at the exit of RSD no storage time for the raw substrate is assumed, only at the entry of RSP in average 7 days storage occurs. If RSD and RSP are two different actors, raw substrate needs to be stored at both stages for average 7 days.

Model construction and parameterization

The model was constructed in collaboration with the INSECTFEED consortium,[1] which consists of insect experts from science and industry. Material flow examples, which were provided by business partners, were the basis for the technical module. In regular consortium meetings all members were updated on the status and could provide remarks and tips.

At the time that the model structure was getting shape, we provided a list of required input parameters to all consortium members. This list included currently assumed values that could be found in literature or extracted from material flow examples. In multiple personal meetings with experts of different fields within and beyond the INSECTFEED consortium, the plausibility of the parameters was checked and, if required, parameters were adjusted.

One input that was extracted from material flow examples is the mix of raw substrates. As insects are still seen as "farmed animals" under the EU law, they can only be fed with substrates that are also deemed as save for other non-ruminant animals (IPIFF, 2022). Thus, the example raw substrate mix only includes GMP+ certified raw substrates. As can be seen in Table 2, 15% spent grain provide mainly energy, 55% potato peels deliver the required protein content and 30% wheat bran, which has an DM content of 86.9%, is used as dry component to reach the required DM content of the substrate mix. Opposed to that, price information originates from publicly available literature. More specifically, it was taken from the price tables of Duynie Feed (2022). Assumed parameters like feed preparation losses of 1%, a conversion rate of 4.34 DM/DM and mortalities of 10% and 0.5% (Nur and P&C) were retrieved

1 The members and recent publications of the INSECTFEED consortium can be found at www.insectfeed.nl.

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in personal meetings and are used to calculate the raw substrate demand and costs.

As a failure in neonate production would have very detrimental effects, the reproduction cycle is operated with special insect breeding feed. As there was no specific price data available for insect breeding feed, it is assumed that it has a similar price like industrial poultry feed.

In consultation with our business partners, it was decided that most electricity, gas, water and detergent usages are taken from the most optimistic scenario in the environmental study of Spykman *et al.* (2021). Only in some cases, like the overestimated cleaning water or evaporation energy, parameters were adjusted to more realistic industry values.

Similar procedures of data collection were applied to several prices, like €32.25 per working hour or €787.65 per m2 building, interest rates, depreciation rates and maintenance rates.

As can be seen in Table 3, three different scale scenarios, Small, Medium, and Large, were parameterized in the model. The selected scales base on the current industry standard of the equipment supplier "Bühler Group Insect Technology". The capacities were calculated such that under default production assumptions all capacities, within a specific scale, perfectly match to each other. While the amount of seed larvae and AGL per cycle are binding in the default situation, it is expected that nursery and P&C can handle 50% more ready substrate if needed.

Besides the capacities, labour force, building space and investment in equipment were made dependent on size and directly or indirectly retrieved from interviews with industry partners.

If needed, overhead values were assigned to the individual steps by assumed distribution keys. Labour is assumed to be equally distributed between the three steps RSP, P&C and K&P, the distribution keys of the building space were developed by counting squares on a provided graph (see Supplementary Figure S2) and investment in inventory was allocated by 20%, 35% and 45% to RSP, P&C and K&P.

For the nursery step no direct data was available. Because the nursery has to handle the same number of crates as P&C, but these are smaller and less substrate needs to be handled, 80% of the labour force that is needed in P&C is assumed. Required building space is obtained by multiplying $Sp_{P\&C}$ with the ratio of nursery crate volume and production crate volume and for investment in equipment again 80% of the requirement in P&C is assumed.

Model behaviour

To test if the model behaves as expected, we conducted a scenario analysis, a sensitivity analysis, a contingent sensitivity analysis and a break-even analysis.

Some circumstances were estimated as highly influential by the consortium and thus analysed with specific scenarios that are compared to the default scenario. The first two scenarios are small scale (1.a) operation and large scale (1.b) operation compared to medium scale operation, as already shown in Table 3. Moreover, some operators include no nursery (2) step and rear from neonates to AGL in one production step. Thus it was made possible in the model to skip the nursery step. To analyse the importance of transition costs, one scenario depicts the maximum possible transition costs in the supply chain by assuming that all production steps are performed by different companies (3). Further scenarios deal with the value of by-product values. While insect oil (4.a) is assumed to have the same price as soybean oil in the default scenario, it can also be sold as a premium product for €3,000/tDM. Moreover, frass (4.b) is assumed to have a price of €89/tDM in the default scenario, but for example Frassor currently sells it for €1,685/tDM as garden fertilizer (Frassor, 2023). Using currently not allowed raw substrates, could reduce their costs by half (5.a) or lead to free raw substrates that incur no (5.b) costs. Having high value by-products and no raw substrate costs (6) is seen as the most prospective scenario by the consortium members and is the last specific scenario tested.

To get a broader overview and to find the most influential out of ca. 170 input parameters a sensitivity analysis was conducted by increasing and decreasing every input parameter by 20% (wider range) or 10% (narrow range) while keeping track of the market prices of dLM. Relative response rates (RR) are calculated by dividing the market price change of dLM by the change in input parameters. The sensitivity analysis mostly bases on a one-by-one change of parameters, however in some cases, like dry matter percentage and fat content percentage of the larvae, the technical interrelations were respected (see Supplementary Text S1). Parameters with a RR higher than 0.1 in absolute terms were selected as the most influential ones. They were logically tested for their plausibility and assigned to distinct categories.

The sensitivity of some parameters is dependent on the status of the supply chain. Thus, we conducted a contingent sensitivity analysis to see how sensitivities change. While in the default supply chain it is assumed that, due to re-feeding practice, the binding capacity is the WM larvae per cycle, no re-feeding (A) would

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TABLE 3 Scale dependent parameters

Name	Unit	Small	Medium	Large	Source/calculation
$C^{\frac{\text{ready substrate}}{\text{yr}}}_{\text{RSP},t\ \text{WM}}$	tWM/yr	20,053	60,434	181,301	Bühler
$C^{\frac{\text{neonates}}{\text{yr}}}_{Rep,\#}$	#/yr	28,719,014,889	86,550,455,831	259,651,367,492	
$C^{\frac{\text{ready substrate}}{\text{cycle}}}_{\text{Nur},t\ \text{WM}}$	tWM/cycle	37.0	111.7	335.0	(50% overcapacity)
$C^{\frac{\textit{seed larvae}}{\text{cycle}}}_{\text{Nur},t\ \text{WM}}$	tWM/cycle	5.3	16.0	48.0	
$C^{\frac{\text{ready substrate}}{\text{cycle}}}_{\text{P\&C},t\ \text{WM}}$	tWM/cycle	450.0	1,356.2	4,068.5	(50% overcapacity)
$C^{\frac{\textit{grown larvae}}{\text{cycle}}}_{\text{P\&C},t\ \text{WM}}$	tWM/cycle	72	218	653	
$C^{\frac{\textit{grown larvae}}{\text{yr}}}_{\text{K\&P},t\ \text{WM}}$	tWM/yr	4,260	12,839	38,516	
$Lab_{\text{RSP+P\&C+K\&P}}$	#FTE	18.6	28.0	50.0	Bühler
Lab_{RSP}	#FTE	6.19	9.33	16.67	$1/3 * Lab_{\text{RSP+P\&C+K\&P}}$
Lab_{Rep}	#FTE	3.00	8.00	17.00	Insectocycle
Lab_{Nur}	#FTE	4.96	7.47	13.33	$0.8*_{Lab\text{P\&C}}$
$Lab_{\text{P\&C}}$	#FTE	6.19	9.33	16.67	$1/3 * Lab\text{RSP + P\&C + K\&P}$
$Lab_{\text{K\&P}}$	#FTE	6.19	9.33	16.67	$1/3 * Lab\text{RSP + P\&C + K\&P}$
$Sp_{\text{RSP+P\&C+K\&P}}$	m^2	5,000	10,000	20,000	Bühler
Sp_{RSP}	m^2	524	952	1,714	Counted squares / total squares $* Sp_{\text{RSP+P\&C+K\&P}}$
Sp_{Rep}	m^2	584	1,616	4,107	Insectocycle
Sp_{Nur}	m^2	599	1,359	3,041	Ratio of crate volumes $* Sp_{\text{P\&C}}$
$Sp_{\text{P\&C}}$	m^2	2,633	5,976	13,371	Counted squares / total squares $* Sp_{\text{RSP+P\&C+K\&P}}$
$Sp_{\text{K\&P}}$	m^2	1,843	3,071	4,914	Counted squares / total squares $* Sp_{\text{RSP+P\&C+K\&P}}$
$Eq_{\text{RSP+P\&C+K\&P}}$	Mil. €	5.87	20.00	39.50	Bühler
Eq_{RSP}	Mil. €	1.17	4.00	7.90	$0.2 * Eq_{\text{RSP+P\&C+K\&P}}$
Eq_{Rep}	Mil. €	0.56	1.32	3.34	Insectocycle
Eq_{Nur}	Mil. €	1.64	5.60	11.06	$0.8 * Eq_{\text{P\&C}}$
$Eq_{\text{P\&C}}$	Mil. €	2.05	7.00	13.83	$0.35 * Eq_{\text{RSP+P\&C+K\&P}}$
$Eq_{\text{K\&P}}$	Mil. €	2.64	9.00	17.78	$0.45 * Eq_{\text{RSP+P\&C+K\&P}}$

* Abbreviations: *C* = capacity; *Eq* = equipment; FTE = full time labour equivalent; *Lab* = labour; *Sp* = space.

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mean that the binding capacity is the substrate per cycle instead.

Moreover, the default scenario assumes that there can be relative numbers of actors in the chain. That means that intermediate products can be purchased or sold at the market in all amounts for the internal supply chain price and the full capacity is always used. In other words: The supply chain is newly set up and everything is perfectly aligned. Contrary, the no-market scenario (B) assumes that intermediate products cannot be purchased or sold at the market. This implies that the supply chain must produce the intermediate products in exactly the right amounts with an integer number of actors. It is possible that not the full capacity is used and thus the no-market scenario shows the maximum response to changes in production parameters. However, to keep it plausible, the status of labour was changed into "variable labour" such that the amount of labour varies with the percentage of capacity that is used.

The default model assumes that there is no interrelation between FCR and the individual larval end weight (IEW) of AGL. In other words, changes in these parameters result from genetical improvements or changes in diet. Nevertheless, FCR and IEW are heavily interrelated (C) if they are only manipulated by the underlying larval density.

The last applied analysis method is the break-even analysis. It was tested how much key parameters have to change such that the larvae products, AGL or dLM, become price competitive with traditional protein suppliers, soybean meal (SBM) and fish meal (FM), in animal feed. The break-even prices were calculated by assuming that the same protein content must be delivered. Resulting differences in energy, which can be metabolized by broilers, were priced with €0.2/kcal. Thereafter, the MS Excel solver was used to test how much parameters have to change to achieve break-even prices. The exact economic formulas that were used in the analysis can be found in Supplementary Text S1.

3 Results

Results of the default situation are presented first, followed by the model behaviour results, and finally a brief summary of the key findings is given.

Default situation

Table 4 shows the required amounts of inputs in the dLM production for the default situation. Default situation means one company conducting all steps from RSP up to K&P, a medium production size and most likely values as deterministic input.

As visible in the second column of Table 4, with an assumed feed conversion rate of 4.35, mortalities of 10% and 0.1% (Nur and P&C), and losses due to aerobic digestion, 5.57 tDM raw substrate are needed to produce 1 tDM dLM. Moreover, 266.42 units of neonates (27 million individuals) are required for 1 tDM dLM.

For example, the production step Rep, produces 0.02 tDM frass, 0.003 tDM exuviae and 0.003 tDM dead adults for each 266.42 units of neonates in the chain. It requires 4.57 h labour, 0.12 MWh energy and 6.93 t water for the same amount. As Table 4 shows, in a centralized approach, neonates directly go over to Nur and no storage is required. Also transportation and margin are not applicable. Besides variable inputs, per production of 266.42 neonate units within one year, 0.54 m^2 building space and €440 equipment is required. As all inputs in the different production steps are standardized on 1 tDM dLM, the sum of one column represents the sum required to produce 1 tDM dLM respecting the whole supply chain.

The main supply chain by-product amounts are frass and oil with 2.23 tDM and 0.22 tDM. While Frass mostly appears in the P&C steps, oil only stems from the K&P step. The amount of exuviae and dead adults, which are only produced in the Rep step, is quite low. One medium sized company produces ca. 11 tDM (0.003 tDM * 3,249 tDM) of each of them. Although exuviae might contain some interesting ingredients like chitin, it is questionable if it is economically viable to invest in processing techniques for such low amounts. It is more likely to be organic waste (S. Salari, personal communication).

There is a huge difference between the total amount of raw substrates (5.57 tDM) and the sum of alive grown larvae and frass (1.23 tDM + 2.46 tDM = 3.45 tDM). The difference between these comes from gaseous emissions (5.57 tDM – 3.45 tDM = 2.12 tDM).

The amount of labour and water required in the supply is quite high. In total 25.5 h of labour and 17.01 t of water are needed to produce 1 tDM dLM. Labour requirement is high in all production steps, with RSP demanding a little bit less and P&C demanding more labour force. Water is mainly required in Rep and P&C. Insect breeding feed (0.03 t) and detergent (0.01 t) are not required in huge masses. In case of detergent, the amount is low because it is only concentrated 0.13% in the cleaning water. In total, 1 tDM dLM requires 4.93 MWh energy and 4.15 m^2 building space. The low

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TABLE 4 Amounts in dLM production per ton dLM (default situation: one central medium sized company)

Production step	Production step outputs						Variable inputs								Fixed inputs			Transition	
	(Intermediate) products		Frass/ fertilizer (t DM)	Oil (t DM)	Exuviae (t DM)	Dead adults (t DM)	Raw substrate (t DM)	Insect breeding feed (t DM)	Labour (h) (fixed or variable)	Electricity (MWh)	Gas/ heating (MWh)	Input water (t)	Waste-water (t)	Detergent (t)	Storage capacity (m^3)	Building (m^2)	Inventory (th €)	Transportation to the next stage (km ∗ t)	Margin to next stage (% on cost-price)
RSD	5.57	t DM raw substrate					5.57								0.45			1,883	
RSP	5.50	t DM ready substrate							3.86	0.43		2.29	2.29	0.00	0.45	0.29	1.23		
Rep	266.42	units (of 100,000) neonates	0.02		0.003	0.003		0.03	4.57	0.09	0.03	6.93	6.93	0.01		0.54	0.44		
Nur	0.11	t DM seed larvae	0.22						5.69	0.16	0.05	0.22	0.22	0.00		0.54	1.72		
P&C	1.23	t DM AGL	2.23						7.11	1.80	0.36	5.50	5.50	0.00		1.84	2.15		
K&P	1.00	t DM dLM	0.00	0.22					4.27	0.13	1.88	2.06	4.69	0.00	0.04	0.95	2.77	110	5
Sum			2.46	0.22	0.00	0.00	5.57	0.03	25.50	2.61	2.32	17.01	19.63	0.01	0.94	4.15	8.32	1,993	

* All values in Table 4 are divided by the total amount of dLM (3,249 tDM) in the supply chain, such that the benchmark is always 1 tDM dLM.

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building space supports the claim of a low soil surface requirement for insect production compared to other protein production like soybeans (Huis, 2022). However, to produce 1 tDM dLM per year, currently equipment for €8,320 is required which is quite a huge investment. As production is done by one central company, transportation occurs only in the first and last production steps of the supply chain. With 1,879 km ∗ t, the raw substrates induce the highest transportation due to the high amounts required and mostly wet raw substrates (70% water).

Coming from amounts to costs, Table 5 displays the costs and by-product revenues of the different production steps divided by the total amount of dLM in the supply chain. Thus, the net added production costs column shows how much production costs each step contributes to the costprice of 1 tDM defatted BSF meal. The fact that the two main product streams, substrate, and neonates, come together in the nursery is represented by the dotted lines in Table 5. The net total production costs of the nursery are calculated by 2,660 ∗ 9,0% + 333 + 476 ≈ 1,049 (nTC of RSP ∗ % of ready substrate in nursery + nTC of Rep + nAPC of Nur). Net total costs further include transition costs and in the last column intermediate product prices are given. All values (except for the last column) can be read as €/tDM dLM.

The highest cost factors are the raw substrate and the building and inventory with €1,936 and €1,459 per tDM dLM. While raw substrate costs per definition only occur in the RSD, building and inventory costs are the highest in P&C and K&P (€432 and €455). Although the amount of labour and water seemed quite high, labour is only a medium cost contributor with €822 and water a minor cost contributor with €91 per tDM dLM. The energy sources electricity and gas together contribute to €693 of the costs. Highest energy costs appear in P&C and K&P with €324 and €253 per tDM dLM. As gas and electricity have different prices in different countries, optimal equipment also depends on the relation of electricity and gas prices in the production country (J.W. Heesakkers, personal communications). Neglectable are the costs for insect breeding feed and interest for animals. Intertest for animals is neglectable, because of the very short lifetime of BSF larvae.

In the default situation, the by-product value of frass and insect oil is €219 and €307 per tDM dLM, which reduces the production costs by €526. Contrary, the transition costs, transportation and margin, increase the costs by €551 per tDM dLM (€309 + €243).

Production steps that add the highest costs to dLM production are RSD and P&C. RSD adds production costs of €1,952 per tDM dLM which mainly stems from the raw substrates itself. P&C adds €821 production costs that is mainly driven by building and inventory costs. The production step that adds the lowest costs is Rep with €333.

The sum of all nAPC is €4,564 per tDM dLM and represents the pure net production costs of all production steps. Including the transition costs of €551, nTC (and *p*) of 1 tDM dLM is €5,116. Assuming a protein content of 46% of the DM, it would mean a protein price of €11.12 per kg. Interesting prices for intermediate outputs are for example €484 per tDM ready substrate or €1.25 per 100,000 neonates. Only if the company was offered these products for a cheaper price, it should outsource that production.

Figure 5 shows the cost composition of alive grown larvae, which are the product of the high cost adding production step, P&C. Although, P&C is the second highest production cost contributor, in total 77.26% of the grown larvae price comes from the intermediate inputs seed larvae (23.37%) and ready substrate (53.89%). Around one third of the seed larvae costs originate in buildings & inventory and labour. At the same time, more than 70% of the ready substrate price stems from the raw substrate costs. Due to the high impact of the intermediate input products on the cost price of AGL, these costs contributors, raw substrate (43.09%), buildings & inventory (22.23%) and labour (15.11%) are also the three highest (indirect) cost contributors to the grown larvae production. However, costs still dilute. While insect breeding feed makes up for 1.06% of the seed larvae costs, it only explains 0.25% of the alive grown larvae costs.

Model behaviour

Table 6 shows the changes in intermediate output prices of different scenarios compared to the default situation. Apparently, reducing to small scale (1.a) would increase the product prices in a similar magnitude like increasing to large scale (1.b) would reduce the prices. The price for AGL, which is €3,503 in default, varies between €3,026 and €3,984 and the price for dLM between €4,271 and €5,894 depending on the size.

With the default assumptions, skipping the nursery (2) leads to a €127 higher price for grown larvae. The main reason is the ineffective usage of crate and thus factory volume, because newly hatched larvae need much less space than older larvae.

In the all different companies scenario (3), the additional transaction costs increase the dLM price by €1,253. That is a higher change than the cost reduc-

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TABLE 5 Costs in dLM production in €/tDM dLM

Production step	Production step outputs		Costs										By-product revenue		Transition costs		Sum of costs and revenues			Price (p) of (intermediate) products (€/unit intermediate product)	
			Raw substrate	Insect breeding feed	Labour	Electricity	Gas/heating	Water	Consumables	Storage	Interest animals	Building and inventory	Frass	Oil	Transportation (to the next stage)	Margin	Net added production costs (nAPC)	Net total production costs (nTPC)	Net total costs (nTC)		
RSD	5.57	t DM raw substrate	1,939							12					292		1,952	1,952	2,244	403	€/t DM raw substrate
RSP	5.50	t DM ready substrate			124	67		11	8	12		193					417	2,660	2,660	484	€/t DM ready substrate
Rep	266.42	units (of 100,000) neonates		11	147	14	4	34	24			100	1				333	333	333	1.25	€/units (of 100,000) neonates
Nur	0.11	t DM seed larvae			183	25	6	1	1	0	0	279	19				476	1,049	1,049	9,406	€/t DM seed larvae
P&C	1.23	t DM AGL			229	280	44	27	6	0	1	432	198				821	4,291	4,291	3,503	€/t DM alive grown larvae
K&P	1.00	t DM dLM			138	20	233	18	3	5	0	455	0	307	17	243	564	4,856	5,116	5,116	€/t DM defatted insect meal
	0.22	t DM lipid																			
Sum			1,939	11	822	406	287	91	42	30	1	1,459	219	307	309	243	4,564				

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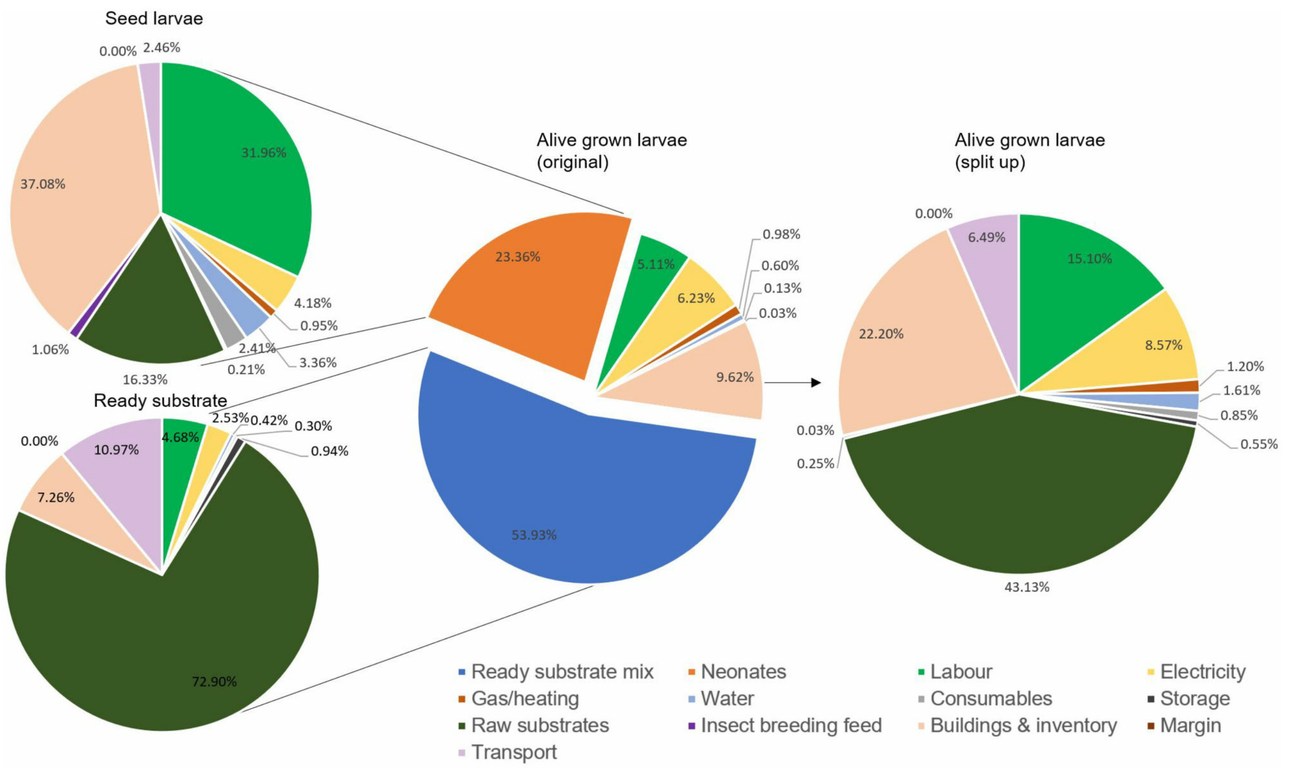

FIGURE 5 Flow of costs and cost composition of grown larvae in P&C. Left: cost composition of the intermediate inputs, seed larvae and ready substrate; middle: original cost composition of AGL; right: cost composition of AGL with intermediate inputs split up in their cost components.

tion of large-scale operation compared to medium scale operation.

Due to the high amount of frass in the chain, the impact of the frass price (4.b) is very high and could reduce dLM price by €4,130. While frass appears as by-product in several stages, insect oil prices (4.a) could only reduce the costs of the K&P step by €381.

Halving the raw substrate costs (5.a), would reduce the dLM price by €1,019. In a linear trend, assuming no raw substrate costs (5.b), would reduce the dLM price by €2,037.

Having high value by-products and no substrate costs at the same time (6) is of course the most favourable option and would reduce the alive grown larvae price to –€1,291/tDM (€3,503 – €4,794 tDM) and the dLM price to –€1,433/tDM (€5,116 – €6,549). Then, the larvae product could become the by-product with the focus on waste sanitation and frass production.

Table 7 shows the result of the sensitivity analysis for the default situation. Only the 16 parameters with an absolute relative response rate greater than 0.1 are shown. The upwards directed (20%) RR of 0.21 for potato peel prices means that the price of dLM increases by 0.21% if the default price for potato peels increases by 1%. As the downwards directed (–20%) RR is also 0.21, decreasing the potato peal price by 1% would also decrease the costs of dLM by 0.21%. RRs for the wider range (±20%) are very similar to the RRs in the narrow range (±10%). Thus it is selected to focus on the wider range.

The 16 parameters can be summarized in 12 most important categories:

1. The *price of the raw substrates* (potato peels and wheat bran) is influencing the production costs very much. To decrease the costs, lower value raw substrates have to be found which might yet not be legal to use.
2. *Energy prices*, which depend on the location as well as on potential own energy production e.g. from solar panels.
3. *Labour force* in form of wage and working hours per full time labour equivalent. Again highly dependent on the production location.
4. Depreciation rate of *equipment*, which represents the useful life and automatization level. Due to the low soil surface requirement, depreciation of the building plays not an important role.
5. Higher *DM percentages of AGL* at the end of rearing lead to lower costs, because less water needs to be removed in the K&P. Furthermore, fixed costs

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TABLE 6 Changes in intermediate output prices for different scenarios

Default scenario (medium scale)	Small scale (1.a)	Large scale (1.b)	No nursery (2)	All different companies (3)	High value oil (3,000 €/t DM) (4.a)	High value frass (1685 €/t DM) (4.b)	Half raw substrate price (5.a)	No raw substrate costs (5.b)	High value oil & frass and no raw substrate costs (6)	
403	0	0					–174	–348	–348	€/tDM raw substrate
484	20	–22	0	78			–176	–352	–352	€/tDM ready substrate
1.25	0.26	–0.25		0.13		–0.10			–0.10	€/units (of 100,000) neonates
9,406	2,228	–2,178	N.A.	1,185		–3,368	–782	–1,564	–4,932	€/tDM seed larvae
3,503	481	–477	127	828		–3,211	–792	–1,584	–4,794	€/tDM alive grown larvae
5,116	778	–845	164	1,253	–381	–4,130	–1,019	–2,037	–6,549	€/tDM defatted larvae meal

are diluted with a higher larvae DM production, because the binding capacity is the WM larvae per cycle. For the wider range (20%), the downward RR (–0.6) is higher than the upward RR (–0.4) in absolute terms, which means that a decrease in DM percentage is more detrimental than an increase could reduce costs. The difference is lower for the narrow range (10%) with RRs of –0.44 and –0.54.

6. In the default situation, one percent higher *individual end weight of AGL* reduces the dLM price by 0.14%. This can be explained by the lower number of required neonates and seed larvae.
7. A better *growth rate of biomass*, represented by a shorter time in P&C, can dilute the same fixed costs by a higher production volume. Reducing the cycle by one day from 6 to 5 days reduces the dLM price by 2.66% ($1/6 * 100 * 0.16$).
8. The *feed conversion rate in P&C*, which is the main parameter for feed trials, has the second highest relative response in absolute terms. Decreasing the FCR by 1% decreases costs by 0.47% due to reduced raw substrate requirement.
9. The *larvae density in P&C*, which changes feed conversion rate and individual end weight, also has a high influence on costs. Increasing the current larvae density of 4.79 # larvae/gDM substrate by 1% decreases costs by 0.21%. Reducing the density by one percent seems to have a higher impact than increasing the density by one percent. Thus, operating at a slightly to high density might be optimal with considering natural variations in production.
10. Everything else staying the same, a one percent higher *fat content of AGL* increases costs by 0.14%. The lower selling price for insect oil compared to the protein meal is the reason for that. The, due

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TABLE 7 Relative response rate of dLM price to upwards and downwards directed changes in input parameters for the default scenario (in %/%)

Category	Input parameter	Value (€)	Unit	Upwards (20%)	Downwards (–20%)	Upwards (10%)	Downwards (–10%)
Prices	Potato peels	74.80	€/tWM	0.21	0.21	0.21	0.21
	Wheat bran	295.46	€/tWM	0.12	0.12	0.12	0.12
	Energy in general			0.14	0.14	0.14	0.14
	Labour wage	32.25	€/h	0.17	0.17	0.17	0.17
Exchange, depreciation, and maintenance rates	Hours per full time labour equivalent	1,650.00	h/FTE	0.13	0.14	0.13	0.14
	Depreciation rate of equipment	8.00	%/yr	0.14	0.14	0.14	0.14
Production parameters	DM percentage of AGL	31.00	%	–0.40	–0.60	–0.44	–0.54
	Individual end weight of AGL	0.17	g WM/larvae	–0.14	–0.21	–0.15	–0.19
	Time in P&C	6.00	*d*	0.16	0.16	0.16	0.16
	Feed conversion rate in P&C	4.35	FCR (DM/DM)	0.47	0.47	0.47	0.47
	Larvae density in P&C (external factor)	4.79	# larvae/g DM substrate	–0.21	–0.30	–0.23	–0.27
	Fat content of AGL	30.00	% of DM	0.14	0.12	0.14	0.13
	Target DM% of solid phase	48.00	DM%	–0.07	–0.11	–0.08	–0.09
	Capacity of Nur (seed larvae)	16.01	tWM seed larvae/cycle	–0.08	–0.12	–0.09	–0.11
	Capacity of P&C (AGL)	217.57	tWM AGL/cycle	–0.12	–0.17	–0.13	–0.15
	Capacity of K&P	12,838.53	tWM AGL/yr	–0.10	–0.15	–0.11	–0.14

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TABLE 8 Relative response of dLM price to upwards and downwards directed changes in production parameters for different scenarios (in %/%)

Input parameter	Value	Unit	Default scenario		Substrate binding: no re-feeding (A)		No-market scenario and variable labour (B)		FCR & IEW interrelated: same substrate and genetical material (C)	
			20%	–20%	20%	–20%	20%	–20%	20%	–20%
Weight of seed larvae	0.02	g WM					0.32			
Time in production nursery	5.00	*d*					0.33			
Feed conversion rate (neonates)	4.35	DM/DM			0.14	0.14				
DM percentage of larvae	31.00	%	–0.40	–0.60	–0.21	–0.31	–0.26	–0.65	–0.40	–0.60
Individual end weight of grown larvae	0.17	g WM/larvae	–0.14	–0.21	–0.13	–0.19		–0.55	1.58	0.45
Time in production rearing	6.00	*d*	0.16	0.16	0.16	0.16	0.39	–0.52	0.16	0.16
Feed conversion rate (seed larvae)	4.35	CR (DM)	0.47	0.47	0.60	0.60	0.64	0.43	0.41	0.34
Larvae density in P&C (external factor)	4.79	# larvae/g DM substrate	–0.21	–0.30	–0.29	–0.40	–0.22	–0.51	N.A.	N.A.
Fat content of alive larvae	30.00	% of DM	0.14	0.12	0.21	0.18	0.13	0.11	0.14	0.12
Target DM% of solid phase	48.00	DM%		–0.11		–0.11		–0.11		–0.11
Capacity of RSP	60,433.69	tWM ready substrate/yr						–0.24		
Capacity of Rep	8.66E+10	# neonates/ yr						–0.21		
Capacity of Nur (ready substrate)	111.65	tWM ready substrate/ cycle				–0.12				
Capacity of Nur (seed larvae)	16.01	tWM seed larvae/cycle		–0.12				–0.34		–0.12
Capacity of P&C (ready substrate)	1,356.16	tWM ready substrate/ cycle			–0.12	–0.17				
Capacity of P&C (AGL)	217.57	tWM AGL/cycle	–0.12	–0.17			0.64	–0.46	–0.12	–0.17
Capacity of K&P	12,838.53	tWM AGL/yr	–0.10	–0.15	–0.10	–0.15		–0.51	–0.10	–0.15

to interrelations, slightly increased dry matter percentage (DM%) of the larvae is not enough to offset that disadvantage.

11. The *efficiency of the first mechanic separation* of the insect puree in form of the target DM% of the solid phase. Higher dry matter of the solid phase means fewer drying costs because the one-stage drying of the solid phase requires much more energy per litre water than the multi-stage evaporation of the lipid phase does.
12. Unsurprisingly, higher *capacities* with the same investment lead to lower total costs.

The default model behaves as expected. There is no major impact parameter, which's effect cannot be explained. Besides The FCR, several other parameters and topics were identified that should be considered and also tested in feeding trials.

As can be seen in Table 8, which is the result of contingent sensitivity analysis, RRs of the production

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TABLE 9 Break-even prices and parameters of substituting soybean meal or fish meal by alive grown larvae or defatted larvae meal (in broiler feed)

Substitute			AGL		dLM		
Substituted product			SBM (€)	FM (€)	SBM (€)	FM (€)	
Substitute price for equal protein			372	953	463	1,185	/tDM
Adjustment for resulting energy difference			304	365	36	112	/tDM
Break-even price of substitute			677	1,318	499	1,296	/tDM
Break-even parameters to reach break-even price	FCR (seed larvae)		N.A.	N.A.	N.A.	N.A.	DM/DM
	Frass		1,494	1,175	1,873	1,565	/tDM
	Oil		N.A.	N.A.	21,058	17,658	/tDM
	Frass & Oil	Frass	1,494	1,175	832	704	/tDM
		Oil	N.A.	N.A.	12,859	10,875	/tDM
	Raw substrate mix		–219	–78	–386	–250	/tDM

parameters are also dependent on the status of the supply chain.

If no refeeding is implemented (**A**) and thus the substrate is determining the capacity of Nur and P&C, several RR change. FCR of the neonates as well as of the seed larvae increases in its importance (from below 0.1 to 0.14, and from 0.47 to 0.60), because higher FCRs also mean lower total production in this scenario. At the same time, with the no re-feeding assumption the system is not able to benefit as much from increased DM percentage of larvae, because that would mean a higher substrate requirement which is restricted. The leftover effect is only due to lower drying costs. Differences in effects of larvae density are only due to differences in the effect of the interrelated FCR. The magnitude of capacity effects is the same, but the effects move from grown larvae capacity to ready substrate capacity.

The second supply chain status is the no-market and variable labour setting (B). RRs in this setting are a little bit "chaotic" and unsymmetric, because of the sudden cost increases when another actor has to start operating to fulfil the demand or process the supplies. Two times, RRs even point in opposite directions. Increasing as well as decreasing the time in production rearing would increase the costs, because a 20% reduction of time in production rearing would mean that two RSP, Rep, Nur and K&P are needed which are all running with a low capacity usage. A similar effect occurs when varying the capacity of grown larvae in P&C. An increase in the most important parameter, FCR, would mean that two RSDs are needed to deliver enough substrate. A decrease in FCR would mean that less substrate is needed than one RSD can produce. Both leads to capacity that is not used and thus to worse effects than in the default situation.

The setting in which FCR and IEW are negatively interrelated (*C*), which means that the same substrate and same genetic material is used, only the impact of the two parameters IEW and FCR differ from the default situation. While it seemed wise to increase the IEW in the default situation due to lower reproduction requirements, this is completely offset by the introduced negative correlation of FCR and IEW. An increase of 1% in IEW larvae now leads to a 1.58% cost increase. At the same time, a reduction in FCR is less beneficial compared to the default situation, because the IEW decreases and leads to a higher reproduction demand.

Table 9 depicts the result of the break-even analysis. Respecting protein and energy contents and digestibility, alive grown larvae may cost €677/tDM AGL (€1,318/tDM AGL) or less to be price competitive with SBM (FM) (in the broiler feed). Surprisingly, the higher protein content in dLM does not outweigh the lower energy content. The break-even price to substitute SBM by dLM is €178 (€499 – €677) lower per tDM larvae product than if you would substitute by AGL. The same holds true for the break-even price of FM substituted by dLM, which is €22 (€1,296 – €1,318) lower than substituting by AGL.

The lower part of Table 9 shows how much certain parameters must change to reach the break-even prices. However, it is not possible to reach the break-even prices by changing only one production parameter. Even the most important production parameter, FCR, cannot be low enough to reach break-even prices, because they are lower than the fixed costs from building and inventory.

For the most favourable option, substituting FM by AGL, a frass price of €1,175/tDM or a negative raw substrate price of €78/tDM would be sufficient to reach price competitiveness.

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Summary of results

To summarize the results, we showed that, with most likely input parameters, 5.57 tDM raw substrate and 26.7 million neonates are required to produce 1 tDM dLM. While the valuable by-products frass (2.46 tDM) and oil (0.22 tDM) appear in considerable amounts, the mass of exuviae (0.003 tDM) and dead adults (0.003 tDM) is neglectable. Per 1 tDM dLM, 2.12 tDM gaseous emissions are emitted, which can be seen as a negative externality.

In the default situation, a price of €5,116/tDM dLM is calculated which equals €11.12/kg protein. Important cost factors are the raw substrate (€1,939/tDM dLM), building and inventory (€1,459/tDM dLM), labour (€822/tDM dLM), and energy (€693/tDM dLM). Less important is insect breeding feed with €11/tDM dLM. The by-product frass reduces the net production costs by €309/tDM dLM and the by-product oil by €243/tDM dLM.

The scenario analysis showed that, while large scale production can reduce the price by €845/tDM dLM, doing every production step with individual actors increases the price by €1,253/tDM dLM. High value frass (€1,685/tDM frass) and no substrate costs can substantially reduce the price by €4,130 and €2,037 per tDM dLM.

Parameters with high (upwards directed) relative response rate towards the price of dLM are the feed conversion rate (0.47), dry matter percentage of larvae (–0.40), raw substrate price (0.21 and 0.12), larvae density (–0.21), labour wage (0.17), growth rate (0.16), and energy prices (0.14).

The contingent sensitivity analysis has shown that sensitivities of input parameters depend heavily on the status of the supply chain. In case of no-refeeding practice (A) the FCR increases in its importance, the no market and variable labour setting (B) leads to "chaotic" and unsymmetric relative response rates, and if FCR and IEW are negatively interrelated (C) FCR decreases in its importance and IEW RRs change to a positive sign.

Finally, the break-even analysis pointed out that AGL has a higher break-even price per tDM than dLM. To substitute fish meal with AGL has a break-even price of €1,318/tDM AGL and substituting with dLM would require a price of €1,296/tDM dLM. Only improving production parameters is not sufficient to reach break-even prices. In the most favourable option, which is substituting FM with AGL, changing prices of raw substrate to –€78/tDM or frass to €1,175/tDM would enable a profitable operation.

4 Discussion

The aim of the developed simulation model, which is described in this paper, is to enable the analysis of full costs of producing defatted larvae meal and to provide insight in the distribution of these costs in the insect supply chain. Different insect supply chains, business models and insect species shall be possible to analyse after quick adaption of settings and input parameters. In this section we will critically reflect if the model structure, available data, default results, and model behaviour enable us to fulfil the model aim.

Model structure

We mostly followed the proposed supply chain structure in Saatkamp *et al.* (2022) and showed small amendments in Figure 1. Our multi-level simulation model including all three layers, technical module, economic module, and transition module, explicitly follows the supply chain structure. Although being vertically linked, each module has interfaces to extract amount and cost data of intermediate products and production steps. Our full-cost approach ensures the completeness of our calculations and that all relevant costs are included in intermediate and final product prices.

Separating the three layers helped to increase the flexibility and the user comfort of the model. It enables the assessment of business models where capacity is not fully used. Moreover, it enables to analyse business models with different levels of vertical integration and production sizes of the production steps.

As the model structure is multi-level (including all production steps), vertically linked with interfaces to extract data in a visible manner and flexible enough to analyse different scenarios, we think, it is a good basis to compare various business models.

Like every model, also this model relies on some simplification. For example, we chose to use the same raw substrate in the nursery and rearing step. For insect value chains with specialized diets in the nursery step, this simplification may give an under estimation of costs of raw substrate. However, due to the low amount of insect breeding feed in the supply chain the simplification was deemed as acceptable.

Moreover, at the moment, demand and supply has to be delivered or processed by the supply chain itself in exact matching amounts. Introducing side markets where the overcapacity of sub-modules can be used with a price discrimination or, in case of undercapacity, intermediate products can be bought for a predefined price would further increase the flexibility of the model.

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Data

The biggest hurdle while building the model was the lack of industrial scale data. Most publicly available data is based on experimental scale (Spykman *et al.*, 2021). However, in multiple consultation rounds with industry and research partners we verified the reliability of our data. To our knowledge, we got the best estimate of industrial scale production costs that is currently available.

It has to be mentioned that selected default parameters do not only impact the final price but also the RR of other parameters. For example if the frass price is very high, a higher FCR can reduce costs instead of increasing it, because more frass is produced in that case. Thus every user of the model must adjust all parameters to their specific circumstances before testing their most influential parameters. Moreover, current data was mainly retrieved from Dutch companies. Also prices mainly reflect the Dutch circumstances. Thus results have to be interpreted in European, more specifically the Dutch, context.

Default situation

The default scenario, which means the most likely setting (one medium sized central company) and parameters, gives insight in masses and costs involved in insect production which can and were checked for plausibility within the INSECTFEED consortium. We presented our model and preliminary results in a meeting with industry partners. Amounts and costs were accepted as plausible by all partners after small amendments.

The model results underpin a high demand for raw substrate (5.57 tDM/tDM dLM) and number of individual insects (26.64 million /tDM dLM). The demand of 5.57 t raw substrate is a result of the assumed FCR of 4.34 DM/DM, which lies within the range that can be found in literature (Surendra *et al.*, 2020) and some other parameters like mortalities and difference in DM content. However, this high demand can become a problem when insect production is upscaled under the current condition that only GMP+ substrates are allowed as insect feed. In such a situation, additional, non-sidestream products are needed and then it becomes questionable if the circularity promise can be kept. Also, the huge number of animals that have to be killed for one tDM dLM can become an ethical problem considering upcoming research about insect welfare (Voulgari-Kokota *et al.*, 2023). Although, we could not find a similar value in literature, it is implicitly given by the weight of alive grown larvae (170 g WM/AGL), DM content of 31% and some minor transformation parameters.

In the default scenario, the by-products frass and oil appear in considerable amounts, however, exuviae and dead adult masses are neglectable. Although research is done on all by-products (Nurfikari and Kuramae, 2022), the focus should be laid on the ones that will be available in considerable amounts. We also showed the high amount of the negative externality gaseous emissions in insect production which illustrates the requirement for effective exhaust air treatments to have a low carbon footprint (Parodi *et al.*, 2020a; Smetana *et al.*, 2022).

Concerning the costs involved, we calculated net total costs of €5,116 per tDM dLM in the default situation which matches in the range of selling prices between €1,816 and €18,190 per ton (Niyonsaba *et al.*, 2021). Compared to the crude protein price between €5.18 and €6.54 per kg calculated by Spykman *et al.* (2021) our price of €11.12 per kg seems quite high, but can be easily explained by the fact that our model follows the full-cost approach which also includes fixed and labour costs.

Currently, the main cost factors in the default scenario are the raw substrates, building and inventory, labour, and energy in decreasing importance. A low cost contributor is insect breeding feed which indicates, that choosing high quality insect breeding feed for reproduction with might not highly influence the total production costs while securing a stable amount of neonates.

Pahmeyer *et al.* (2022) agree that building and inventory (capital investment) and energy are high cost contributors. Contrary, they include no costs for the raw substrate, which is sole organic waste for them, and see a high contribution of consumables (detergent) and transportation. Thus the detergent usage was explicitly checked with our industry partner. The difference might be explained by the lower cleaning water usage and concentration of detergent in large scale facilities compared to lab or container scale operations. The difference in transportation costs can be explained by the different approaches of the two models. While we included an average transportation distance of 100 km for the raw substrate and a centralized insect production, Pahmeyer *et al.* (2022) analysed a decentralized container approach. The distance and price of transportation always must be adapted to the transported good and the selected business model.

Model behaviour

The scenario analysis showed that only scaling up the current technology will reduce the price of dLM, but only to €4,271/tDM dLM. A reduction of costs was expected in that case, but to reach a proposed price of

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€1,500 – €2,500 in 2030, like prospected by Jong and Nikolik (2021), more innovation is needed.

The all different companies scenario showed that costs and margins increase the dLM price a lot, which shows the need for clever business models. While some production steps like K&P benefit a lot from scaling up, like proposed by Pahmeyer *et al.* (2022) and the companies Amusca or Better Origin, rearing might benefit from operating small scale containers at the origin of the raw substrates. Being fed with appropriate data, our model gives the tool to explicitly compare these business models.

As expected, high value by-products decrease the price of dLM. Even if the extremely high impact of Frass price surprised a bit, Pahmeyer *et al.* (2022) agree with that high impact. It shows the need to further explore the benefits and utilization possibilities of frass. Only for the usage as garden fertilizer, amounts (2.46 tDM frass/tDM dLM) will become too much in the scaling-up phase.

We showed a high impact of reducing the raw substrate price by including e.g. manure, which is preferred by the insects itself (Parodi *et al.*, 2020b), as substrate. Nevertheless, a one-by-one scenario is not always very realistic. A different substrate also impacts developing times, FCR, IEW and nutrient contents. These parameters are impossible to predict by a model but must be experimentally tested and included as "substrate scenarios" to assess their economic impact. Another fact that should not be ignored is that low value substrates also increase the hazard of contaminations and might require further decontamination equipment or lead to a product that is not allowed to be fed to animals as it could be a food safety risk (Saatkamp *et al.*, 2022). Furthermore, it is questionable if low value raw substrates will result in high value frass as the frass composition is very dependent on the original substrate.

The sensitivity analysis successfully identified critical parameters and helped to understand and test the model behaviour. One limitation of our RR is that it cannot be seen as a direct ranking of importance. To obtain a ranking of importance, realistic variations will need to be introduced, which are currently not available. However, the sensitivity analysis showed that the reactions of the presented model always can be logically explained and thus is a usable tool to find production parameters that need to be optimized.

One important parameter in SA was the price of energy. It will be key for the industry to switch as much as possible to renewable (Huis, 2022) and cheap energy. Another important parameter was the FCR. Finding substrates and methods to optimize FCR is the goal of most operating companies and research (Surendra *et al.*, 2020).

Coming to the contingent sensitivity analysis, a major purpose of supply chain models should be to improve the capacity planning. The no refeeding setting (A) showed the importance of explicitly thinking about the capacity or the bottleneck of each production step. The setting (WM substrate is binding capacity) decreased the possibility to gain from potential improvements of FCR which should be considered when setting up a production. When planning the capacities, the default scenario, where relative numbers of actors are possible and thus all capacities perfectly match, should only be used to get a first overview of required capacities. Contrary, the presented no-market scenario (B) enables the user to get an extensive ex-ante understanding of the impacts of selected capacities and associated reaction towards parameter changes. Therefore, our model is able to support people who want to get involved in insect production to find optimal capacities.

Contingent sensitivity analysis also highlighted the importance of respecting interrelations between density, FCR and IEW (C). Recently, Guillaume *et al.* (2023) tested the interrelation of density, FCR and IEW for chicken feed as raw substrate and summarized the results in exponential functions. Implementing such functions in the supply chain model can be done quickly and enables to solve for optimal production parameters. However, users of the model have to test their specific interrelation first, because that depends on strain and substrate very much. There might be more interrelation which the authors are not aware of. However, new interrelations can be implemented very quickly as the inputs are organized in clear input tables. Further interrelations may allow for even more precise estimation of optimal parameters.

The goal of the break-even analysis is to assess how realistic a profitable production will be in future. It showed that only by improving production parameters, it will be difficult to become price competitive to the standard products SBM or FM. Only optimal input and output prices might change the profitability quite quickly. The question is how realistic these prices are.

Frassor, which is currently sold for €1,685/tDM, would beat the required price of €1,175/tDM. However, compared to the calculated frass in our model with a DM% of 45, Frassor is a dried product with 88.7% DM and will incur some drying costs. Moreover, Pahmeyer *et al.* (2022) calculate with a Frass price of €690/t (DM or WM not indicated) and our industry partners claim that

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a price of €89/tDM would be realistic for large scale operations.

The report of Bastein *et al.* (2013) shows the waste treatment prices of biotic waste streams in the Netherlands, which are in descending order €227, €150, €75 and €21 per tDM for sewage sludge, cattle and pig slurry, horticultural crop residues and poultry manure. Only sewage sludge and cattle and pig manure would beat the required price of €78/tDM. Unfortunately, these waste streams come with contamination risks and impacts on the performance of the larvae. Furthermore, they are very wet such that they would require a mixture with other dry products, a pre-treatment or a continuous feeding approach (W. Jansen, personal communications). The (wet) horticultural crop residue treatment price is on the edge to the required (negative) input price. However, also these raw substrates require dry mixtures and will become a positively priced good in case of mass production.

Although there is uncertainty in the data, the substantial difference between the calculated production price (€5,116/tDM dLM) and break-even prices (max. €1,296/tDM dLM) still suggest that insects will likely not be part of mass farm animal feed in near future. Low inclusion levels with specific aims for farm animal welfare and health might be possible but require further economic investigation.

Conclusion

We developed and presented a simulation model to calculate the cost price of insect production, which (1) includes all production steps, (2) is able to extract and display results in visible manner, (3) is flexible enough to compare different business models and (4) is a good basis for further extensions. We showed that the results of the default scenario depict realistic values, which are, to our belief, currently the best estimate of industrial scale production costs available. All scenarios, relative responses and contingent relative responses can be logically explained and can help the user to find important production parameters and improve capacity planning. The break-even analysis helps the user to assess the likelihood of being profitable in future.

Unfortunately, the calculated price of €5,116/tDM dLM in the default situation is too high to compete with conventional protein suppliers SBM and FM. To become profitable, the four main cost factors raw substrates, building and inventory, labour and energy have to be reduced and the value of by-products has to be increased. Focusing on the 12 most important categories, that were pointed out in the sensitivity analysis, will be a good starting point.

Supplementary material

Supplementary material is available online at: https://doi.org/10.6084/m9.figshare.25205483

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Conflict of interest

The authors have no conflict of interest to declare.

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