

Article

Method of Planning and Scheduling the Production Process of Yellow Mealworm Larvae for a Small Enterprise

Arkadiusz Kowalski 

Faculty of Mechanical Engineering, Wrocław University of Science and Technology, 27 Wybrzeże Wyspiańskiego St., 50-370 Wrocław, Poland; arkadiusz.kowalski@pwr.edu.pl

Abstract: In the context of the growing demand for alternative protein sources with the growth of the human population and increasing ecological awareness, the rearing of yellow mealworm larvae (*Tenebrio molitor*) is a promising option for the production of sustainable protein. The article presents a comprehensive approach to planning and scheduling the production of yellow mealworm larvae in a small enterprise, focusing on the organizational, technical, and economic aspects of the production process. The production installation, the method of rearing using an automated feeding system, and the monitoring of larvae development were described and an attempt was made to identify the key parameters of the process that affect its efficiency. Particular attention was paid to the calculation algorithm implemented in the spreadsheet, which allows the selection of the production batch size and the frequency of their launch, so as to maximize the available capacity of storage racks for cuvettes. In addition, the article analyses logistical challenges related to the production of larvae, including transport activities in order to meet, among others, the demand for feed. Finally, the estimation of revenues and economic indicators, such as profitability and return on investment, is presented, pointing to the need for further improvements in the production process and cost optimization to achieve favorable financial results. The results of the research emphasize the potential of rearing yellow mealworm larvae as a sustainable source of protein while simultaneously pointing to key areas that require further research and development.



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Keywords: rearing of mealworm larvae; production process; production plan; scheduling; production system design; indicators

1. Introduction

With the growth of the human population, the risk of protein deficiencies in the human diet increases. This results in the need to seek new edible protein sources [1]. One of the viable solutions is quality nutritional value protein from the larvae of yellow mealworm, black soldier flies, and crickets, which are the most commonly bred insect species in Europe [2]. Insect larvae, including yellow mealworm (*Tenebrio molitor*), can also be used as a source of feed for farm animals, including poultry [3], fish [4], and domestic animals [5].

An undoubted advantage of insect larvae farms is their minimal impact on the environment, unlike cattle rearing. Meeting the nutritional needs of growing animal husbandry requires more and more feed. Rearing yellow mealworm larvae are characterized by a high ratio of feed utilization to the obtained protein mass, the value of which is comparable to poultry farming. According to the US Department of Agriculture, the ratio of cereal feed to the final protein product of animal origin is about 17 kg of feed to provide one kg of beef [6]. Insect larvae also use much less water: 1 kg of beef consumes 22,000 L while 1 kg of edible insect protein needs 1 to 10 L of water [7].

It can be stated with full responsibility that mealworm larvae farming has a low ecological footprint. The mealworm larvae do not secrete enteric CH₄ and have a high reproduction rate, typical of insects. Industrial production of insect-derived protein is

more energy efficient than animal husbandry or aquaculture. As a result of the life cycle analysis of yellow mealworm larvae, the reduction in the production of greenhouse gases was proved [8].

Insect protein has been classified as a novel food (NF) in accordance with Article to Regulation (EU) 2015/2283. The European Food Safety Authority (EFSA) Panel on Nutrition, Novel Foods and Food Allergens (NDA) issued a positive opinion on the human consumption of frozen and dried yellow mealworm formulations [9]. In this context, sensory tests (appearance, smell, taste, and consistency) of insect larvae as an ingredient of dishes are no longer surprising [10].

It seems reasonable to conclude that insect larvae should be considered the most balanced source of protein rich in amino acids (i.e., isoleucine, leucine, and lysine) [11] and minerals (i.e., magnesium, zinc, iron, copper, and manganese) [12], lipids, and calcium [13].

Insect larvae, in particular the black soldier fly, can be used in closed-loop production systems since the insects can convert a wide range of organic waste and by-products into nutritious feed [14], which then returns to the production cycle. In this case, however, the insect larvae are intended only for feed purposes.

One of the few publications on the practical issues of the production of yellow mealworm larvae describes the organization of rearing and processing in medium-sized (approx. 400 tons of larvae per year) and very large (approx. 2000 tons of larvae per year) processing installations [15]. However, it is difficult to expect that a few publications will embracingly discuss a set of issues related to planning and scheduling the production of insect larvae. This is partly because the results and outcomes of research that are intended for patenting are not published until patent protection is obtained. An important complement to the issue of how to implement the production process of insect larvae is research on reducing the risk of the rapid spread of pathogens and parasites in insect larvae culture, without the need to use antibiotics [16]. The aim is to prevent and limit the effects of potential epizootics [17].

The answers to the questions of what and how to effectively feed insect larvae are sought. The impact of a diet consisting of organic by-products differing in protein and starch content was checked and then the effectiveness of feed usage and the profile of crude protein and fatty acids of yellow mealworm were assessed [18].

Despite the immense potential of rearing yellow mealworm larvae as a substitute source of nutrients, there are still many legislative and behavioral challenges and in particular, there is a lack of knowledge about the design and organization of industrial production. Particularly, this lack of knowledge concerns the sector of small- and medium-sized enterprises, for which the production of insect larvae for food purposes is an opportunity for profitable activity in a market with high development potential.

The article proposes a calculation algorithm, implemented in a spreadsheet, which enables, i.e., the determination of the maximum size of the production batch and the frequency of their launch, to maximize the use of the entire available capacity of cuvette racks. For this purpose, it was necessary to determine the growth rate of larvae depending on the adopted method of feeding. The parameterized description of the production process made it possible to obtain a schedule of maintenance activities for the entire rearing of yellow mealworm larvae. The further step included the aggregation of production volumes from different rearing batches. The deterministic nature of the feed demand made it possible to use Material Requirements Planning (MRP) algorithms to calculate related logistic issues.

2. Description of the Production Installation of Yellow Mealworm Larvae for a Small Enterprise

In an experimental production hall with an area of about 200 m², two rows of racks accommodating 4000 Euro Containers 600 × 400 × 120 mm were set up. The rack made it possible to place eight cuvettes in one column, one above the other. For the purposes of

pedigree rearing, conducted in the same cuvettes, another set of racks placed in a separate building was used.

The production hall was equipped with an automatic ventilation system with recuperation; air temperature and humidity were monitored and kept, respectively, in the range of 28–29 °C and 55% and the concentration of CO₂, NH₄, and O₂ in the air was monitored. In addition to the harvesting larvae, chitinous molts (chitin for the needs of the cosmetics industry) and their frass (as a component of fertilizer for potted plants) were obtained. The initially planned annual production was about 30 tons of yellow mealworm larvae.

Even with a relatively small scale of rearing of mealworm larvae, process automation is economically justified; there is also the possibility of facilitating automated farming with a monitoring system. Understandably, the main goal is to reduce human labor costs. The expected functionality of the monitoring system includes the identification of individual developmental stages of *Tenebrio molitor* (larvae, pupae, and beetles) and automated recognition of dead larvae and pests, based on the analysis of images using machine learning models, more widely described in [19].

3. Management of the Fattening Process of Yellow Mealworm Larvae

The method of rearing yellow mealworm larvae has been adapted to the limitations of a small enterprise founded as a startup, based on a review of the literature information [15]. The production process of mealworm larvae begins with pedigree rearing and initial incubation for 14 days, then sorting is carried out, separating the larvae into cuvettes and segregating them into two “larger” and “smaller” fractions. The number of larvae in the cuvettes was determined experimentally, considering their generally understood well-being, in such a way that each time it was initially about 500 g of larvae. Depending on their size, their number varies between 13,600–16,100 larvae in each cuvette.

Thanks to sorting, after the rearing stage, the yellow mealworm larvae are separated, resulting in 2.5 times more cuvettes than in the initial incubation. According to the plans, the “larger” larvae fraction is fed for 34 days, while the “smaller” larvae fraction for 58 days. The larvae were subdivided into “larger” and “smaller” fractions in a 50/50 ratio by sorting them; the scheme of the entire fattening process is shown in Figure 1.

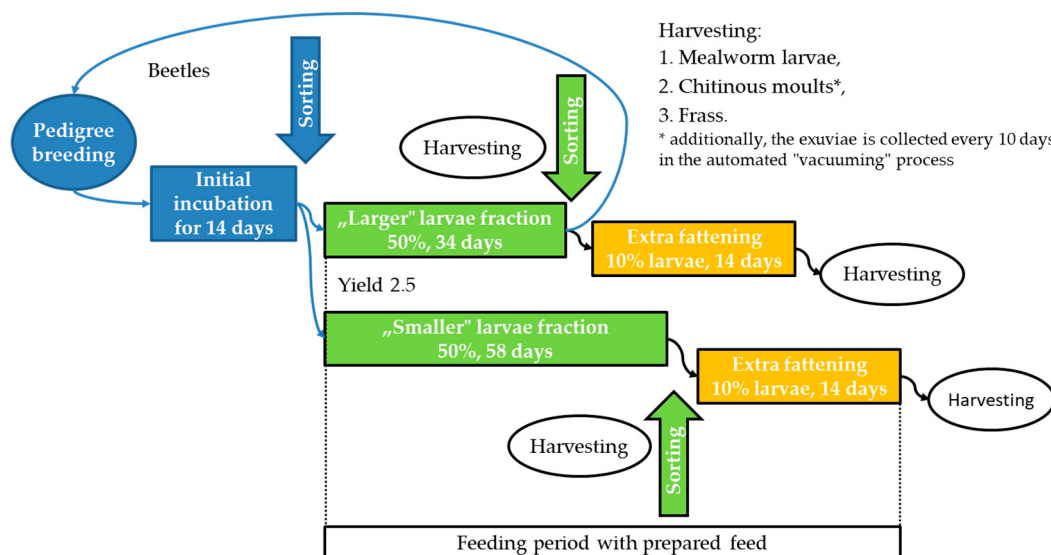


Figure 1. The proposed shape of the production process of yellow mealworm larvae is divided into “larger” and “smaller” larvae fractions and “extra fattening”.

At the end of the rearing, re-sorting takes place, and larvae, chitinous molts, and frass of yellow mealworm are harvested. The smallest larvae (about 10%) are placed in cuvettes for an additional 14 days of fattening. The entire process of running subsequent batches

in production is repeated every 7 days. Consequently, at one time, cuvettes with larvae of different ages from 10 consecutive batches are placed on the racks.

The appearance of pupae (and all the more beetles) in the larval cuvettes is detected using an automated monitoring system after analyzing the images taken before the feeding activity; as a consequence, it means immediate cessation of rearing in a specific cuvette. However, beetles and pupae are obtained for rearing only from the “larger” larvae fraction; thus, changing the frequency of the genotype is implemented since only larger specimens are intended for reproduction, which is of course beneficial for the breeder. A summary of the values of the key production parameters of yellow mealworm larvae included in the sample calculations for the production plan is presented in Table 1.

Table 1. Summary of key parameters of yellow mealworm larvae production.

Harvesting Larvae			
rack capacity [pcs.]			4000
running frequency of subsequent batches [days]			7
efficiency from pedigree rearing			2.5
Fractions:	Rearing time [days]	Fraction share [%]	Number of larvae in the cuvette [pcs.]
incubation	14	100	-
“larger”	34	50	13,600
“smaller”	62	50	16,100
“larger” extra fattening	14	10	15,500
“smaller” extra fattening	14	10	15,500
Harvesting chitinous molts			
“vacuuming” every 10 days [g/cuvette]			2
sorting after the incubation phase [g/cuvette]			5
sorting after fattening phase [g/cuvette]			10
sorting after extra fattening phase [g/cuvette]			10
Harvesting frass			
sorting after the incubation phase [g/cuvette]			50
sorting after fattening phase [g/cuvette]			200
sorting after extra fattening phase [g/cuvette]			200

The proposed method of feeding yellow mealworm larvae assumed feeding with dry and wet feed, with carrots being the only component of wet feed. The feed recipe is presented in Table 2.

Table 2. Feed recipe for feeding yellow mealworm larvae.

Feed Ingredients		Share [%]	Dry/Wet Share [%]
dry	wheat flakes	70	
	wheat bran	20	70
	additives	10	
wet	carrot	100	30

The amount of feed administered was increased in three stages during the fattening phase of the mealworm larvae. For the first 24 days, 70 g of feed per cuvette was automatically administered. This was increased to 108 g per cuvette for the following 28 days and then to 150 g per cuvette for the final 19 days. The adopted model of larval feeding during the fattening phase is shown in Figure 2. The implemented method of feeding resulted from the necessary assumptions and technical limitations: the lack of employee supervision on Sundays prevented daily feeding since the capabilities of the feeding automaton, including the accuracy of the weight of the dispensed feed, have not yet been sufficiently tested.

The effect of the adopted feeding method of yellow mealworm larvae in the fattening phase was the increase in their volume (and weight) shown in Figure 3.

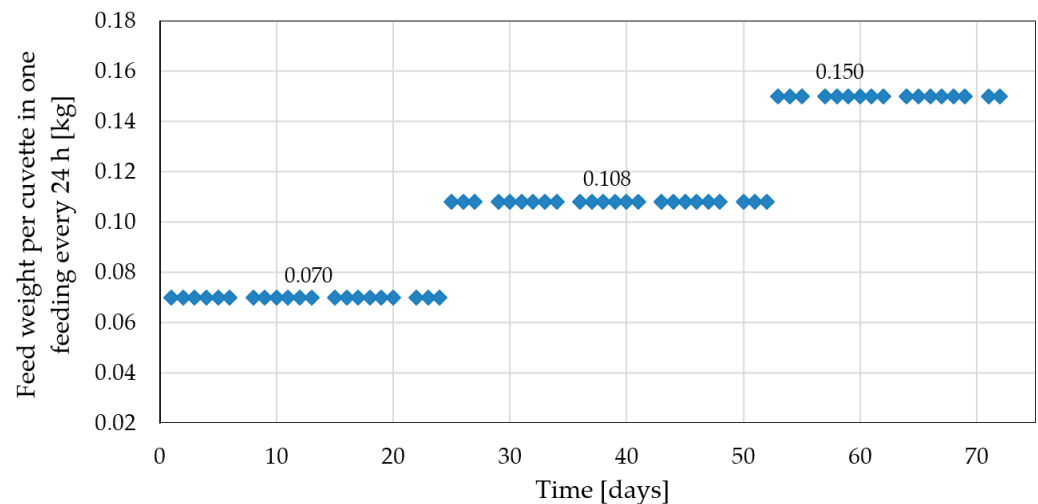


Figure 2. The proposed three-level method of yellow mealworm larvae feeding.

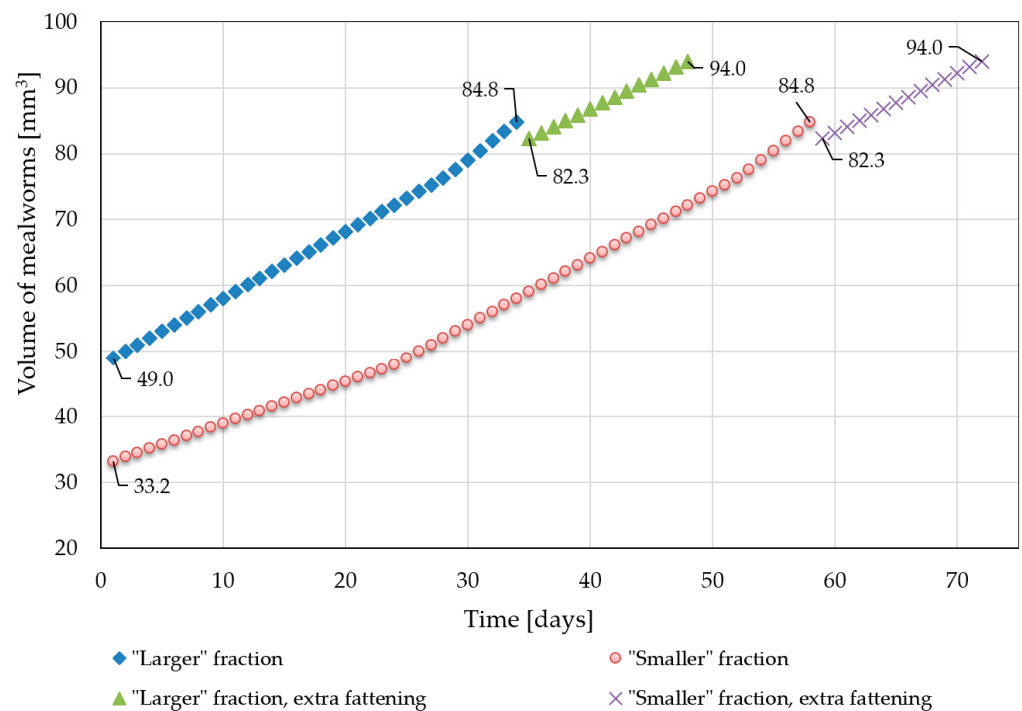


Figure 3. The growth rate of yellow mealworm larvae of various size fractions for the adopted feeding method.

The larval mass measurement was carried out using the previously developed method of determining larval size distribution based on the convolutional neural network of regression (RegCNN). The width of larvae was chosen as the main measured parameter of larvae due to the ease of registration. The length of the larva and its volume were determined indirectly, using the determined regression models of length and width, as described in detail in publications [20,21]. Yellow mealworm larvae from the “larger” fraction at the beginning of fattening averaged 21 mm in length and 49.0 mm³ in volume, while larvae from the “smaller” fraction averaged 17.5 mm in length and 33.2 mm³ in volume. The length of fattening for the “smaller” and “larger” fractions was selected in such a manner that during the harvest, larvae from both fractions reached about 85.0 mm³. During the 14-day extra fattening, the larvae reached 94.0 mm³ in volume. For the calculations, a conversion factor was used: 1 m³ of yellow mealworm larvae is 750 kg of weight.

There is a correlation between the increase in the feeding dose and the acceleration of the growth rate of yellow mealworm larvae (about 25 days of fattening for the “larger” fraction and 25 and 55 days of fattening for the “smaller” fraction) but in order to parameterize this obvious cause and effect relationship, further studies should be carried out in laboratory conditions. As part of the long-term nutritional experiments carried out for the purposes of planning and scheduling production, growth models were developed for individual larval fractions only for the used method of feeding (Figure 2). For each analyzed group, a linear regression model was determined [22]. Using such a model, it is possible to predict the biomass growth within the specified time, which is visualized in Figure 3.

Importantly, such dependencies must be determined before production planning begins. In addition, they have a unique character for each of the manufacturers of yellow mealworm larvae because a change in the method of feeding, namely the amount or composition of the feed, entails a dependence on the weight gain of the larvae. Another variability factor will be, for example, a change in the amount of light reaching the cuvettes.

4. Development of a Tool for the Preparation of the Yellow Mealworm Larvae Production Plan

The production of yellow mealworm larvae has the features of continuous production; the growth of larvae is a continuous process by nature, it cannot be stopped at any time and resumed at a convenient moment or carried out at different speeds. Speaking more precisely, only to a limited extent can we control the growth of larvae by choosing the feeding method, doses, and frequency of feeding. In addition, we can note that this is an irreversible process. There is also no typical Bill of Materials (BOM) product structure in this case but the amounts of yellow mealworm larvae, chitinous molts, and frass obtained are deterministic and, consequently, calculable.

When planning the production of yellow mealworm larvae, we seek answers to several questions, including

- How many batches of larvae should be directed to rearing in order to achieve the assumed production plan?
- At what frequency shall we start subsequent batches for pedigree rearing?
- How should the production of yellow mealworm be scheduled?
- How large should the batches of larvae in the pedigree rearing be, making maximum use of the entire available capacity of cuvette racks?
- What quantities of feed should be provided with the assumed production volume?
- Will the assumed method of carrying out the rearing process ensure profitability?

Limitations: it was necessary to ensure the ease of modification of the developed tool for planning the production of one of the startup’s employees, while none of them had sufficient programming skills. As a consequence, a decision was made to implement a prototype of a production planning tool in MS Excel 2016; in this case, there should be no problems with unassisted modification (Figure 4).

The proposed production planning tool uses a defined timeline and mapping of the characteristic elements of rearing yellow mealworm larvae in a parameterized manner.

- The number of cuvettes in the batch and the frequency of their launch (e.g., every 7 days);
- The division into fractions (two fractions and the possibility of extra fattening);
- Planned rearing time of individual fractions;
- Planned date of harvesting mealworm larvae, chitinous molts, and frass for a specific batch.

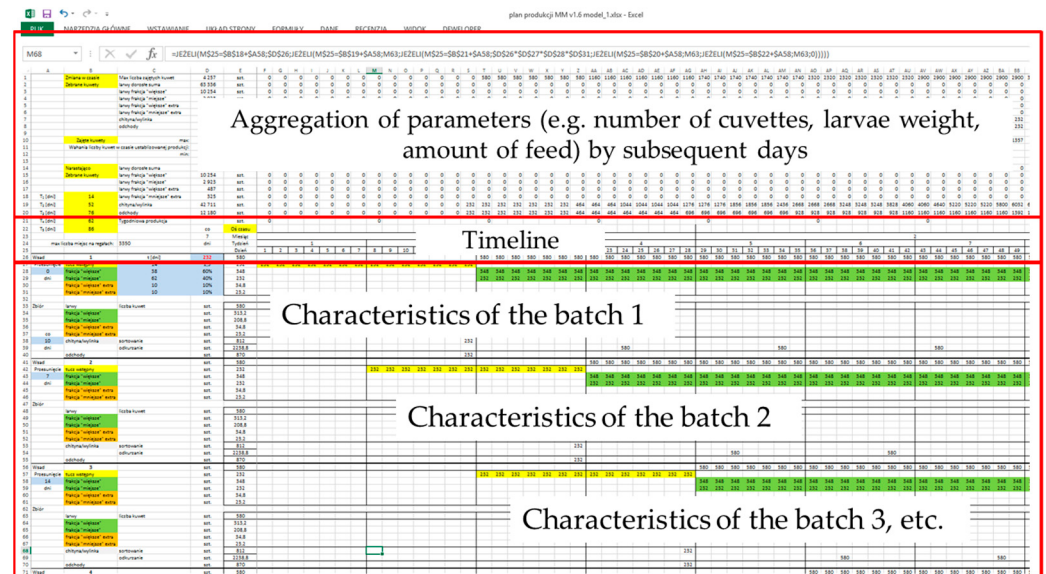


Figure 4. The idea of building a production plan considering the timeline.

It was assumed that the data should be aggregated with an accuracy of 1 day. On this basis, a schedule of works necessary for the entire rearing was obtained. The result of the schedule development was the establishment of an activity timetable: launching individual batches, sorting larvae, chitinous molts, frass, etc. For serial production, in the exemplary 12 weeks from the start of the first batch of pedigree rearing, the activities collected in Table 3 were planned to be carried out.

Table 3. Summary of activities to be carried out during the exemplary 12th week of yellow mealworm larvae fattening.

Day Number in Week 12	Name of the Scheduled Maintenance Activity
day 78	launch of a new batch of pedigree rearing, 220 cuvettes
day 79	no activities
day 80	completion of rearing of yellow mealworm larvae in the “large” fraction, 275 cuvettes, sorting and obtaining larvae, chitinous molts and frass
day 81	starting the rearing of larvae of the extra fattening fraction, 27 cuvettes
day 82	no activities
day 83	completion of rearing of yellow mealworm larvae in the “smaller” fraction, 275 cuvettes, sorting and obtaining larvae, chitinous molts and frass
day 84	completion of rearing larvae of the extra fattening fraction, 27 cuvettes, sorting and obtaining larvae, chitinous molts and frass

In the completed schedule of tasks, a variable demand for the number of people to handle larval rearing was observed: one day only current supervision, while on another day there was the need to perform sorting for 275 cuvettes, which is a task beyond the power of one employee. Conclusion: the task of completing the rearing of the “larger” fraction should be scheduled for two days.

The production plan and schedule prepared in MS Excel perform calculations of the current volume of larvae in the culture, the degree of filling the racks with cuvettes, and the demand for feed on a weekly basis and calculates production indicators according to the algorithm presented in Figure 5.

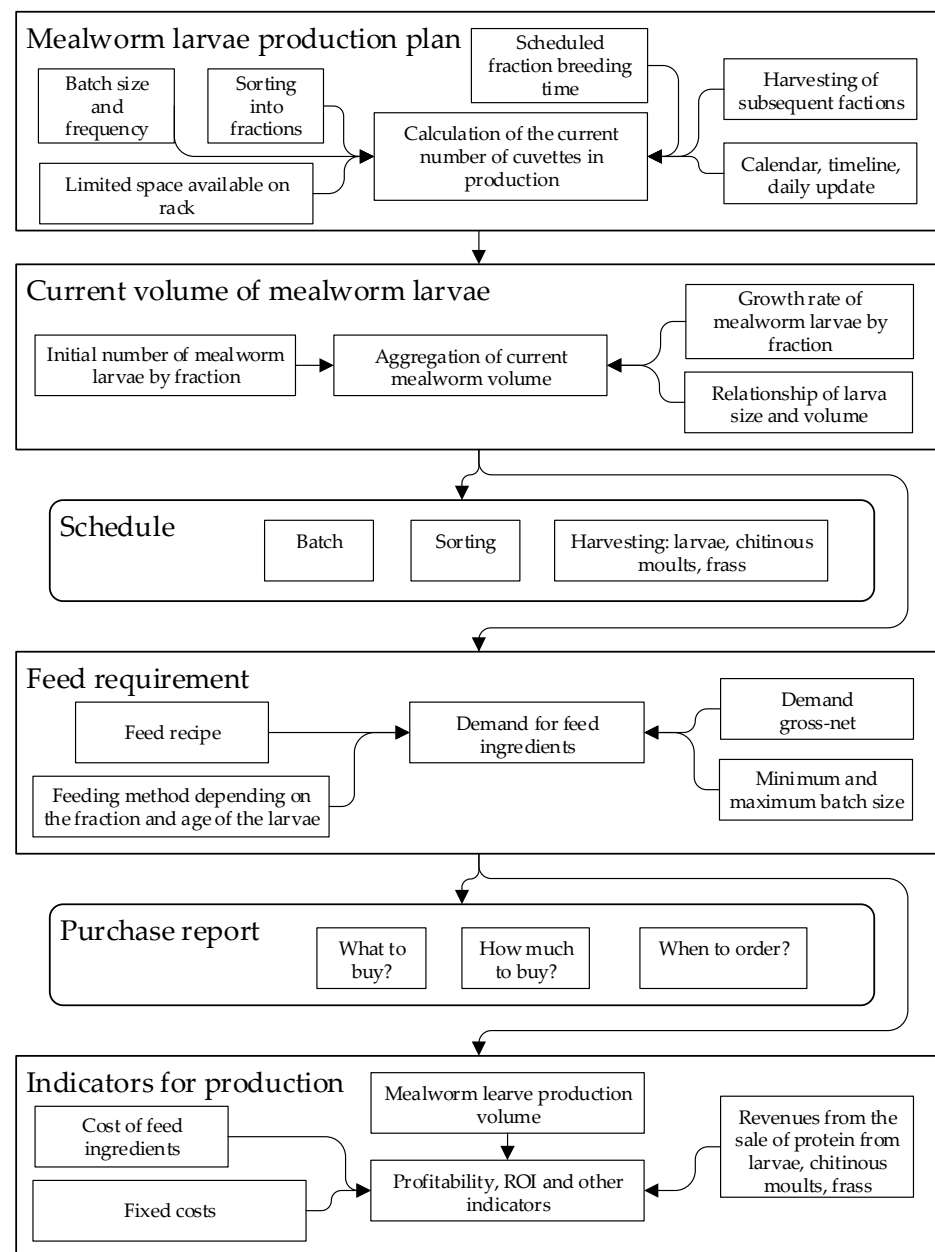


Figure 5. Schematic diagram of calculations for the production schedule and plan.

The number of cuvettes populated with larvae in each batch, launched every 7 days, was calculated using a production plan model, so as to achieve the highest possible occupancy (use) of places for storing cuvettes in racks. For this purpose, a computational model of the production plan of yellow mealworm larvae in MS Excel was used, looking for a solution on the basis of conducting “what if” simulation tests. The maximum peak rack occupancy in the experimental installation was achieved for 220 cuvettes in each subsequent batch, within 11 weeks from the start of continuous production. The planned peak occupancy is 3960 out of 4000 cuvettes, which translates into an average weekly occupancy rate of 88%. The stepwise nature of the changes in the number of cuvettes on the shelves during the start-up of individual batches is shown in Figure 6.

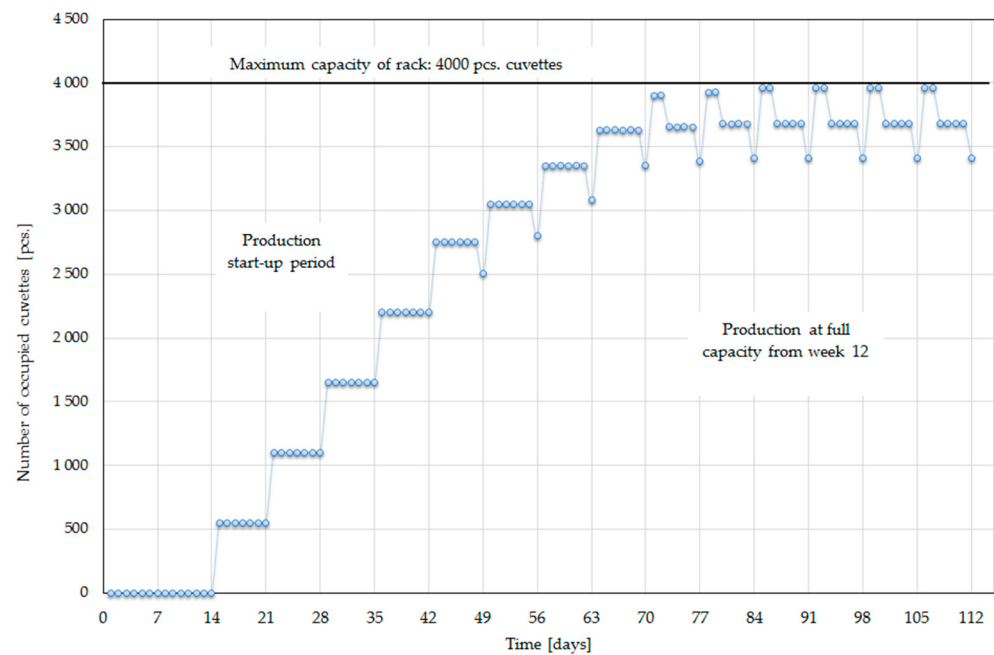


Figure 6. Determination of the maximum number of occupied cuvettes when starting full-scale production.

On the basis of the current number of occupied cuvettes, it is possible to know the number of vacancies on the shelves and the amplitude of their fluctuations: in the analyzed case, there are 550 vacancies, which results from the time of rearing of yellow mealworm larvae in individual fractions and running batches with a specific fixed number of cuvettes every 7 days. Considering the number of cuvettes populated in each batch, the growth rate of larvae, and the day of rearing, the planned mass of larvae to be obtained on a weekly basis was calculated, as shown in Figure 7. It shows the start-up rate of production reaching the target capacity in the 13th week from the start of the first batch of yellow mealworm larvae rearing.

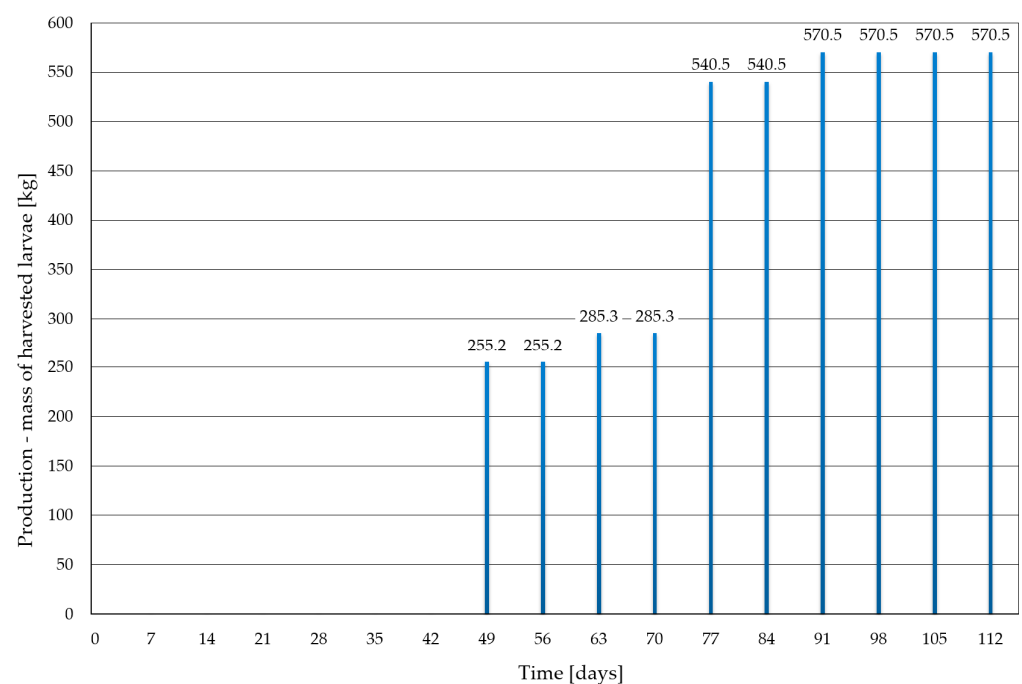


Figure 7. Weight of harvesting larvae when starting subsequent batches of 220 cuvettes every 7 days.

The result of the computational model of the production plan consisting of individual batches of rearing yellow mealworm larvae is the calculation of a number of indicators describing the production process. The proposed set of quantitative and time indicators is presented in Table 4.

Table 4. Summary of indicators characterizing the production process of yellow mealworm larvae.

	“Larger” Fraction	“Smaller” Fraction	“Larger” Fraction, Extra Fattening	“Smaller” Fraction, Extra Fattening
number of cuvettes [pcs.]	275	275	27	27
initial weight of larvae in the cuvette [kg]	0.500	0.535	0.999	0.999
final weight of larvae in the cuvette [kg]	0.923	1.093	1.093	1.093
weight gain of larvae in the cuvette [kg]	0.423	0.691	0.094	0.094
number of occupied cuvettes [pcs.]	minimum 3410		maximum 3960	
rack usage [%]	85.2		99.0	
end time of single batch rearing [days]			86	
number of batches per year [pcs.]			52	
harvest from a single batch [kg]	larvae weight 570.53		chitinous molts weight 11.06	
			frass weight 71.50	

Valuable information in Table 5 is a summary of the feed demand calculated for a single batch and per year, necessary for calculations related to the costs of larvae rearing.

Table 5. Summary of demand for the agreed production program.

Ingredients of Feed [kg]	Single Batch [kg]	Annual Statement [kg]
wheat flakes	1013.7	52,712.3
wheat bran	289.6	15,060.6
additives	144.8	7530.3
carrot	620.6	32,272.8
total	2068.7	107,573.0

It is also a convenient starting point for calculations related to logistic activities in the enterprise, searching for answers on how to parameterize the placing of purchase orders for feed ingredients.

5. Logistic Challenges during the Production of Yellow Mealworm Larvae

One of the factors determining the nature of logistic activities in small- and medium-sized enterprises starting the production of insect larvae is frequently their location in rural areas. This is due to the fact that these companies can use existing buildings, e.g., farms where rearing other animals has already been ceased. As a consequence, the distance from the motorway network should be expected to result in significant transport costs, exceeding the storage costs of feed components.

By knowing the demand for feed from the production plan, aggregated from different batches of larvae for individual days, one can proceed to calculations typical for the well-known MRP algorithm, as follows:

- Determination of gross needs broken down into individual feed ingredients;
- Determination of net needs, considering stock levels;
- Net needs are converted into batch size; there are several popular possibilities to use, e.g., Economic Order Quantity (economic size of the purchase batch) [23] or the Wagner–Whitin Algorithm [24];
- Determining, regarding the delivery time, the date of launching the order for the purchase of feed ingredients.

After determining the net needs, thus taking into account the stock levels for individual feed components, calculations regarding batching are carried out, taking into account, among others, the minimum and maximum size of a single batch. For example, wheat flakes are most often ordered in paper bags of 30 kg, with 20 stacked on a pallet, and carrot is transported in the amount of 800–1000 kg in big bags. A fragment of the MRP record calculations for wheat flakes in the 12th week of rearing yellow mealworm larvae, taking into account the minimum batch size, before using, e.g., the Wagner–Whitin algorithm or a fixed period of needs, is presented in Table 6.

Table 6. A fragment of the MRP record for one of the feed ingredients in the 12th week of rearing yellow mealworm larvae.

Wheat Flakes	Week 12 of Larval Rearing						
day	78	79	80	81	82	83	84
gross needs [kg]	230.2	230.2	228.9	213.2	213.2	213.2	199.9
stock [kg]	121.7	491.5	262.6	49.4	436.3	213.1	23.2
net needs [kg]	0	108.5	0	0	163.7	0	0
planned delivery [kg]	0	600	0	0	600	0	0

As a safety stock, the value of the smallest batch possible for transport (600 kg for oatmeal on a full pallet) was discretionarily adopted. At this stage of the process design, archival data were not yet available for how long the safety stock should ensure the continuity of production in unexpected emergency situations.

In expectation of significant transport costs for the calculation of batch sizes and delivery dates, the use of the Wagner–Whitin algorithm was planned. However, taking into account organizational restrictions in the form of a small number of employees and planned maintenance activities for larvae rearing, it was decided to try a fixed delivery period. The transport and unloading of feed ingredients was planned to be conducted on days free of larvae collection or sorting. It is worth emphasizing that before starting production, the maximum level of stock of feed components should be consciously determined with regard to the rotating stock, buffer stock, and safety stock.

Another logistic task is to transport the obtained yellow mealworm larvae from the farm. In this case, the decision was made to process the larvae on site, building an installation allowing for the production of full-fat protein. There will still be about 70 kg of frass to be harvested per week for fertilizer, 11 kg of chitinous molts, and 190 kg of waste. Alternatively, logistic activities can be conducted, for example, on the basis of a weekly dairy farmer’s course: transport can go around several farms [15], collecting mealworm larvae, chitinous molts, and frass to deliver them to the central processing plant.

6. Estimation of Revenues and Indicators

Revenues were estimated on the basis of the number of harvesting larvae (their volume converted into mass), chitinous molts, and frass. It was proposed that the production process should be characterized using a production planning tool, by the following indicators:

- Revenues from sales, broken down by individual fractions of subsequent batches and on a monthly and annual basis:
 - Yellow mealworm larvae intended for full-fat protein;
 - Chitinous molts intended for chitin;
 - Frass as an ingredient of fertilizers for potted plants.
- Costs of implementation of the production process:
 - Cost of feed;
 - Cost of depreciation of necessary machinery and equipment;
 - Materials, including pedigree rearing materials and tangible assets (rental of land and buildings and means of transport);
 - Materials and energy consumption;

- Workers' remuneration;
- External services;
- Intangible and legal assets.
- Profitability, broken down by individual fractions;
- Return on Investment (ROI), including individual fractions, is calculated before tax (by definition, ROI is calculated after tax, in the case of a startup, this method of calculation is difficult).

For the purpose of calculating economic indicators characterizing the production program and determining the value of a kg of larvae, the following conversion factor was used: 1 kg of mealworm larvae can be processed into 0.5 kg of full-fat meal. Another possibility of using the developed method is to assess the profitability of the larvae fraction transferred for extra fattening, as the answer to the question of what should be the most favorable rearing time of this larvae fraction was sought. The rate of return on investment was chosen as the assessment criterion. When calculating ROI, the costs of implementing the production program were distributed in proportion to the number of cuvettes in each of the larval fractions. Unfortunately, the ROI for the fraction of extra fattened mealworm larvae turned out to be negative, taking into account the income from both larvae, as well as chitinous molts and frass, the summary of values is presented in Table 7.

Table 7. ROI values for individual fractions of extra fattened larvae.

Number of Rearing Days	2	4	6	8	10	12	14
ROI for the “larger” fraction, extra fattening	−16.6	−16.4	−14.9	−14.1	−13.9	−13.3	−12.3
ROI for the “smaller” fraction, extra fattening	−21.7	−21.4	−21.1	−20.8	−20.0	−19.7	−19.4

The obtained values of the indicators presented to the owner of the startup were a big negative surprise. At the same time, they were an impulse to improve the rearing process of yellow mealworm larvae in order to reduce its cost-consumption by simplifying the fattening process. It is planned to limit the number and types of fractions and increase the frequency of starting the batch in order to standardize the age of larvae in cuvettes. The next steps include changes in the method of feeding: portion size proportional to the weight of mealworm larvae in the following days and correction of the feed recipe.

7. Conclusions

Insect rearing on an industrial scale, not only for animal feed but also for human food purposes, is no longer a distant prospect and has become an increasingly common practice in the European Union. In addition to large organizations, small- and medium-sized enterprises are present in the food market and startups eager to seek innovation and reach for grants in various research and development projects are dynamically developing. Insect rearing for human food purposes faces a number of organizational and technological challenges that must be solved in small- and medium-sized enterprises in order to effectively implement the production process.

The article documents the process of building a production system for yellow mealworm larvae, describes the production system and the method of farming, uses an automated feeding system, and monitors the degree of larvae development in cuvettes. However, the main attention was focused on the organizational aspects of the process of rearing, planning, and scheduling production activities. The calculated indicators characterizing the production process, in particular determining profitability and ROI, indicated the need for further improvements in the production process of larvae and optimization of cost-creating factors.

In order to achieve beneficial financial effects, it is advisable to further process insect larvae into high-fat and defatted proteins, flours and protein nutrients, oils and foodstuffs, or their ingredients. An essential element affecting the profitability of the project is the possibility of obtaining chitinous molts and their processing into chitin for the needs of

the cosmetic industry. Insect frass, in turn, can be used as a component of fertilizers for potted plants.

Overall, mealworms present a sustainable and nutritious ingredient for modern food products. Mealworms can be utilized in diverse food formulations, enhancing nutritional content and functional properties. As protein ingredients, mealworm protein powder can be incorporated into protein shakes, bars, baked goods, and pasta, significantly boosting their protein content. The fat from mealworms can be used in cooking oils, baked goods, confectioneries, and spreads, offering a source of healthy fats. Mealworm proteins also serve as effective emulsifiers, useful in sauces and dressings, and their water-binding capacity improves texture and moisture retention in various foods. Additionally, the mild nutty flavor of mealworms can enhance the overall taste profile of dishes. Compliance with local food safety regulations and consumer education on the benefits of insect-based foods are crucial for acceptance.

Challenges in the industrial rearing of insects include the acquisition of knowledge and skills for their effective rearing (including the full reproductive cycle), ensuring appropriate rearing conditions and the selection of feed ingredients and feeding methods. Enterprises are looking for answers to questions regarding the technical and organizational conditions of the production system. It is necessary to design rearing and processing installations, plant layouts, rearing monitoring systems, or mechanization and automation of daily operations. Logistic issues are an important part of the insect larvae production system, ensuring the supply of feed ingredients and efficient export of the obtained products.

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References

1. Bordiean, A.; Krzyżaniak, M.; Stolarski, M.J.; Czachorowski, S.; Peni, D. Will Yellow Mealworm Become a Source of Safe Proteins for Europe? *Agriculture* **2020**, *10*, 233. [\[CrossRef\]](#)
2. van Huis, A.; Oonincx, D.G.A.B. The Environmental Sustainability of Insects as Food and Feed. A Review. *Agron. Sustain. Dev.* **2017**, *37*, 43. [\[CrossRef\]](#)
3. Bovera, F.; Piccolo, G.; Gasco, L.; Marono, S.; Loponte, R.; Vassalotti, G.; Mastellone, V.; Lombardi, P.; Attia, Y.A.; Nizza, A. Yellow Mealworm Larvae (*Tenebrio molitor*, L.) as a Possible Alternative to Soybean Meal in Broiler Diets. *Br. Poult. Sci.* **2015**, *56*, 569–575. [\[CrossRef\]](#)
4. Iaconisi, V.; Marono, S.; Parisi, G.; Gasco, L.; Genovese, L.; Maricchiolo, G.; Bovera, F.; Piccolo, G. Dietary Inclusion of *Tenebrio Molitor* Larvae Meal: Effects on Growth Performance and Final Quality Treats of Blackspot Sea Bream (*Pagellus bogaraveo*). *Aquaculture* **2017**, *476*, 49–58. [\[CrossRef\]](#)
5. Ng, W.-K.; Liew, F.-L.; Ang, L.-P.; Wong, K.-W. Potential of Mealworm (*Tenebrio Molitor*) as an Alternative Protein Source in Practical Diets for African Catfish, *Clarias gariepinus*. *Aquac. Res.* **2001**, *32*, 273–280. [\[CrossRef\]](#)
6. Gilland, B. World Population and Food Supply: Can Food Production Keep Pace with Population Growth in the next Half-Century? *Food Policy* **2002**, *27*, 47–63. [\[CrossRef\]](#)
7. Miglietta, P.; De Leo, F.; Ruberti, M.; Massari, S. Mealworms for Food: A Water Footprint Perspective. *Water* **2015**, *7*, 6190–6203. [\[CrossRef\]](#)
8. Oonincx, D.G.A.B.; Boer, I.J.M. de Environmental Impact of the Production of Mealworms as a Protein Source for Humans—A Life Cycle Assessment. *PLoS ONE* **2012**, *7*, e51145. [\[CrossRef\]](#) [\[PubMed\]](#)

9. EFSA Panel on Nutrition, Novel Foods and Food Allergens (NDA); Turck, D.; Bohn, T.; Castenmiller, J.; De Henauw, S.; Hirsch-Ernst, K.I.; Maciuk, A.; Mangelsdorf, I.; McArdle, H.J.; Naska, A.; et al. Safety of Frozen and Dried Formulations from Whole Yellow Mealworm (*Tenebrio Molitor* Larva) as a Novel Food Pursuant to Regulation (EU) 2015/2283. *EFSA J.* **2021**, *19*, e06778. [\[CrossRef\]](#)
10. Wendin, K.; Olsson, V.; Langton, M. Mealworms as Food Ingredient—Sensory Investigation of a Model System. *Foods* **2019**, *8*, 319. [\[CrossRef\]](#)
11. Ravzanaadii, N.; Kim, S.-H.; Choi, W.-H.; Hong, S.-J.; Kim, N.-J. Nutritional Value of Mealworm, *Tenebrio Molitor* as Food Source. *Int. J. Ind. Entomol.* **2012**, *25*, 93–98. [\[CrossRef\]](#)
12. Siemianowska, E.; Kosewska, A.; Aljewicz, M.; Skibniewska, K.A.; Polak-Juszczak, L.; Jarocki, A.; Jędras, M. Larvae of Mealworm (*Tenebrio molitor* L.) as European Novel Food. *Agric. Sci.* **2013**, *4*, 287–291. [\[CrossRef\]](#)
13. Rumpold, B.A.; Schlüter, O.K. Nutritional Composition and Safety Aspects of Edible Insects. *Mol. Nutr. Food Res.* **2013**, *57*, 802–823. [\[CrossRef\]](#) [\[PubMed\]](#)
14. Moruzzo, R.; Riccioli, F.; Espinosa Diaz, S.; Secci, C.; Poli, G.; Mancini, S. Mealworm (*Tenebrio Molitor*): Potential and Challenges to Promote Circular Economy. *Animals* **2021**, *11*, 2568. [\[CrossRef\]](#) [\[PubMed\]](#)
15. Maillard, F.; Macombe, C.; Aubin, J.; Romdhana, H.; Mezdoor, S. Mealworm Larvae Production Systems: Management Scenarios. In *Edible Insects in Sustainable Food Systems*; Halloran, A., Flore, R., Vantomme, P., Roos, N., Eds.; Springer International Publishing: Cham, Switzerland, 2018; pp. 277–301. ISBN 978-3-319-74011-9.
16. Grau, T.; Vilcinskis, A.; Joop, G. Sustainable Farming of the Mealworm *Tenebrio Molitor* for the Production of Food and Feed. *Z. Für Naturforschung C* **2017**, *72*, 337–349. [\[CrossRef\]](#) [\[PubMed\]](#)
17. Eilenberg, J.; Vlask, J.M.; Nielsen-LeRoux, C.; Cappellozza, S.; Jensen, A.B. Diseases in Insects Produced for Food and Feed. *J. Insects Food Feed.* **2015**, *1*, 87–102. [\[CrossRef\]](#)
18. van Broekhoven, S.; Oonincx, D.G.A.B.; van Huis, A.; van Loon, J.J.A. Growth Performance and Feed Conversion Efficiency of Three Edible Mealworm Species (Coleoptera: Tenebrionidae) on Diets Composed of Organic by-Products. *J. Insect Physiol.* **2015**, *73*, 1–10. [\[CrossRef\]](#) [\[PubMed\]](#)
19. Majewski, P.; Zapotoczny, P.; Lampa, P.; Burduk, R.; Reiner, J. Multipurpose Monitoring System for Edible Insect Breeding Based on Machine Learning. *Sci. Rep.* **2022**, *12*, 7892. [\[CrossRef\]](#) [\[PubMed\]](#)
20. Majewski, P.; Mrzygłód, M.; Lampa, P.; Burduk, R.; Reiner, J. Monitoring the Growth of Insect Larvae Using a Regression Convolutional Neural Network and Knowledge Transfer. *Eng. Appl. Artif. Intell.* **2024**, *127*, 107358. [\[CrossRef\]](#)
21. Majewski, P.; Lampa, P.; Burduk, R.; Reiner, J. Mixing Augmentation and Knowledge-Based Techniques in Unsupervised Domain Adaptation for Segmentation of Edible Insect States. In Proceedings of the 18th International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications, Lisbon, Portugal, 24 January 2024; Volume 5, pp. 380–387. [\[CrossRef\]](#)
22. Reiner, J.; Kowalski, A.; Majewski, P. *Opracowanie Algorytmów Wspomagających Zarządzanie i Planowanie Produkcji Larw Mącznika Młynarka; Sprawozdanie z realizacji prac badawczych nr 82*; Politechnika Wrocławska: Wrocław, Poland, 2023.
23. Harris, F.W. Operations and Cost. *Fact. Manag. Ser.* **1915**, *2*, 48–52.
24. Wagner, H.M.; Whitin, T.M. Dynamic Version of the Economic Lot Size Model. *Manag. Sci.* **1958**, *5*, 89–96. [\[CrossRef\]](#)

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