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System dynamics modeling for precision beekeeping: Queen rearing optimization for advanced apiary management

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Abstract. The authors propose system dynamics modelling as a new direction in Precision Beekeeping. By modeling the production process in beekeeping, it is possible to forecast the potential production capacity before the season, using the resources available to the beekeeper. The model included in this article reflects one specialisation of beekeeping - queen bee rearing, from the process of queen bee breeding up to the sale of queen bees throughout the entire season. The model helps beekeepers make decisions about the workforce needed to maintain the desired production volume, expected income and costs and resource allocation.

Key words: apiary management, *Apis mellifera*, bee breeding, honey bee, precision beekeeping, system dynamic modeling, queen rearing.

INTRODUCTION

Precision beekeeping, or the incorporation of information technologies into beekeeping, is a recent innovation in the industry that has seen development over the last decade. Various monitoring systems are being developed, such as smart hive scales equipped with sensors that monitor, and process data on hive temperature, humidity, weight changes, sound variations, etc. (Zacepins et al., 2015; Zacepins et al., 2017; Hadjur et al., 2022; Zacepins et al., 2022; Danieli et al., 2023), as well as new tools to assess and precisely determine potential apiary locations and calculate bee colony amounts (Komasilova et al., 2020). Beekeepers can remotely access real-time data through applications. By incorporating machine learning and integrating AI into additional data processing and analysis, beekeepers will be able to receive specific notifications about particular bee colonies within applications, rather than dealing with large volumes of data (Zacepins et al., 2017; Hadjur et al., 2022). The implementation of remote apiary monitoring helps efficiently plan the beekeeper's time and prepare purposefully for apiary inspections.

Another tool that can help address questions related to effective resource planning is system dynamics modeling. This modeling is based on systemic thinking, or the exploration of cause-and-effect relationships between various variables and understanding how each variable influences others and how everything is interconnected (Forrester, 1994). Models can simulate real-life processes. It is necessary to map out all variables, assign values to them (based on empirical data or theory), and describe relationships with formulas. Models drawn in specialized computer programs simulate behaviour, showing how one variable changes depending on another and how the system as a whole operates. At the core of modeling are problem formulation, dynamic hypothesis creation, model formulation and simulation, model testing, policy creation, and testing (Senge & Forrester, 1980; Forrester, 1994; Barlas, 1996). In beekeeping, various mathematical models have been developed, and system dynamics modeling has been applied. To inform important policy decisions, research has explored how the impact of beekeeping affects wild honey bee populations (Gill, 1996). Models have been used to test changes in the *Varroa* mite population and bee colony development (DeGrandi-Hoffman & Curry, 2004; Becher et al., 2014), as well as how bee colony development varies based on the availability of pollen and nectar sources, food reserves in the hive (Khoury et al., 2013; Russell et al., 2013; Myerscough et al., 2017; Hempel, 2022), and artificial feeding of bee colonies (Paiva et al., 2016). The influence of abiotic and biotic factors on bee colony health has been assessed, and productivity indicators have been forecasted (Gilioli et al., 2018). Profitability from migratory beekeeping has been modeled, taking into account the flowering crops at the apiary site (Pilati et al., 2018). It has been examined whether larger apiaries with a greater number of bee colonies have a higher prevalence of pathogens (Bartlett et al., 2019).

The aim of this article is to present a system dynamics model that can forecast production capacity in a subsector of beekeeping related to the breeding of queen bees. The model reflects the process of queen bee breeding for commercial purposes, aiding in decision-making regarding necessary human and bee colony resources to effectively meet planned production capacities. For the first time in beekeeping, a system dynamics model is described that comprehensively encompasses commercial beekeeping, incorporating human resources and reflecting queen bee rearing, which is essential in the reproductive material propagation subsector of beekeeping. The creation of such models, based on practical data that simulate the production process and capacity, enabling decisions for effective resource utilization, is presented as one of the subdirections of precision beekeeping.

MATERIALS AND METHODS

Definition of problem

The purpose of rearing queen bees is to propagate reproductive material that can be introduced into other colonies by acquiring either virgin queens or mated-laying queens. In Latvia, the queen bee rearing season is short, spanning 16 weeks from May 1st to August 31st. Honeybee colonies start actively collecting the first pollen from willows as early as the end of March (Klavins, 2024). This marks the beginning of active development for bee colonies. The queen bee rearing system requires strong bee colonies to ensure the queenless colonies for queen bee rearing and mating nuclei. The outcome of rearing new virgin and laying queen bees depends on both weather conditions (Büchler et al., 2013) and the efficiency of the rearing system. The establishment and maintenance of a queen rearing and mating system are time-consuming and complex. Therefore, system dynamics modeling will be employed to reflect the system, aiming to understand the necessary resources for production, the production process, and limiting factors and to define indicators characterizing efficiency.

The model addresses the research question: What is the optimal size of the production system (production capacity) that a beekeeper with limited time resources (40 hours per week) can sustain as functional and profitable for the entire 16 weeks while maximizing the efficiency of resource utilization?

Background information

To understand the model, we must first delve into the biology and behaviour of bees. A bee colony is a superorganism comprising female organisms, the queen bee and worker bees, as well as male organisms known as drones. The queen bee, living for an average of 3–4 years, is the sole individual capable of laying fertilized eggs (Cobey, 2007). Worker bees maintain the colony: they feed and groom the queen, feed the larvae hatched from eggs, construct wax cells, collect water, pollen, and nectar, maintain cleanliness in the hive, defend it, and in summer, they also care for and feed the drones. Drones constitute 5% of the colony's population in summer, and their sole purpose is to take flight to mate with new queens, thus passing on their genes to other colonies (Oxley & Oldroyd, 2010).

It is possible to propagate bee colonies by isolating a portion of the bee population with honey and brood combs. When worker bees detect a queenless state, they decide to feed the youngest worker bee larvae with royal jelly, aiming to raise them into new queens. This behaviour is utilized in queen rearing. Strong colonies without queens are created, and beekeepers introduce grafted 12–24 hour-old larvae, derived from known bee breeding material, into artificial cells. Worker bees then start feeding and raising these larvae into queens (Büchler et al., 2013). A queenless colony can optimally rear 40 queen bees in one batch, and a total of around 160 queens in 3–4 weeks (Author's experience). After that, a new queenless colony must be formed for rearing queens. The queen bee develops in 16 days: 3 days in the egg stage, 6 days in the larval stage (a crucial period that can take place only within the bee colony), and 7 days as a pupa, during which development occurs in a sealed queen cell (this phase may take place within the bee colony or a special incubator) (Page & Peng, 2001).

The queen bee is introduced to a queenless bee unit (nucleus) a day before or after her birth, where worker bees feed and care for her (Büchler et al., 2013). The queen bee reaches sexual maturity within 5–6 days after birth (Page & Peng, 2001; Cobey et al., 2013). After maturation, on warm days (with an outdoor temperature of at least + 20 °C), the queen bee takes 1–3 mating flights, mating with an average of 10 drones and storing the sperm in a special organ - the spermatheca - for her entire lifespan (Page & Peng, 2001; Cobey et al., 2013). Upon returning to the nucleus, the queen bee starts laying eggs within an average of 5 days (Page & Peng, 2001). If the queen bee successfully mates, she lays fertilized eggs, which develop into worker bees. If not, she lays unfertilized eggs, which develop into drones. Therefore, it is necessary to check the brood comb 9 days after the start of laying, as the capping is visually different for workers and drones (Page & Peng, 2001; Büchler et al., 2013). The optimal time from the queen bee's birth to the examination of a mated, laying queen is 3 weeks. Both mated queen bees and virgin, unmated queens can be sold to other beekeepers, who introduce them into their colonies and renew the reproductive material.

To implement the breeding process, apiaries and main bee colonies are necessary. The recommended maximum number of bee colonies in one apiary is 30 (Büchler et al., 2013), linked to the availability of nectar sources. However, in Latvia, if both bee colonies and mating nuclei are placed in the same apiary, the maximum number of colonies in one apiary is 20, and for nuclei - 100 (author's recommendation based on experience). In the first half of the season (May, June), bee colonies actively develop, exhibiting a greater swarming tendency, and during this period, it is possible to create a maximum of 5 new nuclei from one parent colony. Regular inspections of bee colonies and nuclei are essential to establish and maintain bee colonies, as well as to assess the acceptance of new queens and the success of mating outcomes.

If queen bee rearing is the main source of income, then within 16 weeks, one must generate income to cover the annual costs of maintaining bee colonies, nuclei, etc. Therefore, the model includes the assumption that the annual costs for one bee colony are 100 EUR (winter feeding with sugar syrup, treatments, wear and tear on equipment, purchase of beeswax, transportation costs), and for a nucleus, the costs are 20 EUR (stimulative feeding during the absence of nectar flow, equipment wear and tear, transportation costs). To maintain the system, a person is also required, acting as the limiting factor - a time resource (40 hours per week) and as a cost component - labour wages. The model incorporates the average gross hourly wage for a beekeeper in Latvia in June 2023, which is 6.10 EUR/hour (SRS, 2023), assuming work specifically for 4 months for the purpose of queen rearing. Of course, there are other expenses related to marketing, customer service, and to some extent, processing of beekeeping products and preparation of equipment for the next season, which require additional human resources. Revenues are also influenced by demand and weather conditions affecting production volume. The primary goal of the model is to reflect the production process and the operational principles of the model, predicting production capacity in relation to limited human resources. The detailed income and expenditure section, along with factors influencing supply and demand, are additional model components that will remain beyond the scope of this article.

The dynamic hypothesis

Stocks, flows, and influencing factors. The model defines key resources as 'stocks' that accumulate and are utilized in the production process. Stocks also feature incoming and outgoing flows that regulate their value. Meanwhile, various additional factors or parameters influence these flows. The main resources in the queen rearing model are:

- Stock 'Mating nuclei': This stock has one incoming flow, 'Formation of nuclei', influenced by the resource 'Bee colonies'. One strong bee colony can create 5 mating nuclei, and this formation is possible gradually only in May and June. Another influencing factor is the 'Number of apiaries', as the maximum capacity in one apiary location is 20 bee colonies and 100 mating nuclei.
- Stock 'Production overtime': This stock has an incoming flow 'Time consumed for production', influenced by the time spent on queen grafting, inspections of bee colonies and mating nuclei, and the packaging of queens for sale. The outgoing flow 'Time has passed' is constant and corresponds to the planned 40 hours per week.
- Stock 'Virgin queens': The incoming flow 'Queen rearing' depends on the defined number of rearing colonies, as each rearing colony can rear 40 virgin queens. If

overtime hours occur, the incoming flow 'Queen rearing' stops due to time constraints and resumes if overtime hours do not occur. The outgoing flows 'Addition of virgin queens to mating nuclei' depend on the number of mating nuclei created at the given moment, as one unit can accommodate 1 virgin queen. The outgoing flow 'Sale of virgin queens' depends on the surplus of virgins after adding them to mating nuclei.

- Stock 'Queens in mating nuclei' has two outgoing flows. After adding a queen to the nucleus, some queens may not be accepted or may disappear during the nuptial flight and not return. On average, the proportions of non-acceptance and disappearance are 30%. Meanwhile, 70% successfully mate, and within 3 weeks of being added to the nuclei, they become mated, laying, tested queens ready for sale (Smilga-Spalvina et al., 2024).
- Stock 'Naturally mated, laying, tested queens' accumulates all tested mated queens for sale. The stock has one outgoing flow 'Sale of naturally mated queens'.
- The system includes additional stocks, 'Virgin queens sold', 'Naturally mated queens sold', and 'Money in the bank', which characterize production profitability. It should be noted that the model assumes that all queen bees are sold and does not investigate how changes in demand affect the circulation of queen bees in the system.

Causal loop diagrams. After defining stocks, flows, and influencing factors, causal relationships and their mutual impact on feedback loops are identified. Causal loop diagrams help visually represent these relationships (Fig. 1). If the variables within a loop act in opposite directions (if one variable increases, the other decreases), the influence is indicated by an arrow and a 'minus' sign. If there is an odd number of 'minus' signs within the loop, the loop is called balancing or negative. If the variables within a loop act in the same direction or 'drive each other forward' (if one variable increases, the other also increases), the influence is indicated by an arrow and a 'plus' sign. Conversely, if there are only 'plus' signs or an even number of 'minus' signs within the loop, the loop is called reinforcing or positive.

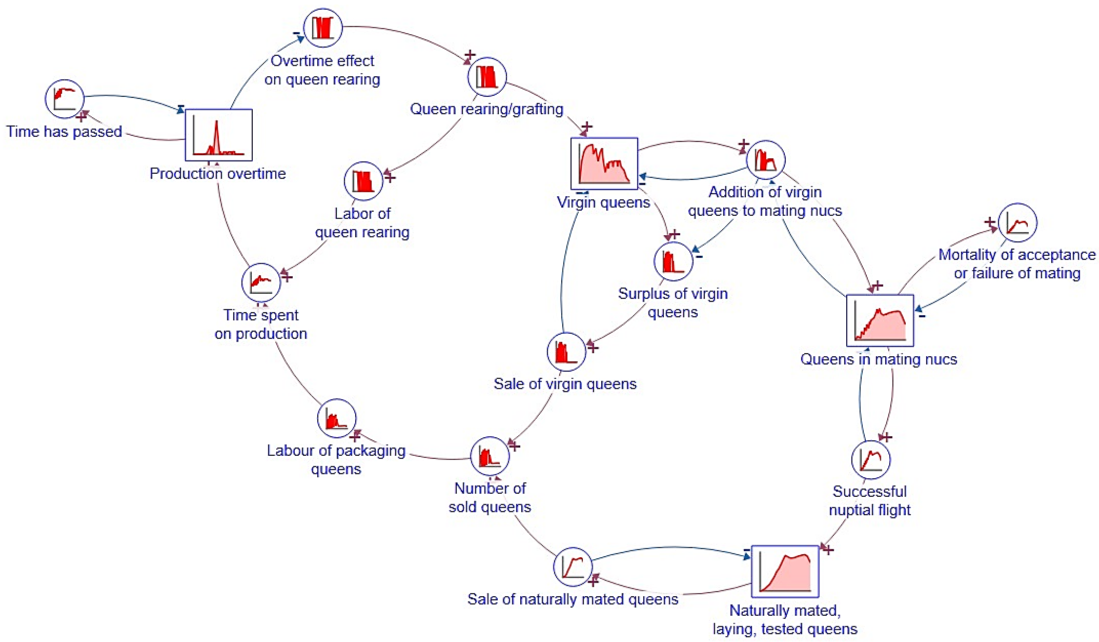

Figure 1. Causal loop diagram for the dynamic hypothesis of queen rearing process.

In the queen bee rearing model, the following causal loops are at play:

- Addition of virgin queens to mating nuclei: This action is governed by two balancing loops with the following relationships: the more virgin queens are added into mating nuclei, the fewer virgin queens remain in the stock, and vice versa. Another relationship is that the more virgin queens are added into mating nuclei, the more occupied the nuclei will be. The more occupied the nuclei, the fewer virgin queens can be added to them.
- Acceptance of virgin queens in nuclei and mating: Two balancing loops are also present here. The first: the more queens perish due to unsuccessful acceptance in the nuclei or during mating flights, the fewer queens will remain in the nuclei. The second: the more queens successfully mate, the fewer queens will remain in the nuclei.
- Sale of virgins and mated, laying queens: For mated queens, a balancing loop determines that the more queen bees are sold, the fewer queen bees will remain in the stock. In contrast, for virgin queens, a reinforcing loop dictates that the more queens are added to nuclei, the smaller the surplus of queens. The smaller the surplus, the fewer virgin queens need to be sold. Fewer queens sold result in a larger queen surplus.
- Regulation of production overtime: If the queen rearing system results in an increase in the time consumed by production, exceeding 40 hours per week, creating overtime, the system is regulated by the parameter 'overtime effect on queen rearing'. If overtime increases, the overtime effect coefficient decreases (from 1 to 0), and queen rearing is halted. Conversely, if overtime does not occur and does not exceed 40 hours per week, the overtime effect value increases from 0 to 1, restarting the queen rearing process. The creation of overtime is heavily influenced by packaging both types of queens. Meanwhile, the task related to the rearing of new queen bees in the system is the only one that can regulate the overall queen bee flow in the system.

The model itself is constructed using the *Stella Architect* software. The table of all parameters and equations in model is available in Annex 1 and Annex 2.

Within the framework of dynamic hypotheses, such a model, incorporating the previously described main stocks, flows, and causal loops will respond if any of the limiting factors of system capacity are exceeded, for instance, if the 40-hour workweek is exceeded. The model will precisely indicate the production capacity. Model validation is still required to ensure the model's reliable behaviour. The behaviour and forecasting results of the model will be described in the analysis section.

Validation

Model structure test: The model has been compared with a real system (based on empirical data and theoretical information about bee biology and behaviour). The stocks, flows, parameters and values included in the model correspond to real-life situations and theories. The level of detail is sufficient to analyse the mutual impact of each variable and its effect on the workload and time consumption. All structural elements included in the model, along with their values, are summarized in Annex 1 and Annex 2.

Model behaviour test: The model's variable quantities have been tested with extreme values, and the model's behaviour is consistent with real-life scenarios, avoiding any inexplicable behaviour. For instance, if there are no apiary locations, it is impossible to create mating nuclei. Only as many queen bees can be added to the nuclei as the number of mating nuclei that have been established or how many of them are queenless at a given time. Since the model aims to forecast production capacity, it includes the time resource (time spent inspecting bee colonies and nuclei, queen rearing, queen packaging). Accumulation of overtime pauses queen rearing for a while. If the production capacity is optimal, the model exhibits S-shaped behaviour, as it is restricted by the system's capacity, i.e., the number of established mating nuclei. If overtime occurs in the system, the model generates a decline after an increase.

The policies that will be used to change behaviour:

• Policy – constants, parameters, numbers. Parameters such as 'count of mating nuclei' and the parameter 'planned virgin queens per week,' affecting the flow of 'queen rearing,' will be altered.

• Policy – the size of buffers and other stabilizing reserves relative to their flows. The stabilizing reserve is 'Production overtime'; if the stock becomes > 0, the parameter 'overtime effect on queen rearing' immediately influences the flow of 'queen rearing.'

• Policy – system rules. The system constraint is the parameter 'Expected time for production' – in the given model, it is set to 40 hours, and if exceeded, overtime hours accumulate, immediately regulating or temporarily halting the flow of 'queen rearing.

RESULTS AND DISCUSSION

In the Results section, 4 different production capacities will be examined to demonstrate the varying behaviour of the system dynamics model, which helps make decisions regarding production capacity planning.

Capacity: 200 queen bees per week and 200 mating nuclei (Fig. 2)

If a beekeeper has access to 2 apiaries, it is possible to gradually create 200 mating nuclei during the season, where new queen bees will be introduced. The plan is to rear 200 queen bees per week, meaning 200 new virgin queens will be born every week. The newly emerged queens will be added to the nuclei, from which, after 3 weeks, mated, laying and tested queen bees will be available. The surplus of virgin queens and mated, laying, tested queens are sold. Fig. 2, a illustrates the model's behaviour, where resources are utilized efficiently: all gradually created 200 mating nuclei are continuously filled with new queens throughout the entire season, and queen rearing occurs without interruptions, providing 200 virgin queens a week. Initially, in the first 4 weeks (May), there are significant surpluses of virgin queens, but during this period, there is the highest demand in the market for virgin queens, as mated queen bees appear in the market only at the end of May. Queen bee rearing is halted by the 13th week because, by the end of July, the colonies lose their swarming tendency, the season's peak nectar flows have ended, and the colonies refuse to rear queens intensively. The production capacity of 200 queens per week does not exceed 40 working hours per week (Fig. 2, b). Maximum time spent on production in this case is 27.1 hours/week. Queen rearing consumes 2.4 hours, queen bee packaging 8 hours, hive inspections 6.7 hours, and mating nuclei inspections reach 10 hours per week. Under ideal conditions with such capacity, it is possible to produce 1.42 thousand virgin queen bees and 471 laying queens (Fig. 2, c). The model predicts that all queen bees are sold (8 EUR/virgin queen, 22 EUR/laying queen), regardless of demand changes that may affect the circulation of queen bees in the system. Accordingly, with the selected production capacity, it is possible to cover the costs of maintaining bee colonies (100 EUR/colony) and mating nuclei maintenance costs

(20 EUR/nuclei) for the year, as well as provide seasonal salaries, resulting in forecasted surplus funds of 11.2 thousand EUR to cover additional expenses and investments (Fig. 2, d).

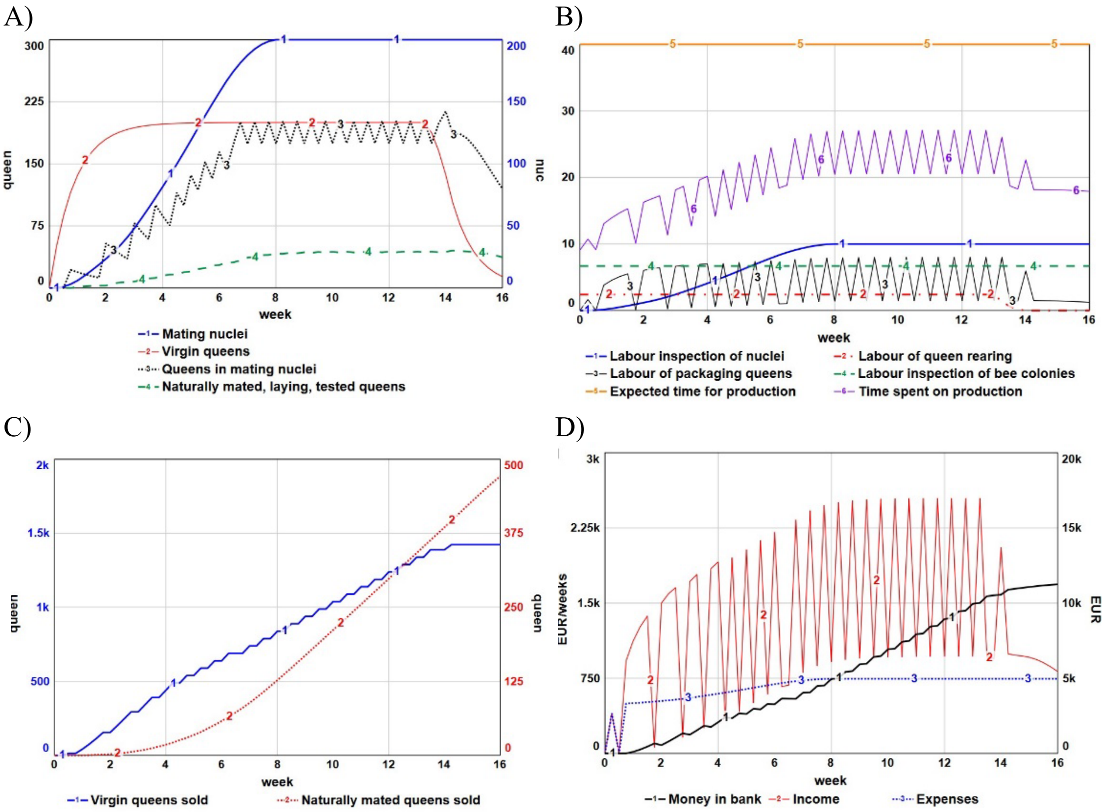

Figure 2. Simulation of the model behaviour by software *Stella Architect.* Production capacity (A), time resource consumption (B), the number of sold queen bees (C) and profit (D): rearing 200 queen bees per week, creating and maintaining 200 mating nuclei over a 16-week period with a 40-hour workweek.

Capacity: 300 queen bees per week and 300 mating nuclei (Fig. 3)

If beekeepers have access to additional apiaries and can increase queen rearing capacity, the system quickly reaches and exceeds 40 hours of production per week, hindering operations and temporarily or permanently interrupting queen rearing (Fig. 3, a, b). For example, by creating and maintaining 300 mating nuclei and rearing 300 queen bees per week, a beekeeper in the second half of the season, after 8 weeks, may encounter overtime hours, reaching 40.5 hours/week (Fig. 3, a, b). In this case, compared to the previous situation, work hours have increased in all positions: queen rearing consumes 3.6 hours, queen bee packaging 11.9 hours, hive inspection 10 hours, and nuclei inspection 15 hours. As the overtime hours are minimal, the system can be maintained functional until the end of the season by periodically suspending new queen rearing. With such capacity, it is possible to produce 1.9 thousand virgin queens and 713 laying queens during the season. Similar to the previous case, with a production capacity of 300 queen bees per week and 300 mating nuclei, it is possible to cover expenses

(994 EUR/week) and ultimately obtain surplus funds amounting to 17 thousand EUR. Of course, it should be noted that in this case, the system balances on the predicted production time limit of 40 working hours per week. As adjustments in the beekeeping process can be influenced by other external factors, it would be risky for a real farm to choose this option. With additional work appearing on the farm, the volume of overtime will definitely increase, and it may no longer be possible to effectively maintain the established queen rearing and mating system with only a few interruptions in queen rearing.

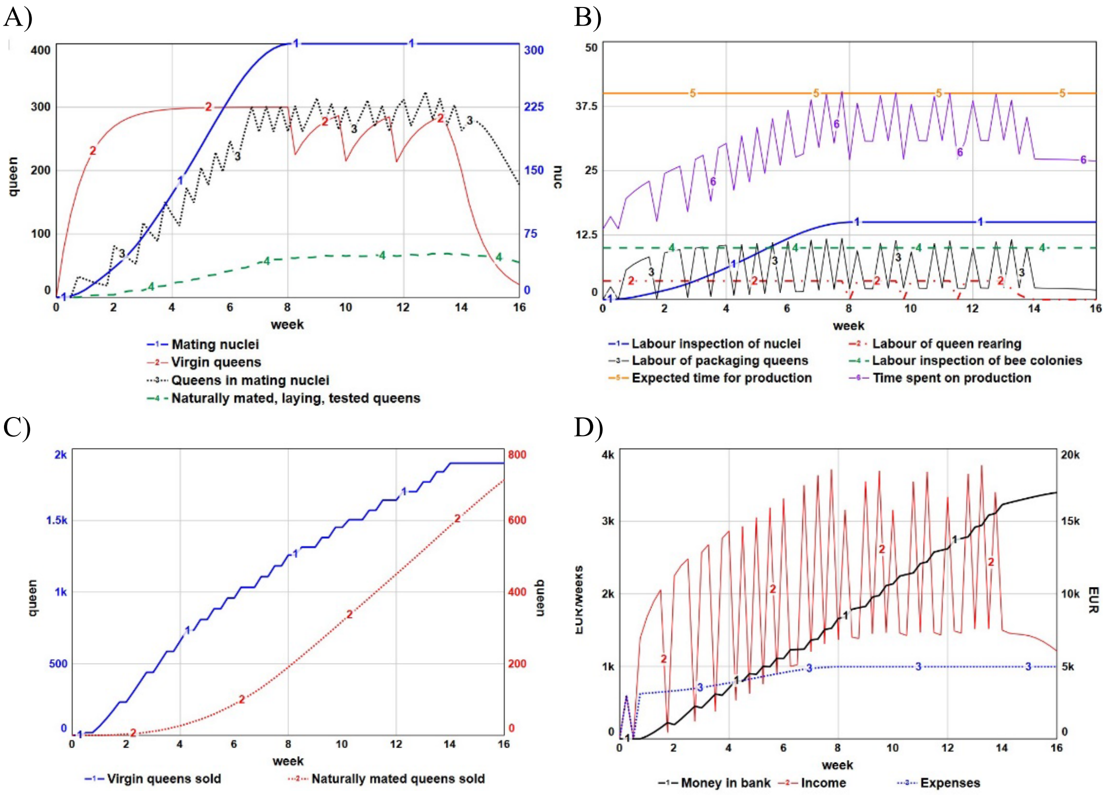

Figure 3. Simulation of the model behaviour by software *Stella Architect.* Production capacity (A), time resource consumption (B), the number of sold queen bees (C) and profit (D): rearing 300 queen bees per week, creating and maintaining 300 mating nuclei over a 16-week period with a 40-hour workweek.

Capacity: 400 queen bees per week and 400 mating nuclei (Fig. 4)

Increasing production capacity to 400 queen bees per week and 400 mating nuclei, the model shows that problems will arise in maintaining the system as early as the 4th week. In the fourth week, for the first time, 40.4 working hours are reached, and the rearing of new queen bees is interrupted (Fig. 4, b). With a larger production system, mating nuclei are formed from more bee colonies. It consumes more time for inspections than in previous cases with lower production capacity, i.e., 13.4 hours for 60 bee colonies. Queen rearing takes 4.8 hours per week, and queen packaging takes 14 hours per week. In total, for these three positions, it amounts to 32.2 hours per week. However, by establishing only a fraction of the intended mating nuclei, overtime hours rapidly accumulate. It takes 20 working hours to inspect all 400 nuclei. In total, the necessary working hours to maintain the system would be 52.2 hours per week. However, in such a system with the corresponding amount of overtime, it is not possible to either resume queen rearing or fill all the created mating nuclei (Fig. 4, a). In case of overload, the number of produced queens also decreases (Fig. 4, c): by the 8th week, 1.34 thousand virgin queens are produced, after which there are no more virgin queens, but the number of produced laying queen bees is 886. Although production in this situation is inefficient, it is still possible to cover expenses and generate surplus funds of 12.9 thousand EUR (Fig. 4, d), which is significantly less than maintaining the system with 300 nuclei and 300 queen bees per week. In this capacity, the main consequence is the unnecessary maintenance of mating nuclei, which cannot be provided with new queen bees, resulting in the waste of bee resources.

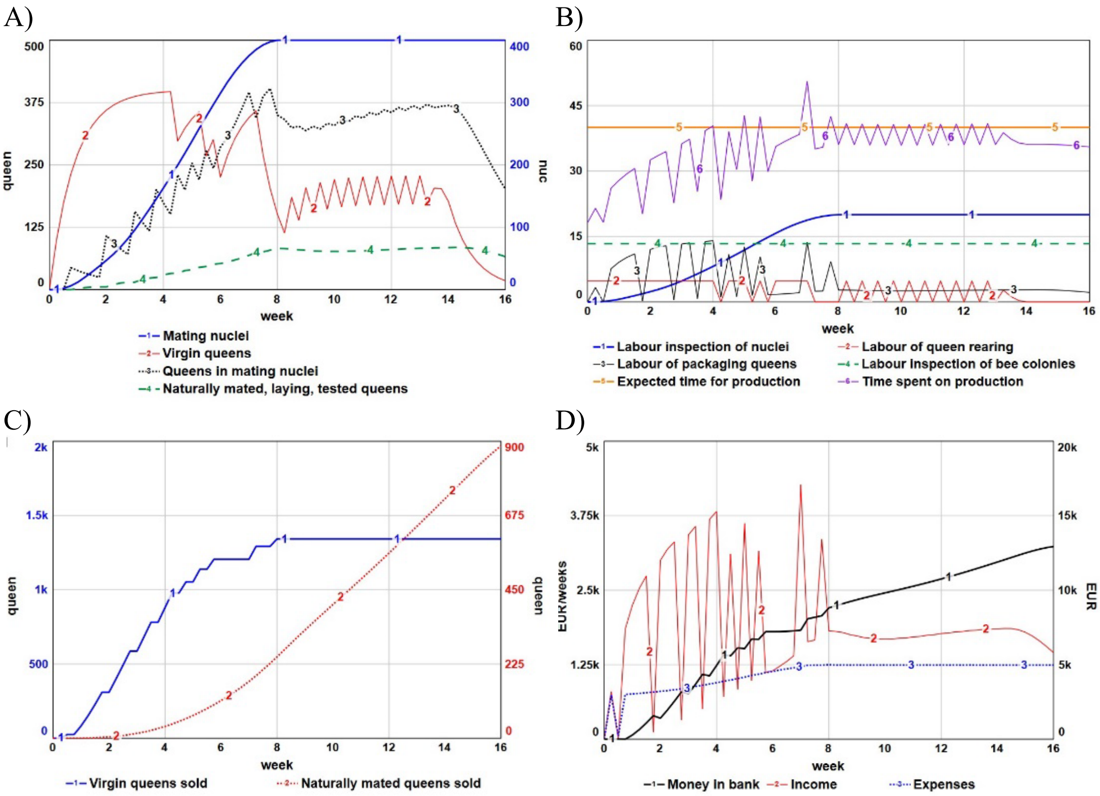

Figure 4. Simulation of the model behaviour by software *Stella Architect*. Production capacity (A), time resource consumption (B), the number of sold queen bees (C) and profit (D): rearing 400 queen bees per week, creating and maintaining 400 mating nuclei over a 16-week period with a 40-hour workweek.

Capacity: 500 queen bees per week and 500 mating nuclei (Fig. 5)

Increasing production capacity to 500 queen bees per week and 500 mating nuclei inevitably results in the first signs of inability to sustain such a volume, appearing as early as the 2nd week, while around the 6th to 7th week, the system completely and irreversibly collapses (Fig. 5, a, b). It requires 16.7 hours for maintaining bee colonies, 6 hours for queen rearing, 15.7 hours for queen packaging, and 25 hours per week for maintaining all planned mating nuclei. At least 63.4 working hours per week are required to maintain such a system. The collapse of the system also reflects on the low number of produced queens for the chosen capacity (Fig. 5, c) and financial resources, running out by the 15th week (Fig. 5, d).

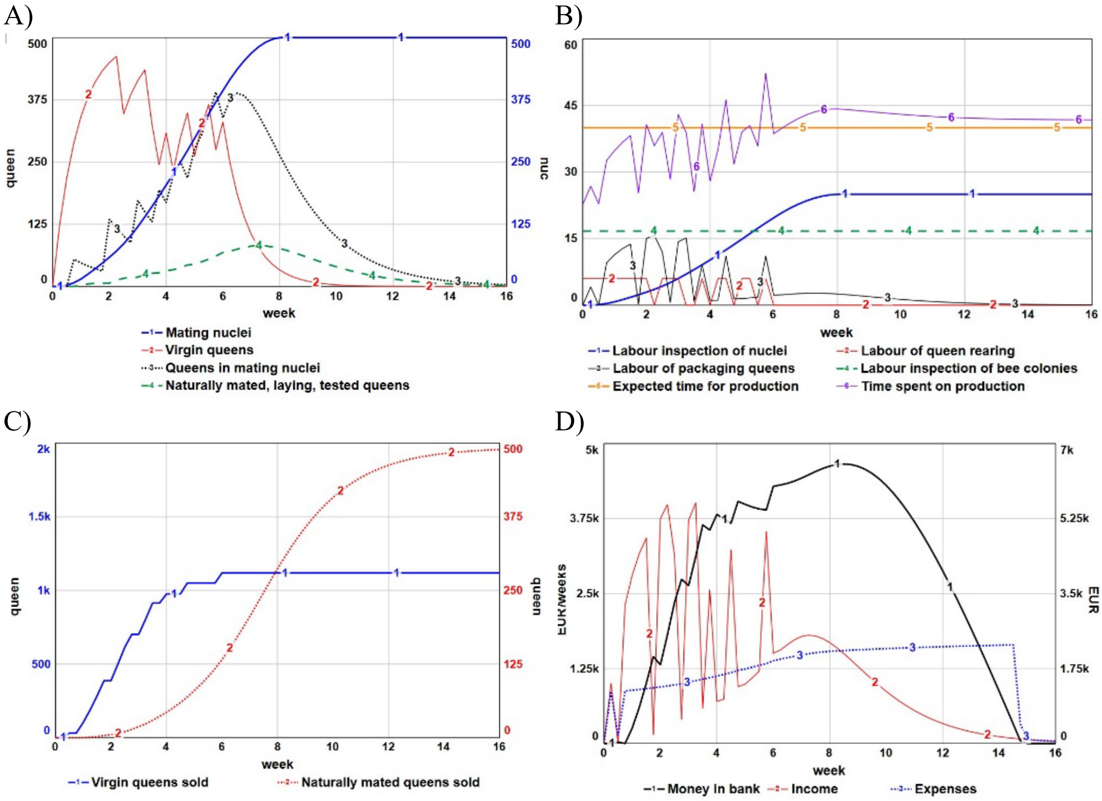

Figure 5. Simulation of the model behaviour by software *Stella Architect.* Production capacity (A), time resource consumption (B), the number of sold queen bees (C) and profit (D): rearing 500 queen bees per week, creating and maintaining 500 mating nuclei over a 16-week period with a 40-hour workweek.

The four scenarios described above illustrate what happens when an excessively large production capacity is chosen at the beginning of the beekeeping season, where the first signs appear when there is a shortage of time resources and what are the consequences of such decisions. Of course, in real life, after realizing that it is not possible to maintain the chosen production system, an alternative option can be selected: either hiring additional staff or reducing the production system's capacity to keep it functional until the end of the season, but making changes during the season also requires additional time. The model demonstrates that depending on the chosen production capacity (reared queens per week and maintained mating nuclei), the first signs or the first overtime hours may develop after 2, 4, or even 8 weeks after starting production, which may not be initially apparent. Therefore, modeling allows to plan for an appropriate production capacity before the season starts with a reserve of working hours necessary for unforeseen circumstances or to make timely decisions about hiring additional labour.

However, it should be noted that the specific model simulates the flow of queen bees without taking into account the prolonged adverse effects of weather conditions. If the weather conditions are consistently unfavourable (wind, rain, temperature below +20 °C), queen bees will be unable to go on nuptial flights, significantly delaying the circulation of queen bees in the nuclei and creating an excessive supply of virgin queens. Additionally, after the age of 14 days, the mating quality of the queen bee decreases; the queen bee may accumulate less sperm, resulting in a shorter lifespan (Cobey, 2013). Although the model already includes the assumption that 30% of queen bees will not be accepted or will be lost during mating flights (Smilga-Spalvina et al., 2024), in prolonged unfavourable weather conditions and periods of interrupted nectar yield, this percentage may be significantly higher.

CONCLUSIONS

System dynamics modeling is one of the precise tools in beekeeping that allows modeling the production process in software applications. Modeling helps to understand the production process in detail and make decisions about possible production capacities with the resources available to the beekeeper. It helps to identify weaknesses in the production process, for example, the time-consuming stages such as queen rearing, packaging of queens, inspection of bee colonies, and inspection of nuclei. To reduce time consumption in packaging of queens, packaging types can be changed, such as using wooden or plastic boxes for queen bees with accompanying worker bees, or employing padded envelopes or cardboard boxes for shipping. If too much time is spent on inspecting mating nuclei, where the acceptance, laying, and checking of brood take place, it may be necessary to reconsider the design of the nuclei or change the method of introducing queens to the nuclei (using queen cells or introducing a marked virgin queens).

The queen bee rearing model in the article demonstrates that with limited labour resources of 40 hours per week, it is possible to efficiently maintain 200 mating nuclei and rear 200 queen bees per week consistently without interruptions, utilizing the maximum capacity of the system. Of course, in this scenario, there remains a 32% reserve of time, which can be utilized by slightly increasing capacity or kept unused for unforeseen circumstances that may arise due to weather conditions, errors in planning and beekeeping practices, or variable demand. On the other hand, if the capacity is chosen to be too large, resources are inefficiently utilized, and it becomes impossible to temporarily halt the rearing of new queen bees and restore the system to its previous state. In such a case, quick solutions would be to reduce production capacity (the number of reared queen bees and mating nuclei) or to hire additional labour, which could be challenging during the season. To avoid overload, it is recommended to conduct planning before the season, including a buffer of working hours to address unforeseen circumstances, for example, prolonged unfavourable weather conditions and rapid changes of demand that will delay the circulation of queens.

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ANNEXES

Annex 1. Parameters and equations that represent functional relationships in a system dynamic model

Parameters	Equation	Units
Mating_nuclei (t)	Mating_nuclei (t - dt) + (Formation_of_nuclei) * dt; INIT Mating_nuclei = 0	nuclei
Money_in_bank (t)	Money_in_bank (t - dt) + (Income - Expenses) * dt; INIT Money_in_bank = 0	EUR
Naturally_mated_queens_ sold (t)	Naturally_mated_queens_sold (t - dt) + (Sale_of_naturally_mated_queens) * dt; INIT Naturally_mated_queens_sold = 0	queen
Naturally_mated_laying_ tested_queens (t)	Naturally_mated_laying_tested_queens (t - dt) + (Successful_nuptial_flight - Sale_of_naturally_mated_queens) * dt; INIT Naturally_mated_laying_tested_queens = 0	queen
Production_overtime (t)	Production_overtime (t - dt) + (Time_spent_on_production - Time_has_passed) * dt; INIT Production_overtime = 0	hour
Queens_in_mating_ nuclei (t)	Queens_in_mating_nuclei (t - dt) + (Addition_of_virgin_queens_to_mating_nuclei - Successful_nuptial_flight - Mortality_of_acceptance_or_failure_of_mating) * dt; INIT Queens_in_mating_nuclei = 0	queen
Virgin_queens (t)	Virgin_queens (t - dt) + (Queen_rearing/grafting - Sale_of_virgin_queens - Addition_of_virgin_queens_to_mating_nuclei) * dt; INIT Virgin_queens = 0	queen
Virgin_queens_sold (t)	Virgin_queens_sold (t - dt) + (Sale_of_virgin_queens) * dt; INIT Virgin_queens_sold = 0	queen
Addition_of_virgin_ queens_to_mating_ nuclei	(IF Queens_in_mating_nuclei < Mating_nuclei THEN Virgin_queens ELSE 0)	queen/ week
Expenses	Expenses_for_wages_a_week + Expenses_bee_colonies_a_week + Expenses_for_nuclei_a_week	EUR/ week
Formation_of_nuclei	IF Bee_colonies * Formation_of_nuclei_factor/ Number_of_apiaries > Density_of_nuclei_in_one_apiary THEN Density_of_nuclei_in_one_apiary * Number_of_apiaries ELSE Bee_colonies * Formation_of_nuclei_factor	nuc/ week
Income	Income_from_the_sale_of_virgin_queens + Income_from_the_sale_of_naturally_mated_queens	EUR/ week
Mortality_of_acceptance_ or_failure_of_mating	Queens_in_mating_nuclei * Mortality_rate	queen/ week
Queen_rearing/grafting	Total_grafting_places_for_rearing * Virgin_production_factor_(grafting_every_5_days) * Overtime_effect_on_queen_rearing	queen/ week
Sale_of_naturally_mated_ queens	Naturally_mated_laying_tested_queens	queen/ week
Sale_of_virgin_queens	Surplus_of_virgin_queens	queen/ week
Successful_nuptial_flight	Queens_in_mating_nuclei * Ratio_of_mating_success * Time_for_laying_and_tested_queen	queen/ week
Time_has_passed	Expected_time_for_production	hour/ week
Time_spent_on_production	Labour_inspection_of_nuclei + Labour_inspection_of_bee_colonies + Labour_of_queen_rearing + Labour_of_packaging_queens	hour/ week
Bee_colonies	Density_of_bee_colonies_in_one_apiary * Number_of_apiaries	bee colony
Count_of_mating_nuclei	400 (user defined)	nuclei
Density_of_bee_colonies_ in_one_apiary	20	bee colony/ apiary
Density_of_nuclei_in_one_ apiary	100	nuc/ apiary

Expected_time_for_ production	40 (user defined)	hour
Expenses_bee_colonies_a_week	Bee_colonies * Expenses_for_one_bee_colony_a_week	EUR/ week
Expenses_for_nuclei_a_ week	Mating_nuclei * Expenses_for_one_nuc_a_week	EUR/ week
Expenses_for_one_bee_ colony_a_week	100/16	EUR/ bee colony/ week
Expenses_for_one_nuc_a_ week	20/16	EUR/ nuc/ week
Expenses_for_wages_a_ week	Labor_a_week * Gross_labor_wage_rate	EUR/ week
Formation_of_nuclei_ factor	GRAPH(TIME) Points: (0.00, 0.000), (1.00, 0.400), (2.00, 0.500), (3.00, 0.800), (4.00, 0.900), (5.00, 1.000), (6.00, 0.900), (7.00, 0.500), (8.00, 0.000), (9.00, 0.000), (10.00, 0.000), (11.00, 0.000), (12.00, 0.000), (13.00, 0.000), (14.00, 0.000), (15.00, 0.000), (16.00, 0.000)	percent
Gross_labor_wage_rate	6.10	EUR/ hour
Income_from_the_sale_of_naturally_mated_queens	Price_of_naturally_mated_queen * Sale_of_naturally_mated_queens	EUR
Income_from_the_sale_of_virgin_queens	Price_of_virgin_queen * Sale_of_virgin_queens	EUR/ week
Labour_inspection_of_ bee_colonies	Bee_colonies * Labour_inspection_of_one_bee_colony	hour/ week
Labour_inspection_of_ nuclei	Labour_inspection_of_one_nuc * Mating_nuclei	hour/ week
Labour_inspection_of_one _bee_colony	0.167	hour/ bee colony/ week
Labour_inspection_of_one_ nuclei	0.05	hour/ nuc/ week
Labor_a_week	Expected_time_for_production + Production_overtime	hour/ week
Labor_of_queen_rearing	Queen_rearing/grafting *Labor_of_queen_rearing_one_unit	hour/ week
Labor_of_queen_rearing_ one_unit	GRAPH(TIME) Points: (0.00, 0.012), (1.00, 0.012), (2.00, 0.012), (3.00, 0.012), (4.00, 0.012), (5.00, 0.012), (6.00, 0.012), (7.00, 0.012), (8.00, 0.012), (9.00, 0.012), (10.00, 0.012), (11.00, 0.012), (12.00, 0.012), (13.00, 0.012), (14.00, 0.000), (15.00, 0.000), (16.00, 0.000)	hour/ queen/ week
Labour_of_packaging_ one_queen	0.033	hour/ queen/ week
Labour_of_packaging_ queens	Number_of_sold_queens * Labour_of_packaging_one_queen	hour/ week
Mortality_rate	0.3	percent
Number_of_apiaries	Count_of_mating_nuclei/100	apiary
Number_of_grafting_places _in_one_rearing_colony	40	place
Number_of_rearing_ colonies	Planned_queens_per_week/40	bee colony
Number_of_sold_queens	Sale_of_virgin_queens + Sale_of_naturally_mated_queens	queen
Overtime_effect_on_ queen_rearing	IF Production_overtime >0 THEN 0 ELSE 1	percent
Planned_queens_per_week	400 (user defined)	queen
Price_of_naturally_mated_ queen	22	EUR/ queen
Price_of_virgin_queen	8	EUR/ queen
Ratio_of_mating_success	0.7	percent
Surplus_of_virgin_queens	IF Virgin_queens > Addition_of_virgin_queens_to_mating_nuclei THEN Virgin_queens - Addition_of_virgin_queens_to_mating_nuclei ELSE 0	queen
Time_for_laying_and_ tested_queen	0.33	week

Total_grafting_places_for_ rearing	Number_of_rearing_colonies * Number_of_grafting_places_in_one_rearing_colony	place
Virgin_production_factor	GRAPH(TIME) Points: (0.00, 1.000), (1.00, 1.000), (2.00, 1.000), (3.00, 1.000), (4.00, 1.000), (5.00, 1.000), (6.00, 1.000), (7.00, 1.000), (8.00, 1.000), (9.00, 1.000), (10.00, 1.000), (11.00, 1.000), (12.00, 1.000), (13.00, 1.000), (14.00, 0.000), (15.00, 0.000), (16.00, 0.000)	percent

Annex 2. Run Specs for model in software *Stella Arhitect*

Run Specs	Value	Run Specs	Value
Start Time	0	Pause Interval	0
Stop Time	16	Integration Method	Euler
DT	1/4	Keep all variable results	True
Fractional DT	True	Run By	Run
Save Interval	0.25	Calculate loop dominance information	True
Sim Duration	1.5	Exhaustive Search Threshold	1000
Time Units	week		