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Executive Summary of the Thesis

A new approach to cricket farming through integer linear optimization

Laurea Magistrale in Computer science and engineering - Ingegneria informatica

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1. Introduction

In recent years, the global landscape of food production has undergone a paradigm shift, driven by the growing demand for sustainable and efficient protein sources. As traditional livestock farming faces challenges such as environmental impact, resource depletion, and ethical concerns, alternative protein sources have gained prominence. Among these alternatives, crickets (*acheta domesticus*) have emerged as a promising candidate, offering a sustainable solution to the ever-increasing demand for protein. Managing a cricket farm involves maintaining specific environmental conditions, including temperature, humidity, and lighting, to create an optimal habitat for the insects. Furthermore, careful attention must be given to formulating a balanced and nutritionally rich diet, ensuring growth, development, and overall health. Finally, regular cleaning and maintenance of habitats are imperative to prevent the buildup of waste, diseases, and potential disruptions to the cricket colonies. Harvesting, a critical phase in cricket farming, requires precise timing to ensure maximum yield while maintaining the welfare of the insects, and is an interesting subject to study because the *acheta domesticus'* growth profile is not linear. This thesis addresses these management aspects, providing insights and recommendations to streamline the cricket rearing process for sustainable protein production. In particular, this study proposes a new approach to house more crickets and maximize yields: instead of using standardized condos (term used to indicate the habitats where crickets live) of the same size for all crickets, a more efficient usage of space can be achieved with the employment of a "two condo" strategy: using a smaller habitat in the first stage of life of the insects, and moving them to a bigger one to finish development. This paper will present two different models: one aimed towards small/medium farms that want to reach steady-state production in the shortest time and most efficient way possible, and another aimed at maximizing production cycles, synchronizing the stay in both big and small condos in order to increase profits.

2. Methodology

As of today, many studies have been published about crickets and their growth. The two most researched topics are by far diet and temperature, as these two are key elements in the growth of these insects. A poor diet leads to smaller adults and higher mortality, while low temperatures slow down growth dramatically. Themes such as light-night cycles, humidity, and rearing density have been researched much less, even though they can cause significant changes in yields. For this research, numerical data has been collected from two different papers: growth profiles for crickets reared at two different temperatures were processed starting from weekly weights reported by Morales-Ramos et al. [2], while considerations on how to handle density during the life cycle were deduced from the work of Tennis et al. [3]. Unfortunately, literature is still quite lacking, as interest in novel food has historically been marginal at best, and only recently it has had a huge boost in popularity; this made the research of data quite difficult, and many assumptions had to be made in order to proceed with the work, mainly regarding the fact that different studies were conducted with different conditions, such as temperature, humidity, and diet, making it mandatory to assume that small changes in those parameters would not affect the studies' results validity under other conditions. Other assumption involved crickets' oviposition, how changing habitats would affect growth, and the quantity of work needed for each task.

3. Finite model

The first model we have developed is defined over two dimensions, condos and days. For each condo on each day, there are multiple binary variables that define what action may be performed: the formulation works at the finest granularity possible, trading extreme precision with extreme complexity, and the final solution gives information about the daily optimal schedule to follow, with instructions about the actions to perform on each individual condo. To cover all the sub-problems needed to properly represent a cricket farm, 38 classes of constraints are needed, and they can be grouped in these macro categories: population (manage condos and their populations, for what concerns receiving or removing crickets), nursery (manage eggs collection and hatching, to ensure generational change), cleaning, feeding, harvesting, cooking (turn live crickets into flour), work management (ensure that there are enough workers to complete all tasks). Furthermore, two different start settings may be used, giving the formulation a "cold" or "hot" start: by adding some constraints, it is possible to make it so the farm starts with a parametric number of crickets, and this may be used to reach steady-state production in the most efficient way possible; instead, by ignoring these constraints, we can find out the setup to maximize yields in a given time span; even if this model allows for hot start, it is focused and optimized around the cold start settings, as the second model makes a better job at optimizing steady-state production. Finally, circularity constraints are also present, and their job is to ensure that the last x days of the time frame studied will repeat the x days before them; in this way, we can create a period that can be repeated indefinitely, and that will be at least close to optimal; this is necessary because of performance: when studying the management of a farm with 500 condos over a timeframe of 500 days, the resulting model after presolve (initial phase in which the solver removes redundant constraints and variables) contains 3,011,264 constraints, 2,042,504 variables, and 12,615,058 nonzeros. All this complexity derives from the many degrees of freedom the model offers, and leads to solve times in the domain of hours. In particular, we observed that the time needed to optimize grows exponentially with both the number of condos, and the time frame studied. This makes it very hard to study broad intervals, so the solution adopted involves calculating a cycle that may be repeated how many times necessary, using circularity constraints. As for the period x of the cycle, its value should be set to the optimal theoretical harvest age, which can be found using the cyclic model. The following images show the optimal solution for a farm that start with a number of crickets equal to 2% of its capacity, and how condos get filled over time, in order to maximize yields in the given time frame.

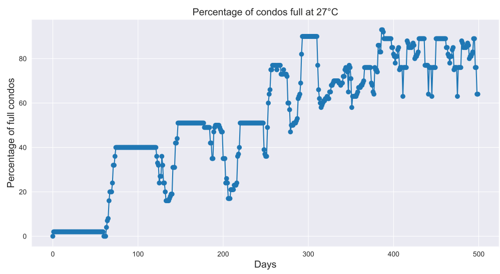


Figure 1: Number of full condos over time, 27°C

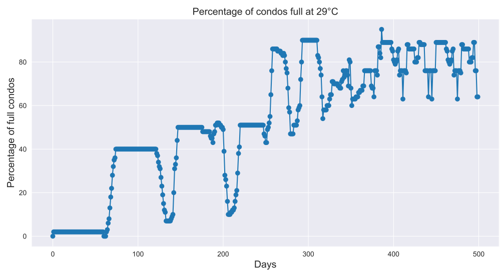


Figure 2: Number of full condos over time, 29°C

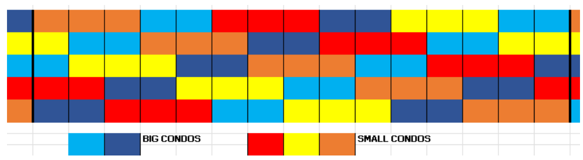
Both cold start solutions with crickets reared at 27°C and 29°C are very similar, and this derives from the short time frame studied, which is mostly used by the farm to reach steady-state production, and leaves too little time for the differences in management to be very impactful: runs were performed on a time frame of 365 days (shortening optimization time greatly) on 500 condos, and more than half of this time gets spent trying to fill up to capacity; additionally, due to the limited number of possible harvests within the timeframe, more frequent harvests at smaller ages are employed, even if they may be suboptimal in longer runs (this is particularly inefficient for crickets reared at 27°C, where growth is slower and optimal harvesting age is at over 60 days). This model is severely limited because of its nature: all the management aspects it regulates lead to complexity and long solving times, and the short time frame leads to cycles that may not be optimal if repeated on longer time frames. Still, this formulation should be the one adopted by a small/medium farm interested in optimizing all steps of the process, as the solution covers all main tasks.

4. Cyclic model

This second model takes a different approach than the first one: instead of focusing on single condos, and giving each of them many degrees of freedom, it is developed on the intuition that it is possible to synchronize the movements of populations in order to create a strict circular schedule, in which each group of condos is used to its maximum potential, without wasting any time or resources. A group of condos contains a set number of small and big condos, and their number depends only on two integer parameters we call *staySmall* and *stayBig*, i.e., how much time crickets stay in small and big condos. Given staySmall and stayBig, we can retrieve all parameters we need, in particular:

- gcd = greatest common denominator of staySmall and stayBig
- nSmallCondosPerGroup = $staySmall/gcd$
- nBigCondosPerGroup = $stayBig/gcd$
- workFrequency =gcd
- nCondosPerGroup =(staySmall+stayBig)/gcd
- period = $staySmall \cdot nCondosPerGroup$
- nGroups =$\lfloor nCondos/nCondosPerGroup \rfloor$

The following image tries to explain the intuition: given the fixed stay of crickets in small and big condos, it is possible to create a group of condos that can perfectly interact with each other, ensuring that as soon as a population gets removed or harvested, one is ready to arrive.



In this example, we represent a situation where the stay in small condos is of 3 days, and 2 days in bigger ones; each unit represents a day, and when color changes, it means that the population inside the condo got either moved (if it was in a small condo) or harvested (if it was in a big condo). The representation using multiple lines is actually only used to better visualize the concept, there is no real meaning between the different "production lines". To create a group that allows maximum usage, we need 5 condos (3 small and 2 big), the period of completion for each cycle is $3 \cdot (3+2) = 15$ days, and operations are performed daily ($gcd = 1$): this setup allows for condos to never stay idle, as when they get rid of their population, new crickets are ready to get in, either from nursery or smaller condos.

4.1. Notation

Parameters:

- nBigCondos, nSmallCondos: number of big/small condos used in the farm
- stayBig, staySmall: number of days crickets remain in big/small condos
- wNewPop: work needed to bring newborn crickets from nursery to a small condo
- wTransf: work needed to move crickets from a small condo to a big one
- wHarvest: work needed to harvest crickets from a big condo
- mult: turns live weight of crickets harvested to kg of flour produced
- wCost: cost for a unit of work
- pay: fixed pay for workers
- maxDailyWork: maximum amount of work each worker can perform
- size: expected weight of crickets harvested

Variables:

- $nHarvest_d \in N$: number of condos harvested on day D
- $nNewPop_d \in N$: number of small condos that received crickets from nursery on D
- $nTransf_d \in N$: number of small condos that got their population moved to bigger condos in their same group
- $wN_d \in Q$: work to move newborn crickets to small condos
- $wT_d \in Q$: work units to move populations to bigger condos
- $wH_d \in Q$: work units to harvest crickets
- $w_d \in Q$: total work units needed on day d
- $flourQty_d \in Q$: flour produced on d
- $nW \in N$: number of workers employed
- $cost_d \in Q$: cost to perform all operations and pay workers on day d

4.2. Formulation

$$\max \quad \sum_{d \in D} harvQty_d \cdot price - \sum_{d \in D} cost_d \qquad (1)$$

s.t.

$$\mathrm{nNewPop}_d = \mathrm{nHarvests}_d \qquad \forall d \in D \qquad (2)$$
$$\mathrm{nNewPop}_d = \mathrm{nTransf}_{d+staySmall} \qquad \forall d \in D \qquad (3)$$
$$\mathrm{nTransf}_d = \mathrm{nHarvests}_{d+stayBig} \qquad \forall d \in D \qquad (4)$$
$$\mathrm{nNewPop}_d = nNewPop_{d+staySmall} \qquad \forall d \in D \qquad (5)$$
$$\mathrm{wH}_d = \sum_{d \in D} nHarvests_d \cdot wHarvest \qquad \forall d \in D \qquad (6)$$
$$\mathrm{wN}_d = \sum_{d \in D} nNewPop_d \cdot wNewPop \qquad \forall d \in D \qquad (7)$$
$$\mathrm{wT}_d = \sum_{d \in D} nTransf_d \cdot wT \qquad \forall d \in D \qquad (8)$$
$$\mathrm{w}_d = wN + wT + wH \qquad \forall d \in D \qquad (9)$$
$$nW \cdot maxDailyWork \geq w_d \qquad \forall d \in D \qquad (10)$$
$$cost_d = w_d \cdot \alpha(d) \cdot wCost + nW \cdot pay \qquad \forall d \in D \qquad (11)$$
$$flourQty_d = nHarvests_d \cdot size \cdot mult \qquad \forall d \in D \qquad (12)$$
$$\sum_{d \in subD} nNewPop_d \leq nSmallCondos. \qquad (13)$$

with $\alpha(d) =$ weekendBonus if $d \in \{6, 12, 18, 24, ...\}$ or $d \in \{7, 14, 21, 28, ...\}$ (i.e. if the day is in weekend), 1 otherwise.
with $subD = \{d \in D : d < staySmall\}$: set of first $smallDays$ days.
Objective function (1) maximizes profits. Constraints (2)-(5) force the correct management of the populations, moving them from nursery to small condos, and from small condos to big condos, and lastly harvesting adult crickets. Constraints (6)-(11) handle how much work needs to be done on each day, how many workers are needed to perform it, and what its cost is. Constraint (12) turns harvested mg of fresh crickets into kg of flour produced, and constraint (13) checks that the correct number of condos receive new populations in the starting period of the farm. This formulation is extremely fast, as there is very little freedom given to the model, and allows for many parallel runs with different value of staySmall and stayBig (parameters on which all other parameters are calculated) in a matter of minutes, exploring all different configurations, while keeping the model linear and swift.
Runs performed on this model show that the optimal harvest age for the crickets reared at 27°C is 64 days (with 63 days being a close second), while temperatures of 29°C change the optimal age to 51 days (56 days yields similar results).

4.3. Space limitation

The previous formulation relied solely on the number of condos as the limiting factor, overlooking the more accurate constraint imposed by actual space availability. The premise of this thesis is to optimize farm volume as much as possible by employing the “two condo” strategy. To utilize space to its fullest potential, it is essential to consider it as the primary limiting factor. When doing this, we start the computation using some new parameter:

- totSpace: how much space is available for the rearing area;
- smallSize: how much space is needed for a small condo;
- bigSize: how much space is needed for a big condo.

Given these three new attributes, and using those computed previously, it is possible to calculate $groupSize = nSmallCondosPerGroup \cdot smallSize + nBigCondosPerGroup \cdot bigSize$, and use it to retrieve $nGroups = \lfloor totSpace/groupSize \rfloor$. Now that we have the number of groups that can be housed, we can easily retrieve the number of small and big condos in the farm. Using these very simple calculations, we now account for how much space each condo takes, and can give a more accurate representation of reality while still using the same model formulation as before. In this particular case, we set bigSize=4smallSize, as suggested by [3]. These changes have a significant impact on the results: now solutions that have a short stay in small condos get heavily penalized, as that means having a larger proportion of big condos, leading to a more inefficient usage of space, decreasing yields.

All optimal solutions now have crickets that stay in the small condos for 33-34 days (34 days being the upper limit for staySmall to avoid high mortality due to lack of space [3]). Optimal harvest ages did not change from the previous approach, but now differences between the best option and the others have been greatly amplified. These two heatmaps show how profits change depending on the fixed stay of crickets in small and big condos.

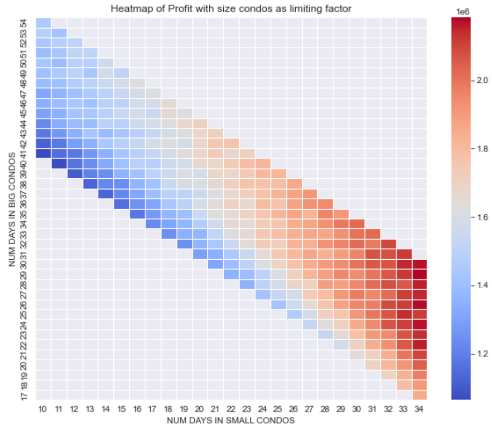


Figure 3: Profits at 27°C when considering size

Figure 4: Profits at 29°C when considering size

5. Results

To supplement the heatmaps, Tables 1 and 2 containing the 5 best combinations for each temperature are shown below.

Profit	Stay (small)	Stay (big)
2.147 M€	34 days	28 days
2.145 M€	34 days	26 days
2.137 M€	34 days	29 days
2.130 M€	34 days	30 days
2.123 M€	34 days	27 days

Table 1: Best 5 settings for maximizing profit when using space as a limiting factor, at 27°C

It is very interesting to see how 27°C leads to slightly better yields than 29°C, contrary to the

Profit	Stay (small)	Stay (big)
2.124 M€	34 days	17 days
2.064 M€	34 days	18 days
2.052 M€	33 days	18 days
2.033 M€	34 days	19 days
2.015 M€	34 days	20 days

Table 2: Best 5 settings for maximizing profit when using space as a limiting factor, at 29°C

conventional wisdom often suggested in the literature, which typically advocates temperatures around 30°C as optimal for maximizing growth [1]. We can also see that all best solution have $stay Small = 34$, with only one with value 33: this is a consequence of the inclusion of space in the problem, as longer stays in smaller condos lead to a better usage of space. It is crucial to recognize that these results are not absolute and universally applicable to all farms. They are heavily influenced by numerous factors, including the genetics of the crickets, the humidity levels within the farm, the light-dark cycle, and most significantly, the diet provided to the insects. Two different farms with varying conditions and cricket breeds may yield vastly different results, even when subjected to the same temperature conditions. Therefore, it is imperative for farmers to collect data specific to their farm conditions and apply the models accordingly to determine the best solution tailored to their particular farm.

6. Conclusions and future developments

This work proposes two different models: the first is aimed at small/medium farms interested in scheduling all operations to ensure perfect synchronization between each task over a relatively short timeframe (about one year/two years max), while the second is aimed a big farm that has a lot of condos to manage, and is interested in optimizing the management over an indefinite period.

Indeed, the “two condo” approach is currently only theoretical, as there are no real-life examples of farms employing this type of setup. Consequently, there is no clear indicator of the feasibility of such operations on a practical level. The potential challenges include uncertainty about how the insects may react to changing their habitats midway through their life and the difficulty of performing such operations. Nevertheless, the results found in this paper appear promising and warrant further investigation and experimentation. In particular, further implementation should consider a more thorough approach to the relation density-age-mortality, and to how moving crickets from one habitat to another can affect their growth rate, mortality, and final size.

On a final note, one of the strengths of these models lies in their potential utility as a foundation for automating a farm. Understanding which condos require feeding, have eggs ready for collection, or contain adult crickets ready for harvest is crucial for any technology aimed at assisting humans in rearing crickets. Moreover, when using results from these models as inputs for an automation system, we can be confident that the operations performed will be optimal, leading to maximum yields, and thus helping cricket flour to become cheaper, and a competitive and cleaner alternative to traditional meat.

References

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[2] Juan A. Morales-Ramos, M. Rojas, and A. Dossey. Age-dependent food utilisation of acheta domesticus (orthoptera: Gryllidae) in small groups at two temperatures. *Wageningen Academic Publishers*, 2018.

[3] Patricia S. Tennis, Joseph F. Koonce, and Mitsuo Teraguchi. The effects of population density and food surface area on body weight of acheta domesticus (l.) (orthoptera: Gryllidae). *Canadian Journal of Zoology*, 1977.