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Concept of a Robotic Beehive Based on a Case Study with a Beekeeping Company

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Abstract

Concept of a Robotic Beehive Based on a Case Study with a Beekeeping Company

Throughout history, beekeepers have developed new types of beehives to improve beekeeping efficiency and enhance honeybees' quality of life. In the past five years, the trend in innovation has shifted toward full automation, with many examples emerging. This thesis follows that direction by investigating one professional beekeeping company, using a case study as the primary research methodology. This thesis explores the research questions: 'Which parameters are inspected by beekeepers?' and 'How can the beehive be automated based on these parameters?'. Participant observation, the researcher's diary, a semi-structured interview and digital imaging were used as data collection methods to gather and validate information relevant to the automation of the beehive. A custom imaging device was developed and employed to acquire approximately 3000 frame images across more than 100 Langstroth beehives. These images served as input for evaluating *Varroa destructor* detection performance using the YOLO-based computer vision system. It was observed that the case study partner (whose core business is honey production) does not measure any specific parameters in the beehive to run a successful beekeeping business. Decisions and actions are based on the evaluation of 20 parameters, the most important of which are the queen's health, temperature, and available space for brood and honey. The greatest challenge in automating the beehive is the localisation of the queen. A magnetic tag and smart frames with digital magnetic sensors are proposed to address this issue. The second challenge involves moving frames that are stuck together, as breaking them loose can sometimes require more than 300 N of force. The third challenge is to move frames between beehive bodies while keeping honeybee losses as low as possible. The collected information was analysed, and the requirements for a robotic beehive are presented along with the overall concept of the robotic beehive. The case study partner describes the perfect beekeeper as someone who 'sees everything and remembers everything.' Since the partner relies on very general notes when making decisions in beehive management, and it is not feasible for humans to memorise images of thousands of frames, a robotic beehive equipped with computer vision and hive management functions is relevant from both scientific and commercial perspectives. It is recommended that the first development phase of robotic beehives be developed to explore possible visual patterns and sound or temperature signatures that could transform beekeeping operations in unprecedented ways.

CERCS: T125 Automation, robotics, control engineering

Keywords: beehive, automation, robotics, computer vision, requirements

Lühikokkuvõte

Robotmesitaru kontseptsioon mesindusettevõttega tehtud juhtumiuuringu põhjal

Mesinduse tõhusust ja mesilaste elukvaliteeti parandades on mesinikud arendanud erinevaid mesitarude tüüpe. Viimasel viiel aastal on innovatsiooni suund muutunud täieliku automatiseerimise poole, millele tekib näiteid aina juurde. Käesolev magistritöö järgib sama suunda, uurides juhtumiuuringu käigus ühte professionaalset mesindusettevõtet. Antud töö otsib vastuseid järgmistele uurimisküsimustele: „Milliseid parameetreid mesinikud mesitaru juures kontrollivad?" ja „Kuidas saab mesitaru automatiseerida nende parameetrite põhjal?". Andmete kogumise meetoditeks olid osalusvaatlus, uurija päevik ja poolstruktureeritud intervjuu, mida kasutati mesitaru automatiseerimisega seotud teabe kogumiseks ja valideerimiseks. Antud töö raames valmistati pildistamise seade, et koguda umbes 3000 raamipilti rohkem kui 100 Langstrothi mesitarust. Saadud pildid sildistati, sorteeriti ning kasutati YOLO-põhise tehisnägemise katsetamiseks *Varroalesta* tuvastamise testimise näol. Juhtumiuuringu partner ei mõõda ega jäädvusta mesitaru parameetreid vaid sooritab otsuseid varasema kogemuse põhjal mesitaru juures parameetreid hinnates. Mesitaru automatiseerimiseks on aga vaja määrata konkreetsed parameetrid, mida mõõta ning töötada välja otsustuskriteeriumid ning töövood. Juhtumiuuringu käigus kaardistati mesiniku otsused ja tegevused ja selle tulemusel kirjeldati 20 parameetrit, millest kõige olulisemad on kuninganna olemasolu, temperatuur ja piisav ruum haudmele ning mee ladustamiseks. Mesitaru automatiseerimise esimene ja suurim väljakutse on kuninganna lokaliseerimine. Selle probleemi lahendamiseks pakutakse välja magnetiline silt (püsimagnet kuninganna seljal) ja nutikad raamid digitaalsete magnetiliste anduritega. Teine väljakutse on raamide automaatne liigutamine, eriti juhul, kui need on mesilaste poolt kokku kleebitud, kuna nende vabastamine võib mõnikord vajada rohkem kui 300 N jõudu. Kolmas väljakutse on raamide liikumine mesitarude vahel viisil, mis hoiaks mesilaste kaotusi võimalikult madalal tasemel. Kogutud teavet analüüsiti ja esitati nõuded robotiseeritud mesitaru jaoks koos targa kärjeraami kontseptsiooniga. Lisaks töötati välja robotiseeritud mesitaru üldkontseptsioon. Juhtumiuuringus osalenud mesinik kirjeldab täiuslikku mesinikku kui kedagi, kes „näeb kõike ja mäletab kõike". Ta teeb mesitaru haldamisel otsuseid märkmetele tuginedes, aga inimestel ei ole võimalik meeles pidada parameetrite täpseid hinnanguid ning nende mustreid tuhandetel raamidel. Seetõttu on robotiseeritud mesitaru, mis on varustatud arvutinägemise ja mesitaru haldamise funktsioonidega, teaduslikest ja kaubanduslikest vaatenurkadest relevantne. Käesoleva magistritöö raames soovitatakse, et robotiseeritud mesitaru esimestes arendusfaasides pannakse rõhk sellele, et mesinike kogemused tõlgitakse roboti jaoks arusaadavateks mõõdetavateks parameetriteks ning protseduurideks. Välja pakutud etapiline arendus võib viia parameetrite mustrite ning omavaheliste seosteni, mis võivad mesindust põhimõtteliselt muuta.

CERCS: T125 Automatiseerimine, robootika, control engineering

Märksõnad: mesitaru, automatiseerimine, robootika, masinnägemine, nõuded

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1. Introduction

Honeybees and their health, together with beekeeping businesses, have generally been of interest to the scientific community for over a hundred years [1], [2], [3]. Honeybees are the most significant pollinators on Earth [4]. Their extinction could have a devastating impact on nature, as most plants rely on pollinators as a crucial part of their reproductive cycle [5]. The motivation for scientific research on honeybees and innovation in beekeeping is driven by beekeepers' struggle with various artificial and natural threats that disrupt bee colonies and can even lead to their collapse [6]. The most important bacterial diseases threatening honeybees are American- and European foulbrood [7]. Ascosphaera apis is a disease caused by a fungus, causing 5 - 37% of honey loss globally [8]. One of the most problematic viruses which honeybees are suffering from is *Sacbrood* virus [9]. Deformed wing virus is also considered one of the most widespread problems that beekeepers must fight against. This virus is often related to Varroa mites (*Varroa destructor*), which emphasises the relevance of the fight against parasitic infestations. [10] *Varroa destructor* is considered the most lethal problem in apiculture and is globally spread (the only mite-free zone is Australia) [11], [12]. In the shadow of *Varroa destructor*, the second subject of scientific interest is the parasite *Acarapis woodi* which has been considered eradicated in Spain, but it is still occurring worldwide [12]. The list of biological problems continues involving aforementioned fungal, viral and parasitic domains [11].

The primary human-caused threat to the honeybees globally is different pesticides used in agriculture [4]. It is crucial to consider the potential problems when a honeybee colony is translocated for pollination purposes, such as the risk of invasive species attacks or disease transmission [2], [13]. In addition, in the process of transporting thousands of colonies, it is challenging to ensure the bees are kept safe as one of the priorities in the beekeeping business is to use as cheap labour as possible [13].

Aforementioned problems have been motivating inventors to develop new methods and more advanced hardware to keep honeybees safe and make the work of beekeepers more efficient. There are patents (or patent applications) which describe smaller parts of beehive reinvented [14], [15], [16]. Furthermore, recent years indicate that inventors are leaning toward full automation of the beehive [17], [18], [19], [20], [21], [22]. There is also motivation for inventing new hardware and methods specifically for controlling *Varroa destructor* [23]. While examples of full automation are rare, systems for measuring parameters such as hive weight, inside and outside temperature, CO_2 levels, and humidity inside the beehive have been proposed in literature [22].

The main research motivation of this thesis is to conduct a case study on the example of **one beekeeping business.**

The essential scientific state-of-the-art overview in this thesis, along with the analysis, focuses on the activities directly related to honeybees inside a beehive. **Automation will be proposed** only for the processes that are conducted directly handling either the frames, honeybees or beehive bodies.

Despite the growing interest in automating beekeeping, real-world implementations remain rare, and the existing literature offers little guidance on how expert intuition can be translated into system logic. This thesis addresses that gap by exploring beekeeping through practical fieldwork combined with an engineering approach, as described in the following chapters.

2. Background and related work

This chapter provides a scientific overview of research and experiments conducted to understand honeybees and improve their lives. The information presented here was used to validate the data collected during the case study (chapter 4), including participant observations and interviews. Additionally, a general understanding of beekeeping helped shape the interview questions. This chapter outlines the parameters that beekeepers use to evaluate beehives.

2.1. Overview of bee colony and the beehive

A healthy colony can contain between 50,000 and 60,000 bees [24], [25]. Among them is only one queen, whose primary purpose is laying eggs, and between 3,000 and 5,000 male bees, whose sole purpose is mating. Worker bees initially perform hive maintenance, care for larvae, serve the queen, regulate hive temperature, build the comb, and finally forage for pollen, nectar, water, and propolis. [24].

Beehives vary in size and shape [26]. An indicative interview with two professional beekeepers in Estonia revealed that the Langstroth beehive is widely used due to its modularity and relatively good price compared to other beehive platforms [24], [27]. Based on this, this thesis focuses on the Langstroth beehive.

Figure 1 presents the assembly and subcomponents of beehive together with short explanations. Frames (No. 10 and 11) are constructed from wood and metal wire. The wire serves as a substrate for wax foundations, which follow the honeycomb pattern to facilitate honeycomb building for the honeybees [24]. The frames are housed within beehive bodies (No. 3 and 5), typically made of wood or polyurethane, providing structural support and protection [27]. A queen excluder (No. 4) prevents the queen from moving between hive bodies. Its small holes restrict the queen's movement, ensuring she doesn't lay eggs in the hive body intended for honey collection, known as the honey super (No. 3). The cover (No. 1) and bottom (No. 6) provide structural support, while certain components (No. 7, 8, and 9) enhance safety features. The entrance reducer (No. 7) is also used to regulate ventilation within the beehive [24].

Swarming is a natural reproductive behaviour in which a portion of the colony and the old queen leaves to establish a new colony, taking many worker bees with them. Swarming is primarily caused by overcrowding in the beehive, poor ventilation, and an aging queen. A swarm takes a significant amount of honey from the hive, resulting in a loss for the beekeeping business [24].

Based on various parameters, the beekeeper can decide whether to rearrange the frames within a single beehive body or move them between different hive bodies. Hive bodies can be added or removed throughout the season to prevent swarming, facilitate honey collection, or maintain a compact winter cluster. Without delving into the specifics of the literature review, this thesis offers a more detailed overview of bee care based on the experience of a single case study partner covered in chapters 4 and 5.

Figure 1. Parts of Langstroth beehive [28]

2.2. Parameters inspected by beekeepers and related actions

This subchapter provides an overview of the parameter's beekeepers assess within beehives to guide their decisions and actions. It also outlines the potential actions that can be taken based on these observed parameters. In addition, general quality requirements, which might be important when composing the concept of an automated beehive, are presented here. As in management theory generally, before acting, one must measure or assess the status of the controlled entity. The beekeeper makes visual inspections using their eyes to evaluate the situation of the beehive, the health of honeybees and the status of resources. done, based on inspection results, then further decisions and actions be made. The number of scientific papers, which provide a full list of relevant parameters, which are traditionally assessed by beekeepers, is minimal. The same applies to decisions and actions which must be conducted when managing the hive. According to the case study partner, beekeepers must start with general beekeeping books, but real knowledge is gained through practical work over the years.

Table 1 summarizes the aforementioned parameters and actions with explanatory quality related notes derived from "Beekeeping for Dummies" [24]. The purpose of this table is to present an initial list of parameters used to form interview questions and validate the parameters assessed by the case study partner. As this table is indicative, its purpose is not to cover all possible parameters that may be mentioned in different sources. The book is composed for people to start successful beekeeping from scratch. There are sources which cover partially or similarly the same parameters and related actions presented in Table 1 without significant additions [29], [30], [31]. There are also some additional actions to consider. For instance, drone brood removal or brood breaking as *Varroa destructor* treatment [32]. There is also a mentioned of the comb-culling technique as action of replacing the old comb with the new one to achieve better hygiene and to fight against pests [33].

Mechanical manipulation of bees or objects next to honeybees should be gentle and slow. Hygiene must be a priority, with measures applied to the equipment, hives, and beekeepers themselves. Also, keeping the records for every beehive is highly recommended. Regular monitoring is one of the key elements in successful beekeeping. It is wise and mandatory to apply pest management techniques (mostly chemical) when *Varroa destructor* or another pest is detected [24]. The most important parameter to assess is the presence of queen. It can be assessed directly (when the beekeeper can find the queen by eye) or indirectly by finding eggs, larvae or capped brood. Eggs present the most updated information (0–3 days) as larvae present 3–7 days' timeframe respectively [24]. There are also parameters evaluated outside the beehive, such as the general integrity of the structure and weather conditions, which are not covered in this chapter but are addressed in chapter 5, based on the experience of the case study partner.

Table 1. Parameters inspected by beekeepers as identified in the literature

ID	Parameter	Quality assessment	Action
1	Presence of queen (on frames).	The queen is present or not found. If found, the queen is healthy or not.	• Ignore. • Replace the queen. / Import new queen.
2	Presence of eggs, larvae, capped brood and empty cells (on frames).	Consistency of eggs, larva and capped broad indicates the good health of queen. Also, the number of eggs (based on month) is an indicator of queen's health. If those parameters are mixed with empty cells, the queen may be sick or too old.	• Ignore. • Replace the queen / Import new queen. • Change the location of the frames inside the hive. • Add more food for beehive. • Add/remove queen excluder (and honey supers).
3	Angle of inclination of the egg relative to the cell bottom. [34]	If the egg is 'standing up' from the cell bottom, it is young. If it is 'lying down' on the cell bottom, it is at least three days old.	• N/A
4	Presence of *Varroa destructor* (in cells, on honeybees, on frames).	Estimation of the number of mites on one frame.	• Ignore. • Apply treatment.
5	Presence of burr comb (mostly on frames).	N/A.	• If not found, ignore. • If found, remove.
6	Presence of pollen (in cells).	If found, indicates the good health of the colony. Colour differences: brown, yellow, grey, blue ect.	• Ignore. • Harvest.
7	Presence of Nectar (in cells).	If found, indicates the good health of the colony.	N/A.
8	Presence of Water (in cells or on frames and honeybees).	Water in cells indicates the hot summer and is being used as coolant. Too much water on honeybees or floating in the hive indicates bad ventilation or corrupted hive.	• If found in cells, ignore. • If found too much water inside hive: o Fix the hive. o Adjust ventilation.
9	Presence of Supersedure cells (on frames).	Located on upper part of frames indicating the birth of a new queen. Old queen may be dead, sick or old.	• Import new queen.
10	Presence of Swarm cells (on frames).	Located on lower part of frames indicating the birth of a new queen and indicating the swarming.	• Add more food for beehive. • Increase space by adding more hive body's.
11	Amount of sugar syrup (in hive feeder).	Indicates the food is consumed due to the big colony and/or the foraging has not been successful enough.	• Ignore. • Add more food for beehive.
12	Capped honey (in cells, on frame).	The amount of honey indicates health of colony.	• Ignore • Change the location of the frames inside the hive. • Add/remove queen excluder (and honey supers). • Harvest honey.
13	Hive ventilation (in beehive).	Can be open or (partially) blocked.	• Ignore. • Clean / Adjust / Cover.
14	Presence of the cluster of bees (in beehive).	The size of the cluster indicates the health of wintering honeybees. If it is as large grapefruit, the colony is probably healthy.	• Ignore. • Restart the colony. • Reverse hive bodies.
15	Temperature outside.	N/A	• Prepare hive for winter or summer.
16	Presence of small hive beetle (in beehive).	Estimation of the number of mites on one frame.	• Ignore. • Apply treatment.

2.3. *Varroa destructor* as one of most urgent problems in beekeeping

Varroa destructor is considered by many honeybee researchers as one of the most significant threats beekeepers are struggling with. Mites are spreading indirectly using flowers as transport hubs to attach to honeybees. The direct spreading method is carried out by honeybees themselves, as they visit neighbouring hives either to steal resources or search for a new hive to inhabit. One strategy to prevent *Varroa destructor* from spreading directly is to place beehives so that the distance between them is at least 300 m. This strategy, however, is considered not to be practical. In addition, it has been discovered, that 25% of mites leave the beehive with honeybees when the colony of honeybees is swarming. Pest management for *Varroa destructor* divides into four categories which are cultural, mechanical, biological and chemical approaches. When treating pests, beekeepers are advised to follow a prescribed order, beginning with cultural approaches and reserving chemical treatments for last.

The following are some cultural methods beekeepers can apply. One of them is caging the queen, preventing her from laying more eggs. Applying this tactic in the right time might decrease reproduction of mites as well, and in addition to that may increase effectiveness of chemical treatment. Another cultural way is to use hygienic honeybee stock (bees, who can detect mites and throw them out of the hive by themselves). Also, sanitary activities like comb culling or sterilization of hive equipment are considered as cultural approach. Mechanical management refers to physical equipment, with examples like screen bottom boards and drone brood trapping. Drone brood trapping is a beekeeping technique that involves encouraging bees to rear drone brood in designated frames or areas, allowing beekeepers to remove and destroy these cells to reduce Varroa mite populations. Also, heat treatment (hyperthermia) can be filed under mechanical domain. Biological management is potentially very promising when successfully applied. The idea is to insert a natural enemy of *Varroa destructor* into a beehive without harming the bees nor not disturbing their activity. There is research made but still no efficient method developed. One obstacle may be that the *Varroa destructor*s natural enemies are not adapted to hunting the mites inside the beehive.

Chemical management is divided into two subcategories, which are synthetic and organic compounds. Four globally most used synthetic compounds are Amitraz (formamidine), Coumaphos (organophosphate), Fluvalinate (pyrethroid) and Flumethrin (pyrethroid). Formic acid, Oxalic acid, Thymol and Hop beta acids belong under organic compounds respectively. Despite decades of research, *Varroa destructor* remains the problem. It is not recommended to trust only one control approach but combine multiple strategies instead (Integrated Pest Management). [35] It seems that a scientific community is moving towards belief that IMP is an only way to fight against *Varroa destructor* [36].

Several IMP approaches have been studied scientifically, with the following examples. Queen caging and trapping comb combined with oxalic acid treatment [37]. Brood removal or queen caging combined with oxalic acid treatment [38]. Glycerol strips combined with oxalic acid combined with frequent monitoring of infestation level [39]. Monitoring of hives combined with regular cleaning and maintenance of hives to keep the ventilation of hives clear of blockages [40]. Formic acid combined with oxalic acid and monitoring [41]. There are mobile applications available that provide Varroa destructor detection via a cell phone camera and computer vision [42].

Despite chemical treatment is globally the most widely used approach for pest treatment against *Varroa destructor*, this is facing significant obstacles. It has been discovered that *Varroa destructor* has tendency to develop resistance against chemicals when treated periodically without changing the approach [35], [43], [44], [45], [46]. Considering the complexity of *Varroa destructor* problem the further research is a high priority [11], [35], [39], [45], [47], [48].

2.4. Construction materials for beehive

This subchapter provides an indicative overview of potential materials for building a beehive. When building the beehive, it is important to use materials which are not poisonous or unsuitable for honeybees. Composite materials developed by high-density polyethylene reinforced with banana fibre are proposed as suitable materials for beehive construction [49], [50]. In addition, it is being used in food industry [49]. Polyurethane presents better thermal and humidity properties than wood. It is providing more stability during day and night, offering better environment for thermoregulatory behaviours [27]. This results in lower food consumption and higher yield of honey [27]. Scientific research, which is specifically dedicated to the potential materials for beehive construction and taking the health of honeybees into account at the same time, are quite limited. Table 2 presents analysis, which covers different materials from different perspective [51]. Based on research the table presents 18 materials in three categories, sorted from best to worst material (nr. 1. is the best in its category). Various categories have been used to evaluate total average: durability, weight, insulation, toxicity, manufacturing and cost [51]. The priority is to use materials that do not affect the health of the honeybees. Good temperature insulation properties have been prioritized in the proposed table. However, in the robotic beehive, temperature drops can be compensated by heating systems, which means this table serves only an indicative purpose for further development.

Table 2. The list of potential materials for building beehive

Toxicity	Insulation	Total Average
1. Paper/Cardboard	1. Foam – Polyurethane	1. Lightweight Concrete
2. Stone	2. Foam – Polystyrene	2. Concrete
3. Lightweight Concrete	3. RM Plastic	3. Brick & Mortar
4. Concrete	4. IM Plastic	4. Paper/Cardboard
5. Clay (unfired)	5. Lightweight Concrete	5. Stone
6. Aluminium Sheet	6. Clay (fired)	6. Pine
7. Brick & Mortar	7. Composite	7. Marine Plywood
8. Marine Plywood	8. Paper/Cardboard	8. Clay (unfired)
9. Clay (fired)	9. Clay (unfired)	9. RM Plastic
10. IM Plastic	10. Marine Plywood	10. Clay (fired)
11. RM Plastic	11. Plywood	11. Plywood
12. Plywood	12. Pine	12. Aluminium Sheet
13. Pine	13. Brick & Mortar	13. Foam – PU
14. Foam – PU	14. Concrete	14. Foam – PS
15. Mild Steel Sheet	15. Aluminium Sheet	15. IM Plastic
16. Foam – PS	16. Stone	16. Composite
17. Cast Iron	17. Cast Iron	17. Mild Steel Sheet
18. Composite	18. Mild Steel Sheet	18. Cast Iron

2.5. Relevance of automation

A few patents mentioned in the introduction of this thesis are related to a company called Beewise, whose inventions show a correlation with findings from participant observations and the interview with the case study partner [20], [52], [53]. The company Beewise has patented many ideas related to the automation of beehives—for example, the concept of moving frames not vertically but back and forth like a drawer, along with ideas to install sensors and heating systems in each individual cell of the frames [54]. At the beginning of 2025, the case study partner contacted Beewise to request financial and technical information about their products but received no cooperative response. Based on this, it was concluded that Beewise is still in the experimental phase and not yet ready for the Estonian market, highlighting the complexity of automating the beehive.

The latest official report from Beewise, published in 2023, highlights three major functionalities of their robotic beehive: regulation of temperature inside beehive bodies, automatic closing of hive entrances, and treatment of *Varroa destructor* using temperature control methods [55]. It is not specified whether the treatment is applied to entire beehive bodies or individual infected cells. According to the report, the company's development efforts are currently focused on the pollination business.

The beekeeper performs annual prophylactic Varroa mite treatment. This thesis hypothesizes that with the help of a robotic beehive, it is possible to develop pesticide tactics where only those hives that contain mites are treated locally. This is one of the reasons why mite detection using computer vision is tested in this thesis.

2.6. Research problem and research questions

The literature review shows growing interest in automating beekeeping, yet practical implementations remain rare. This thesis addresses how automation can be developed through a case study in collaboration with a professional beekeeping company.

Based on literature review, the following scientific questions for driving the work in this thesis are defined.

- Which parameters in the beehive are inspected by beekeepers to make decisions?
    - List of parameters.
    - List of decisions and actions.
- How to automate the beehive based on the studied parameters and decisions?

3. Research methodology

To understand the complexity of beekeeping and define the best strategy for research, several beekeepers were visited in Estonia. Two professional beekeepers, for whom beekeeping is the main source of income and who have 300 and 200 beehives, respectively, and three amateur beekeepers (under 20 beehives) were visited, and initial observations of their work were carried out in the apiaries. The observations confirmed that while beekeepers generally follow the core knowledge taught in beekeeping handbooks, differences appear in specific procedures, the time dedicated to inspections, and approaches to pest treatment and hygiene. Practical input for this thesis is taken from one professional beekeeping company, keeping the focus on their experience and processes through participant observations and interview. Scientific literature and beekeeping handbooks analysed for this thesis show that teaching of beekeeping is rather general, leaving room for beginners to develop their own procedures. As practical output of this thesis is the concept of robotic beehive, it is the first step of many development phases to come until a stable robot is achieved.

Case study was selected as main approach as it binds together both theoretical background and real-world situations. In automation of biological processes, practical experience, or at least empirical observation, is crucial for understanding both biological and procedural aspects [56]. More specifically, the work described in this thesis belongs under the evaluation scenario, which, on one hand, keeps the number of subjects very low, but on the other hand, presents a situation where a deeper understanding of a subject is needed. **Case study provides valuable input from one beekeeping company** through practical collaboration and conversations, allowing crucial aspects to be mapped as thoroughly as needed. [57] Critics have pointed out that focusing on a single case carries risk of missing important information. As counterweight to this, the methodologists of case study have written that reliability and thoroughness of case study are increased by analysis of existing scientific work and process-oriented approach. [58]

Sampling strategy was prepared based on the following requirements. Selected beekeeping company must be in Estonia, to make collaboration more efficient. Company representatives must be motivated to work in a scientific project. A clear, shared understanding of the scope of work is essential, especially since this thesis involves practical work in direct contact with honeybees. The core business and cash flow of this company must be based on beekeeping. The company must have more than 100 beehives or at least ten years of experience as indication of credibility. The company must be well-known among Estonian beekeepers and have references that demonstrate its professionalism.

Participant observation is a key activity in this thesis, providing practical insight into working directly with honeybees. [59] It was conducted seven times in the summer of 2018 and twice in the spring of 2025, with beekeeping tasks performed and notes taken for future interviews and photos taken for robotic beehive development. A researcher's diary was used to document both practical experiences and theoretical ideas related to the robotic beehive concept. Semi-structured interviews were employed to gain a detailed understanding of complex beekeeping systems, with the flexibility to explore deeper aspects based on prior interviews. This approach also acknowledges that beekeepers' muscle memory holds significant knowledge that may not be captured in formal surveys or interviews.

Data analysis of interviews and researcher's diary was carried out using directed content analysis method. According to this method, one starts with the data derived from literature and composes subject related keywords (in this thesis term "list of parameters" is used) based on that. Then the keywords are supplemented in case study through practical and scientific collaboration. [59] Consolidation of gathered data is done to get meaningful results, which then can be used for composing the concept of robotic beehive [60]. Using multiple methods for data collection and analysis is also recognized under triangulation method, which justifies qualitative approach through the comprehensive understanding of subject [61].

Digital images of frames were first analysed manually to identify *Varroa destructors* for later computer analysis. The tests conducted using computer vision, following the manual image inspection and labelling from Subchapter 3.3. YOLO was selected for its widespread use and reliable performance, with the pre-trained model YOLO 11X chosen for its detection time of 12 ms per image, making it suitable for real-time video processing. Manual identification of *Varroa destructor* on frame images and cropping them into 640×640-pixel segments was the most time-consuming task. The 280 images were split into training, validation, and testing pools, with the model training taking approximately one day on a system with an AMD Threadripper 2970WX and 128 GiB RAM. YOLO completed 135 epochs before early stopping, as no further performance improvements were detected. This method is specifically described in chapter 5 with code and further details provided in Appendix C and the associated GitHub repository.

Table 3 provides an overview of conducted activities, which follow the above-described methodology. All activities (except for nr. 1) are covered and referenced in the chapters and sub-chapters of this thesis.

Table 3 List of activities for reaching the goals of this thesis.

ID	Activity	Input	Data collection method	Data analysis	Result(s)
1	Preparations for the thesis.	• Meetings with five beekeepers.	• Communication with five beekeepers.	• Gathering of ideas and trends in beekeeping.	• General understanding of automation. • Selection of case study. • Sampling strategy.
2	Finding a partner for case study (chapter 4).	• General understanding of automation. • Sampling strategy.	• Researcher's diary. • Communication with selected partner.	• Analysis of five beekeepers based on defined requirements.	• Case study partner selected for case study.
3	Review of literature on beekeeping and automation trends in the beekeeping industry. (chapter 2).	• General understanding of automation.	• Literature review.	• Mapping of keywords, which are relevant from automation perspective.	• Understanding of automation and invention trends and general technological level. • Understanding of “traditional” beekeeping. • List of relevant keywords (parameters).
4	Preparations for field work (subchapter 4.1).	• Understanding of automation and invention trends and general technological level. • Understanding of “traditional” beekeeping. • List of relevant keywords (parameters).	• Researcher's diary.	• Research of digital imaging solutions.	• Design and construction of imaging device. • Purchase of safety equipment.
5	Fieldwork in collaboration with the case study partner (subchapter 4.2).	• Understanding of automation and invention trends and general technological level. • Understanding of “traditional” beekeeping. • List of relevant keywords (parameters).	• Participant observation. • Researcher's diary. • Digital imaging of frames.	• Gathering of practical skills in direct contact with honeybees.	• Notes of procedures, parameters and decisions. • Digital images of frames.

6	Testing of computer vision for detecting *Varroa destructor* (subchapters 4.3 and 5.2).	• Digital images of frames.	• N/A	• Research of artificial vision solutions. • Labelling of digital images. • YOLO integrated analysis.	• Selection of artificial vision solution. • Testing and results.
7	Interview for mapping parameters, decisions and actions. (subchapter 4.4).	• Understanding of automation and invention trends and general technological level. • Understanding of “traditional” beekeeping. • List of relevant keywords (parameters). • Notes from researcher's diary.	• Semi-structured interview. • Researcher's diary.	• N/A	• 3 hours of recorded interviews. • Mapped ideas for future automation.
8	Analysis of case study. (chapter 5).	• 3 hours of recorded interviews. • Related work (chapter 2) • Notes from researcher's diary.	• N/A	• Validation of data collected in practice against data gathered theoretically.	• Answers to the research question “Which parameters in beehive are inspected by the case study partner to make decisions?” (subchapter 5.1). • Beehive production flow (subchapter 5.2). • Requirements (subchapter 6.2).
9	Formulating the concept of a robotic beehive. (chapter 6).	• List of parameters, decisions and action. • Beehive production flow.	• N/A	• Analysis of existing work.	• Answers to the research question “How to automate the beehive based on the studied parameters and decisions?”. • Answers to the research question “What requirements must a robotic beehive meet?”. • The concept of robotic beehive.
10	Discussion (subchapter 7).	• All the theoretical and practical work done.	• N/A	• Discussion over findings and results.	• Limitations of work. • Ideas for further development. • Ideas for further research.

4. The case study based on one beekeeping company

This chapter covers all the work conducted in the case study in collaboration with one beekeeping company. The chapter provides detailed explanations of individual work as well as field activities conducted in collaboration with a selected beekeeping company (henceforth "the case study partner"). Practical activities carried out for this thesis are the design and build of frame imaging device, actual work as a beekeeper to understand the procedures, imaging of frames during fieldwork and testing of computer vision software to detect *Varroa destructor*. Theoretical work includes editing of researcher's diary, marking of bees and *Varroa destructor* on digital images, mapping of detailed procedures carried out in direct contact with honeybees, mapping of relevant parameters which are inspected by the case study partner for making decisions and actions and semi-structured interviews respectively. Practical activities as well as theoretical work related to case study follow the activities defined in chapter methodology (Table 3)

Artocarpus OÜ (founded in 1996) was selected as partner for case study in this thesis as this beekeeping company met all requirements defined in methodology chapter (activity nr. 2 from Table 3). Beekeepers in this company have provided bee queens for over 25 years and have educated new beekeepers in Estonia. [62] In addition, one of the founders of the company have been recognised as The Beekeeper of the Year in Estonia in 2006 and 2014 [63].

4.1. Preparations for digital imaging of frames

This subchapter covers the activity nr. 4 from Table 3. Relying on the literature as well recommendations from case study partner, one of the most important parameters, which beekeepers inspect in beehive, is *Varroa destructor*. It was appreciated that the detection of *Varroa destructor* by eye or camera is a challenging task and an interesting research topic. The case study partner has attempted to implement mobile applications that use the phone's camera to detect *Varroa destructor*. However, they find it impractical in an apiary environment, as ensuring the phone's physical safety is challenging, and operating a touchscreen with hands covered in organic, sticky materials is inefficient. Despite this, the case study partner agrees that if *Varroa destructor* detection is automated in a user-friendly way, it would create opportunities for further research and development.

One study suggests that a mobile phone image sensor should have a minimum resolution of 48 MP to achieve an accurate detection rate [64]. In this thesis, a full-frame camera, along with the suitable lens, was selected. 42 MP Sony a7R III and 28 mm Sony FE 28mm F2 were selected respectively [65], [66]. The requirements for the imaging device were defined as follows: The image must cover the entire surface of a Langstroth frame. The image format should be JPG with maximum quality settings. All images must be captured under consistent lighting conditions. To avoid motion blur when imaging, exposure time must not be longer than 1/200 s. Honeybees must be kept safe. For the building of the imaging device, readily available construction materials were used. The body was made of plywood. For artificial lighting, LED strip was utilized. Colour temperature was selected 4000 K (wavelength range of approximately 550–600 nm). Colour rendering index was ignored as it was decided that no matter which lighting technology will be chosen, it must be tested and calibrated anyway. Since Estonian summers can become quite hot, occasionally exceeding 30°C, an aluminium profile was used as a passive heat sink for the LED strips. A lithium-polymer battery was chosen as the power source, electrically connected to the LED strips via mounting wires and a suitable

DC-DC converter. Figure 2 shows the initially designed model in the top left-hand corner, alongside photos of the imaging device produced for fieldwork.

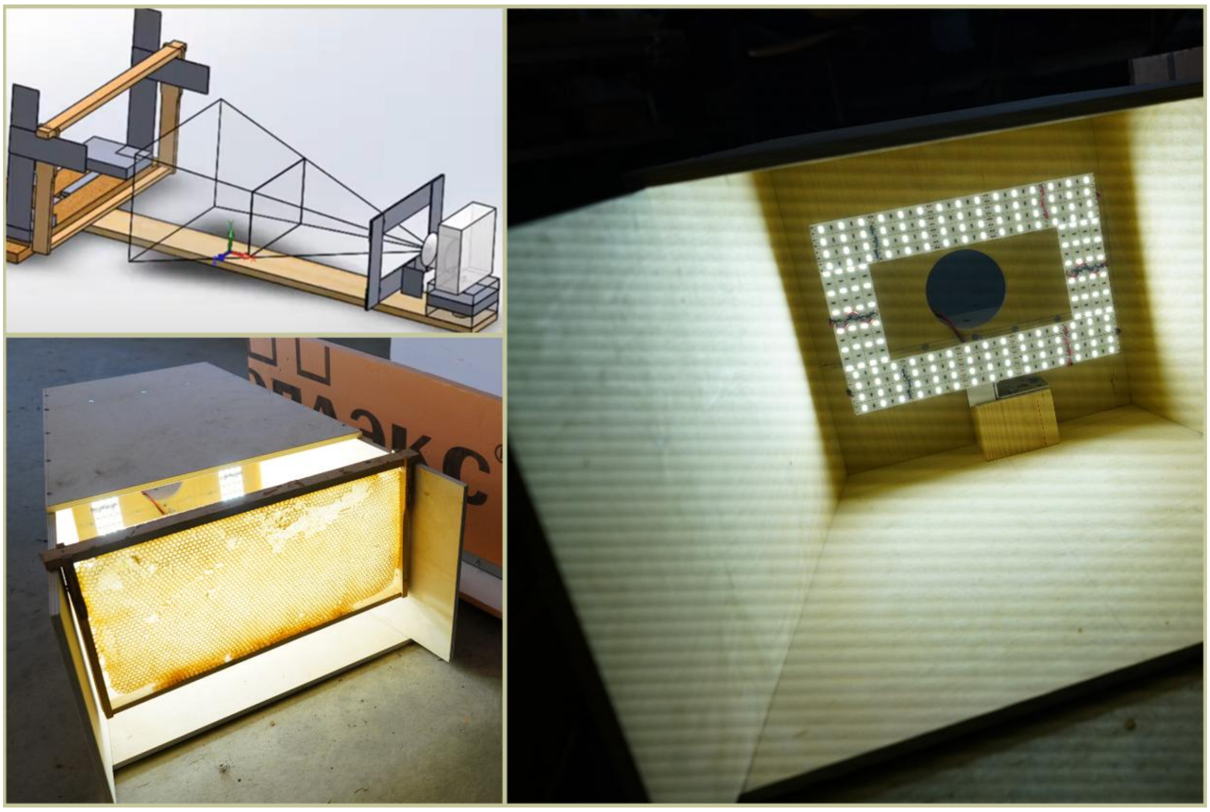

Figure 2. Imaging device

4.2. Fieldwork in collaboration with the case study partner

This subchapter covers the activity nr. 5 from Table 3. The summer of 2018 was dedicated to participant observations and data collection. At the time, the case study partner had 12 apiaries, each containing 14 beehives. Between June and August, all 12 apiaries were observed, and 1,438 frame photos were captured from approximately 1,000 different frames. Additionally, six other beekeepers were visited and a total of 1,790 frame photos were captured from their hives. Empirical work in direct contact with honeybees is crucial for understanding so-called hidden aspects of beekeeping and therefore irreplaceable step towards automation of beehive. It was experienced, that a significant amount of work is made by hands on the way and detail which is not described in literature (as processes are usually defined through quality and requirements). It was understood that beekeepers usually start with theoretical study but become professional beekeeper through practice, which shapes every beekeeper based on their personality and understanding. Collaboration with case study partner turned out to be more thorough than initially planned. Case study partner offered the opportunity to observe one season from January to December, which provided a more complete understanding of beekeeping.

During the fieldwork and participant observation, two additional experiments were carried out. In the first experiment, a neodymium magnet was placed to one of the beehive entrances so that the honeybees could not avoid passing it closely when flying out of and back into the beehive (Figure 3). The purpose of this experiment was to observe to what extent the magnet affects the strength of the chosen colony. The hypothesis is that if the strong magnetic field negatively affects the chosen colony, then the colony's strength would dwindle. The motivation for this experiment stems from the idea to use a permanent magnet as a tag on the back of the queen bee for automated localization. Another aspect is that electric motors emit magnetic fields while previous studies remain superficial on whether these magnetic fields affect honeybees. Since electric motors emit alternating magnetic fields while a permanent magnet does not, this experiment remains indicative.

The chosen beehive is in a group of 14 beehives and the strength of its colony is compared to other beehives by the case study partner every 7 days. For this experiment, a cylindrical N45 neodymium magnet was used, with a diameter of 30 mm and a height of 10 mm. Estimated intrinsic induction of this magnet is 1300 mT [67]. Flux density of this magnet is 14 µT at 1 m distance, where it may be sensible for honeybees [68], [69].

Figure 3. Permanent magnet at beehive entrance

The second experiment involved imaging the removable bottom boards of 97 beehives one day after chemical treatment for *Varroa destructor*. The purpose of this test was to gather data for future development, when it is decided that implementing removable bottom boards in the robotic beehive for *Varroa destructor* diagnosis is feasible. The images were captured using the same camera platform as the imaging device developed for this thesis. Photos were taken manually from approximately 500 mm, under natural lighting conditions without direct sunlight. Figure 4 shows approximately one-tenth of the removable bottom board covered with dead *Varroa destructor* mites.

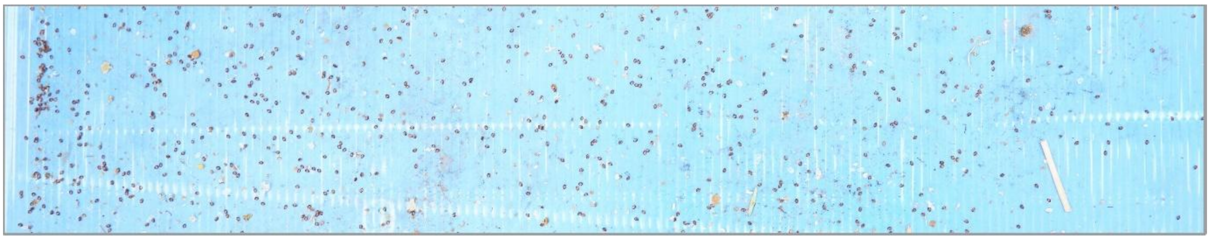

Figure 4. Removable bottom board after treatment covered with dead mites

4.3. Preparations for computer vision testing to detect *Varroa destructor* mite

This subchapter covers preparations of the the activity nr. 6 from Table 3 as subchapter 5.2 outlines the results. During participant observations in apiaries, it became clear that one of the most challenging parameters beekeepers inspect on frames is the presence of *Varroa destructor*, as this parasite is relatively small, measuring 1,1 mm in width and 1,6 mm in length [70]. It was understood that inspecting honeybees or cell patterns is easier due to their larger surface area, which also makes these parameters easier to measure using computer vision. Therefore, it was decided that computer vision tests in this thesis would focus on the detection of *Varroa destructor*. The imaging device constructed for this thesis can capture the entire frame at once, providing an image resolution where *Varroa destructor* attached to the backs of honeybees appears at least 15 × 15 pixels in size, which was evaluated as sufficient for computer vision testing (Figure 5).

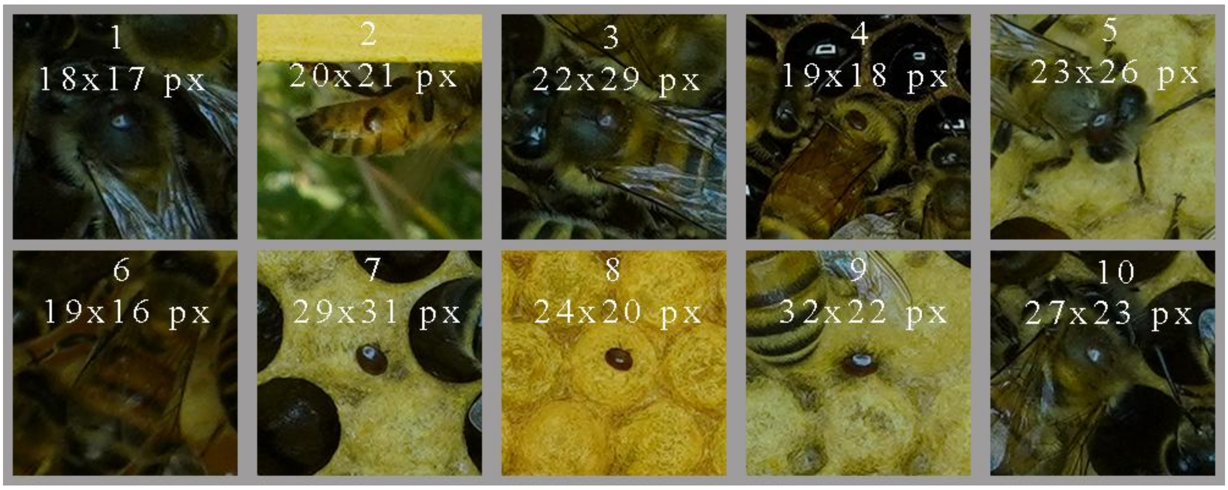

Figure 5. *Varroa destructor* images from imaging device

Manual inspection of approximately 3,000 frame images revealed 73 *Varroa destructor* mites attached to the bodies of honeybees. As the number of discovered mites was rather small, it was decided to also use pictures taken from six other beekeepers to increase the sample size for the computer vision tests. To maintain the quality of manual image inspection, the inspection time per image was kept at approximately four minutes, resulting in a total of 200 hours of work. Mapped Varroa mite pictures were cropped in 5 different positions, with the infected honeybee positioned in the middle and then in each corner of the cropped image. The size of the cropped images is 640x640 px. Based on this and considering the small surface area of *Varroa destructor,* it was decided to define and label two classes using Label Studio [71]. The first class was defined as 'honeybee_clean' and the second as 'honeybee_infected'. For bounding boxes, a fixed angle (no rotation) was used despite the orientation of labeled honeybees on the image.

4.4. Interview for mapping parameters, decisions and actions

This subchapter covers the activity nr. 7 from Table 3. Fieldwork, along with participant observation, played a significant role in the development of interview questions. Since beekeeping relies heavily on visual inspection and many tasks depend on muscle memory, this created an excellent opportunity for verbal discussions during practical work. In other words, while collaborating with the case study partner in the apiary, potential questions were formulated, and their quality was validated. Semis-structured interview was selected for interview format, as it is considered the most effective interview method in qualitative research [72]. In formulation of interview questions, the following aspects were taken into consideration: Firstly, every interview question must follow research questions defined in Chapter 1. To encourage the case study partner to give detailed responses, most questions should be open-ended questions [73]. Since this thesis presents the concept of a robotic beehive as a practical outcome, it is important to avoid leading questions that could influence the case study partner to provide responses biased toward automation [73]. Sub-questions should be asked to get all the necessary input and unclear responses must be verified [73]. “Why” and “how” questions should be key components when formulating sub-questions, as they are crucial for fully understanding the inspected parameters, decision-making processes, and actions involved in developing the robotic beehive concept [73]. The interview questions are filed under Appendix A, categorized based on research questions, and sorted in the order questions are asked. The order of questions was designed to allow the case study partner to start with a general perspective and gradually delve into more details during the conversation. Additionally, the interview was used to validate the case study partner's expertise by comparing their assessed parameters, decisions, and actions to those found in the literature (Table 1).

It was decided that any differences from the literature review must be discussed and mutually understood. Furthermore, this interview plays a crucial role in mapping the production flow for the concept of an automated beehive. One of the outcomes of this interview is a precise production flow that accounts for seasonal differences and other important factors that might affect the automation process. It was agreed that both sides would invest as much time as needed to achieve sufficient results. The interview was conducted in the following steps: in the first step, questions 1 to 6 were asked; in the second step, questions 7 to 23; and in the final step, questions 24 to 35. Each step was audio-recorded for further transcription. In addition, after each step, the case study partner was provided with the initial questions in writing, allowing them time in private to make notes on anything they might not have remembered during the interview. This approach proved successful, as the collaboration was proactive, and the chat system was effectively used for real-time conversations. It was also agreed that a non-disclosure agreement was not necessary during the collaboration and writing of this thesis, as detailed financial aspects were not covered, and the case study partner saw no risks in allowing competitors to investigate their specific production flow in direct contact with honeybees and beehives.

5. Case study results and analysis

This chapter covers the activity nr. 8 from Table 3. In this chapter, the first scientific research question of this thesis is answered based on the case study partner: Which parameters in the beehive are inspected by beekeepers to make decisions? Transcribed data from the interview, the literature review, and notes from the researcher's diary are analysed to complete the list of parameters and related actions. In addition, a beehive production flow is created in collaboration with the case study partner and is presented in this chapter. This chapter also discusses the test results of the computer vision system and highlights relevant findings from the case study that serve as input for the concept of the robotic beehive.

5.1. List of parameters, decisions and action

In terms of inspected parameters, the case study partner evaluates most of the parameters listed in Table 1. The 20 parameters evaluated by the case study partner are presented in Table 4, along with how the case study partner prioritizes them. The parameters written in **bold** are used in Figure 7 as part of the initial production flow for robotic beehive. This table also includes parameters that are not directly related to frame inspection. Since the case study partner has never observed any parasites other than *Varroa destructor*, the inspection for small hive beetle is not included in their routine. Additionally, the case study partner does not distinguish between pollen and bee bread. Since pollen is the main ingredient in bee bread, the two parameters appear visually similar. To simplify visual inspection, the case study partner focuses only on identifying bee bread. Additionally, the case study partner ignores the angle of inclination of the egg relative to the cell bottom and only evaluates the presence of eggs.

Through participant observations, it was found that the case study partner evaluates the consistency of the patterns being assessed. For instance, how many empty cells are between areas filled with capped brood. The case study partner admits that while empirical pattern recognition has evolved, it remains complicated to describe it in words. Based on this, it is recommended to collect data during the first iterations of the robotic beehive to study the patterns of parameters.

As in theory, the priority of the case study partner during frame inspection is the presence of the queen. The inspection for the queen and for laid eggs goes hand in hand, and if either parameter is confirmed, the result is considered successful. If neither eggs nor the queen are found, the partner inspects the presence of capped brood and larvae more thoroughly. At all times, whether the queen's presence is confirmed, assessing the patterns of eggs, capped brood, larvae, bee bread, and capped honey remains a priority. The variety of frames in terms of colour and pattern is remarkably high. A Langstroth frame contains approximately 3,500 cells, resulting in such many possible combinations that, in practice, it is nearly impossible to find two frames that look the same, except for those used solely for storing capped honey.

Table 4. Parameters evaluated by the case study partner for decision-making and action

ID	Parameter	The probability of presence	Priority in daily operations	Quality
1	Empty (new) cells.	High.	Low.	Consistency of patterns is evaluated.
2	**Eggs.**	Low in winter. High in summer.	High.	Consistency of patterns is evaluated.
3	**Larvae.**	Low in winter. High in summer.	High.	Consistency of patterns is evaluated.
4	**Capped worker brood (pupae).**	Low in winter. High in summer.	High.	Consistency of patterns is evaluated.
5	Capped drone brood.	Low in winter. High in summer.	High.	Consistency of patterns is evaluated.
6	Drone.	Low in winter. High in summer.	Low.	N/A.
7	**Bee bread.**	High.	High.	Consistency of patterns is evaluated.
8	Liquid honey.	High.	Moderate.	Consistency of patterns is evaluated.
9	**Capped honey.**	High.	Moderate.	Consistency of patterns is evaluated.
10	***Varroa destructor*** **on honeybee (or on frame or larvae).**	Depends on the season.	Moderate.	If detected visually on honeybees, larvae, or frames, the condition of the beehive is considered to be very poor.
11	Worker bee emerging from cell.	Low in winter. High in summer.	Low.	N/A.
12	Queen.	High, but not always directly observed.	Low, if parameters 2, 3 or 4 observed. Otherwise, high.	Queen is present or not.
13	Supersedure cells and swarm cells.	Low.	High, if detected.	If present, probable swarming is detected.
14	Mould.	Low.	Low.	Mould is present or not.
15	**Temperature (outside).**	N/A.	High.	No action is allowed if the evaluation indicates that the brood temperature would drop below an acceptable level. In hot season parameter 17 must be prioritized.
16	***Varroa destructor*** **on removeable bottom board.**	High compared to parameter 10. Depends on the season.	Usually low. When chemical treatment made, high.	The number of fallen mites is used to evaluate the effectiveness of chemical treatment and the overall health of the colony
17	**Hive entrance opening.**	N/A	Moderate.	Regulates cooling, ventilation, and protective functions.
18	**Amount of food storage.**	High, when feeding period. Low, if not.	High, when feeding period. Low, if not.	Sufficient or insufficient.
19	The mechanical integrity of the beehive components.	N/A	Low, as periodical maintenance is carried out.	Sufficient environment for honeybees or not.
20	**Sound signatures.**	High	Low in summer, moderate in winter.	In winter, colony strength is evaluated based on its sound signature.

Figure 6 shows beehive frames numbered from 1 to 32. All 32 frames were photographed under identical conditions using the same imaging device and cropped in the same way, except frame 3 which is zoomed in. Notably, identical parameters (P following a number of parameter) may appear differently across different frames. **P1** refers to empty cells on a brand-new frame. Frames 1 and 2 show early signs of honeybee activity, while frame 29 is already being used for honey storage. **P2** refers to eggs, which can be observed on frames 2 and 6. **P3** refers to larvae, which are marked on frames 4–11 and can also be found on a few other frames. The size of the larvae varies, and the contrast between the larvae and the frame background causes this parameter to appear very differently across frames. **P4** refers to capped worker brood and is marked on most frames. **P5** refers to capped drone brood and is visible on frames 5, 12, and 13. A drone is shown on frame 18 as **P6**. **P7**, which refers to bee bread, is indicated on frames 7, 11, 16, 18, 22, 30, and 31. **P8** refers to liquid honey and is visible on frames 6, 23, and 24. **P9** refers to capped honey and is marked on frames 24 and 28–31. A *Varroa destructor* mite attached to the back of a honeybee is indicated on frame 10 as **P10**. Although the case study partner does not purposefully inspect **P11** (a young worker bee emerging from a cell) on frames 12 and 32, it is included as a parameter for computer vision in the context of automatic frame inspection. Appendix B covers some possible appearances of different frames that are sometimes found during inspections by the case study partner.

Number of parameters that may simultaneously exist on a single frame creates a large variety of patterns that cannot be parametrically inspected by human when managing multiple beehives. The case study partner uses a cell phone to make written notes at the beehive level in the following format: extreme positive/negative findings, and which patterns or parameters to inspect during next visit. No parameters are measured or counted, as the case study partner successfully manages the beekeeping business by evaluating visual patterns. Furthermore, the case study partner finds it challenging to define measurable qualities or numerical value ranges for the parameters and patterns being inspected. They explain that successful inspection is based on experience, which cannot be recalled or articulated through simple conversation. In addition, during direct interaction with the bees and while inspecting multiple frames, decisions are made on the spot using cognitive experience and memory, without relying on numerical data – and this approach has proven effective.

The case study partner also inspects following parameters (shown in Figure 7) within the beehive: 15) Temperature; 16) *Varroa destructor* on removeable bottom board; 17) Size of the hive entrance opening; 18) Amount of food storage (bee fondant, bee bread and sugar syrup); 19) Mechanical integrity of the beehive components; 20) They also use their sense of hearing to locate a young queen by her 'singing' or to listen to the swarm's sound in winter.

The case study partner focuses on ensuring key conditions within the beehive. When average daily temperatures remain above 10°C, active inspection and work with the honeybees begin, as the risk of undercooling the colony is higher at lower temperatures. During wintering, swarm must remain compact to preserve warmth. In the summer the queen must have space to expand the brood area and additional space must be provided for honey storage. Swarming must be monitored and controlled. In brood-designated beehive bodies, frames containing brood should be grouped at the centre, while frames storing bee bread or honey should be moved to the sides. *Varroa destructor* must be monitored and, if necessary, chemically treated in the spring, and periodically treated again each autumn before wintering. In winter, bottom boards must be used to help retain warmth, while in summer they are removed to improve cooling and ventilation. The hive entrance should also be closed during winter to conserve heat, or temporarily during the summer when pest control treatments are being applied in nearby crop fields.

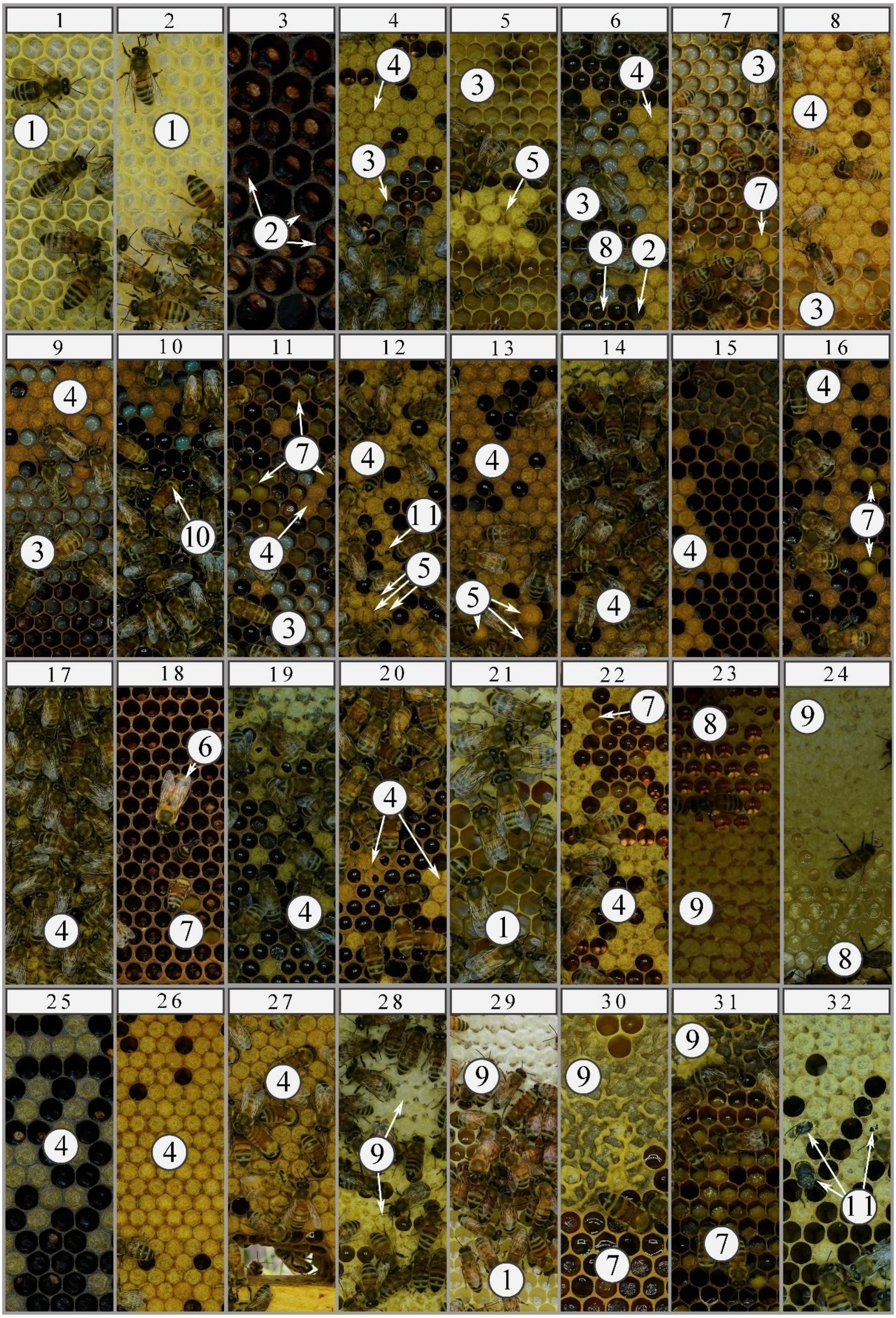

Figure 6. Examples of parameters on frames

The case study partner performs all standard beekeeping actions described in Table 1 based on visual inspections and intuitive interpretation of hive conditions. These include moving frames within or between hive bodies, adding or removing frames, and requeening when needed. Equipment is limited to common tools: hive tool, smoker, brush, and basic safety gear. Seasonal adjustments include adding 3–5 hive bodies in summer and reducing to 1–2 for wintering. Less frequent actions are carried out situationally, based on inspection outcomes. The next subchapter explores the initial production flow, created in collaboration with the case study partner, aiming at the automation in the first development phase of the robotic beehive.

5.2. Production flow

The only parameter used by the case study partner in numerical form is the outside temperature. To some extent, time also plays a role, as certain procedures are linked to specific months, and hive inspections follow periodic patterns. However, it is difficult for the case study partner to define precise time schedules, as the need and timing of actions depend on outside temperature, other weather conditions, and a general health assessment of the apiary.

It was decided that the next step toward automating the beehive would be to combine the mapped decisions and actions with additional insights from the case study partner to define the beehive production flow. To support this, an additional workshop was conducted, and the result is shown in Figure 7. The season is divided into 12 activities, each with an indicative period during which it is usually carried out.

During winter, honeybees do not defecate as they cluster together and do not leave the hive in order to maintain warmth. However, they release gases as a result of metabolism, which causes the overall mass of the beehive to decrease, as substances like CO_2 and water vapour exit the hive. This is why, in **activity 1**, the case study partner lifts the beehives by hand to estimate the beehive's mass (as a secondary parameter for evaluating parameter 18 from Table 4). If food stores are estimated to be insufficient, 1 to 2 kg of honeybee fondant is added. It must be done quickly to avoid the honeybee cluster from cooling down. Fondant is a soft, sugar-based feed in block form.

In **activity 2**, the solid bottom board (No. 6 in Figure 1) is replaced with a cleaned version from stock. Before replacement, the new board is cleared of dead bees and then disinfected using fire or chemicals. This activity is carried out during periods when the outside temperature is between –5 °C and +1 °C, as the honeybees remain in a cluster and are less affected by the movement of beehive bodies compared to times when they are active.

Activities 3 and 4 are the longest, lasting six and eight months respectively, and run in the background by default alongside other activities. In **activity 3**, the case study partner inspects frames and checks, in a specific order, for the presence of eggs, larvae, and pupae. Evaluating the patterns and consistency of the pupae is important for decision-making. Inspection of *Varroa destructor* in **activity 4** is a priority and is carried out visually on both the frames and the removable bottom board. Each time the case study partner holds and inspects a frame, the presence of *Varroa destructor* is also assessed—both inside the cells and on the backs of the honeybees. **Activity 5** involves the inspection of food stores, which, if found to be insufficient, are supplemented with frames filled with bee bread from the previous year's harvest.

Activity 6 involves inspecting the size of the colony. If the colony is evaluated as small, a few frames are removed from beehive body to keep the brood close together and maintain warmth. From January until this activity, the size of the beehive remains at one to two beehive bodies. If the colony is evaluated as strong, a first—but very light—expansion (sub activity 6.1) is carried out by adding one beehive body. If the presence of *Varroa destructor* is evaluated as high, the season's first pest treatment—sub-activity 6.2—is carried out using oxalic acid vapour. For the treatment of *Varroa destructor*, the case study partner uses oxalic acid ($H_2C_2O_4$) and the vaporisation method. Oxalic acid must be stored below 25 °C and kept sealed from humidity. To create the vapour, 1 gram of oxalic acid powder per beehive body is vaporised at 157 °C and vapor blown through the hive over a period of two minutes [74]. After treatment, the dead *Varroa destructor* mites fall onto the removable bottom board, where their presence in the colony can be visually evaluated. The removable bottom board (Figure 4) is used in sub-activity 6.2 and activities 9 to 10, where it is placed between the solid bottom board and the first beehive body.

In **Activity 7**, rapid colony growth is usually observed. If the brood pattern is evaluated as weak, requeening is carried out. If the queen is considered healthy but the colony remains small, a few frames with capped brood are introduced from a stronger colony. During this activity, a queen excluder is always added between the second and third beehive body. Additionally, an extra hive entrance is created for worker bees to carry nectar directly to the honey supers, which are located in the hive bodies above the queen excluder. During the growth period, the height of the beehives may reach five hive bodies, and occasionally even seven or eight. In addition, as the queen lays eggs in the first two beehive bodies, space may become limited. In such cases, some brood frames are moved above the queen excluder and replaced with empty frames, allowing the queen to continue expanding the colony.

Activity 8 involves the harvesting of honey, where the priority is to remove honey-filled frames and transport them away from the apiary. The case study partner uses a brush to guide the honeybees back into the hive or gently shakes the frames, so the bees fall back into the hive. Both methods are considered safe and efficient.

Activity 9 is the periodic *Varroa destructor* treatment using oxalic acid, conducted every season. It is performed at least three times at 7-day intervals to ensure that all generations of brood are treated. Removable bottom boards are used for evaluation. As oxalic acid may also affect honeybees, 10 litres of sugar syrup is provided to support colony strength. Sugar syrup is added in a way that prevents honeybees from drowning in it. **Activity 10** is the second periodic *Varroa destructor* treatment using oxalic acid, conducted only when the outside temperature is above 10 °C and without providing additional food. Removable bottom boards are also used to evaluate *Varroa destructor* levels.

Activity 11 focuses on physical protection against mice, birds, and other small predators that may attack the beehive during winter. The hive entrance is either closed or reduced in size. The only action carried out under **activity 12**, typically in December, is listening to the buzzing of honeybees to evaluate the strength of the colony.

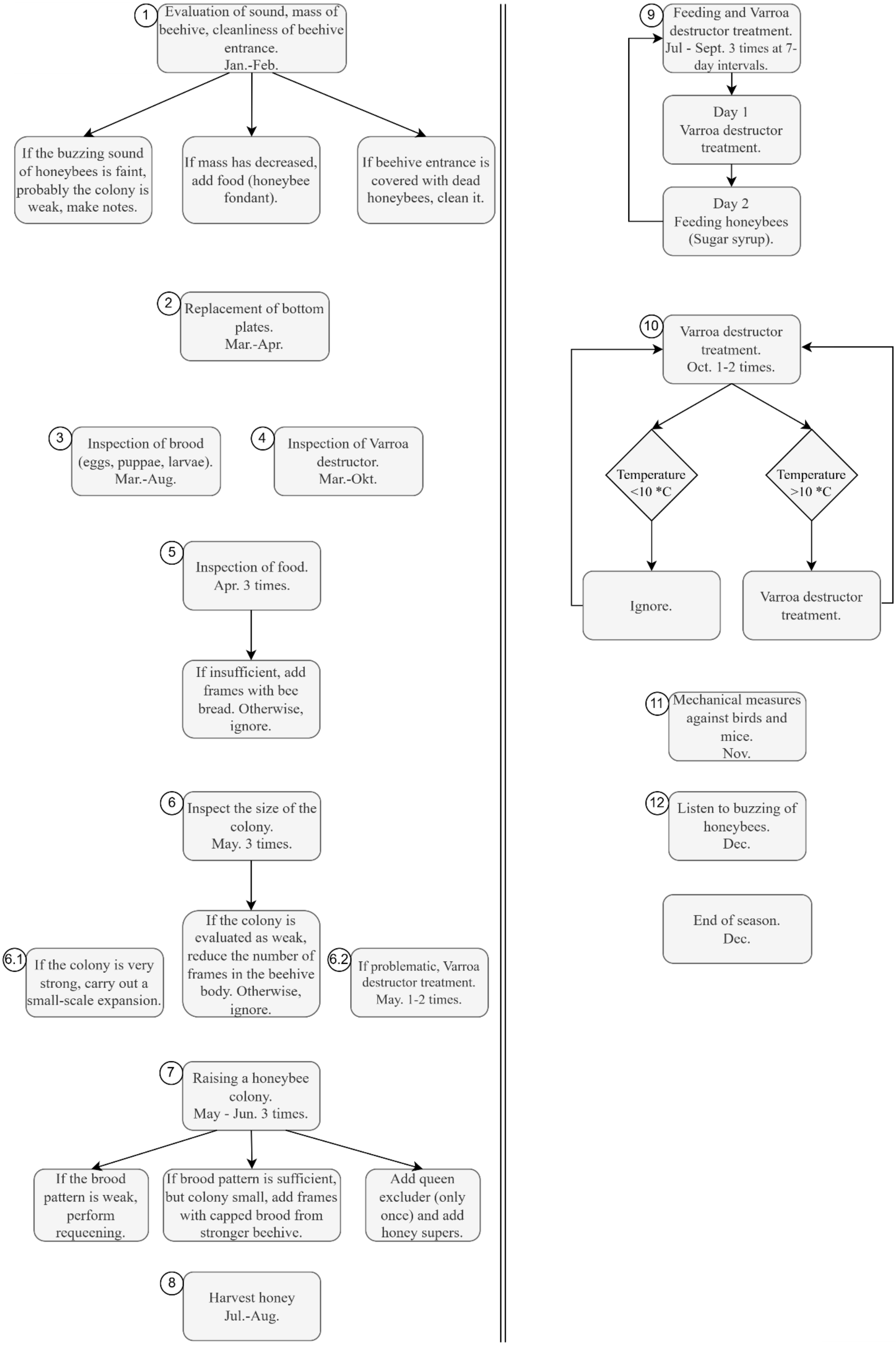

Figure 7. Production flow

5.3. Computer vision model for detecting *Varroa destructor*

Following the manual image inspection and labelling of the images (Subchapter 4.3), this subchapter covers the tests conducted with computer vision. YOLO was selected as the computer vision software due to its widespread use and long version history. YOLO pre-trained model 11X was chosen for its overall performance and a detection time of 12 ms per image, making it suitable for real-time video processing if needed [75]. Setting up YOLO 11X is a relatively easy, requiring only a few lines of code on a Linux machine.

The main time-consuming task was manually identifying *Varroa destructor* on frame images and cropping selected areas into 640 × 640-pixel segments, which is the default input size for YOLO. For the model training 280 images were divided into 224 for the training pool, 26 for the validation pool, and 30 for the testing pool, respectively. YOLO X11 required approximately one day for training on a computer with AMD Threadripper 2970WX 24-core and 128 GiB RAM. Model fitting did not make use of all the cores nor all the RAM even after tweaking batch size and the number of workers. A total of 200 epochs were set, but YOLO early-stopped the training procedure on the 135th epoch, as no further improvements to the model's performance were detected (Figure 8 presents YOLO generated statistics). Appendix C provides written code together with access to Github repository.

Figure 9 shows that the accuracy for detecting clean honeybees on the test set is about 86%, whereas the accuracy for detecting infected honeybees is 84%. The model has difficulties separating clean honeybees from the background. There are two major ideas for increasing the accuracy. Firstly, label the background (frame) as well, and secondly, manually find more infected bees for future training.

In conclusion, it can be said that the detection of *Varroa destructor* using computer vision is feasible, and therefore, detecting parameters with a larger surface area than *Varroa destructor* is likely to be even more accurate. In addition, it was concluded that the detection of *Varroa destructor* on removable bottom boards is worth testing, as the contrast and the density of mites are better.

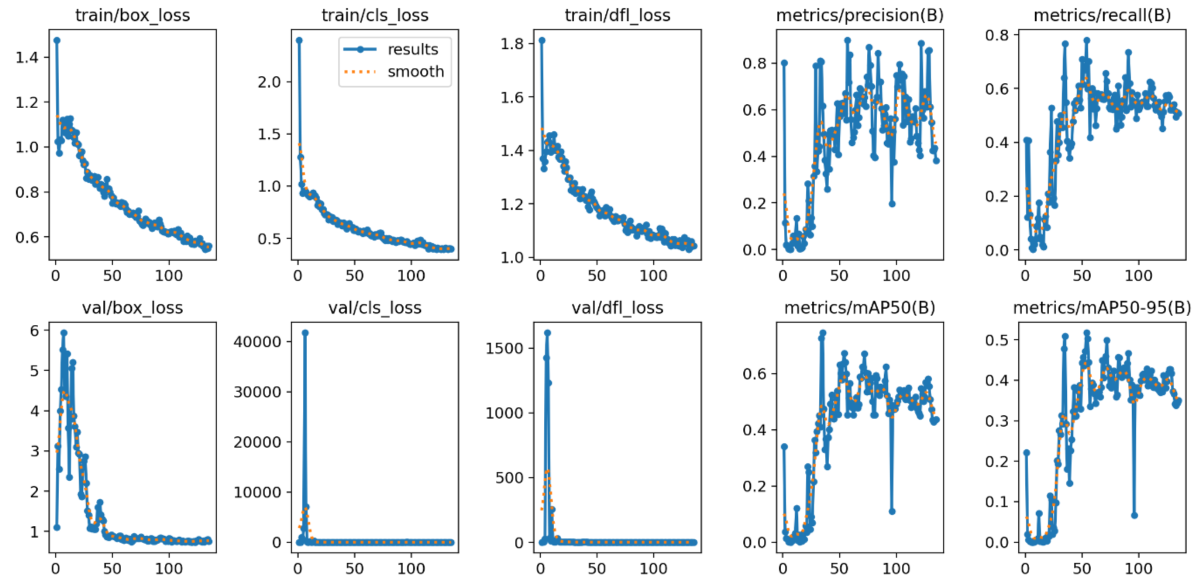

Figure 8. YOLO training metrics

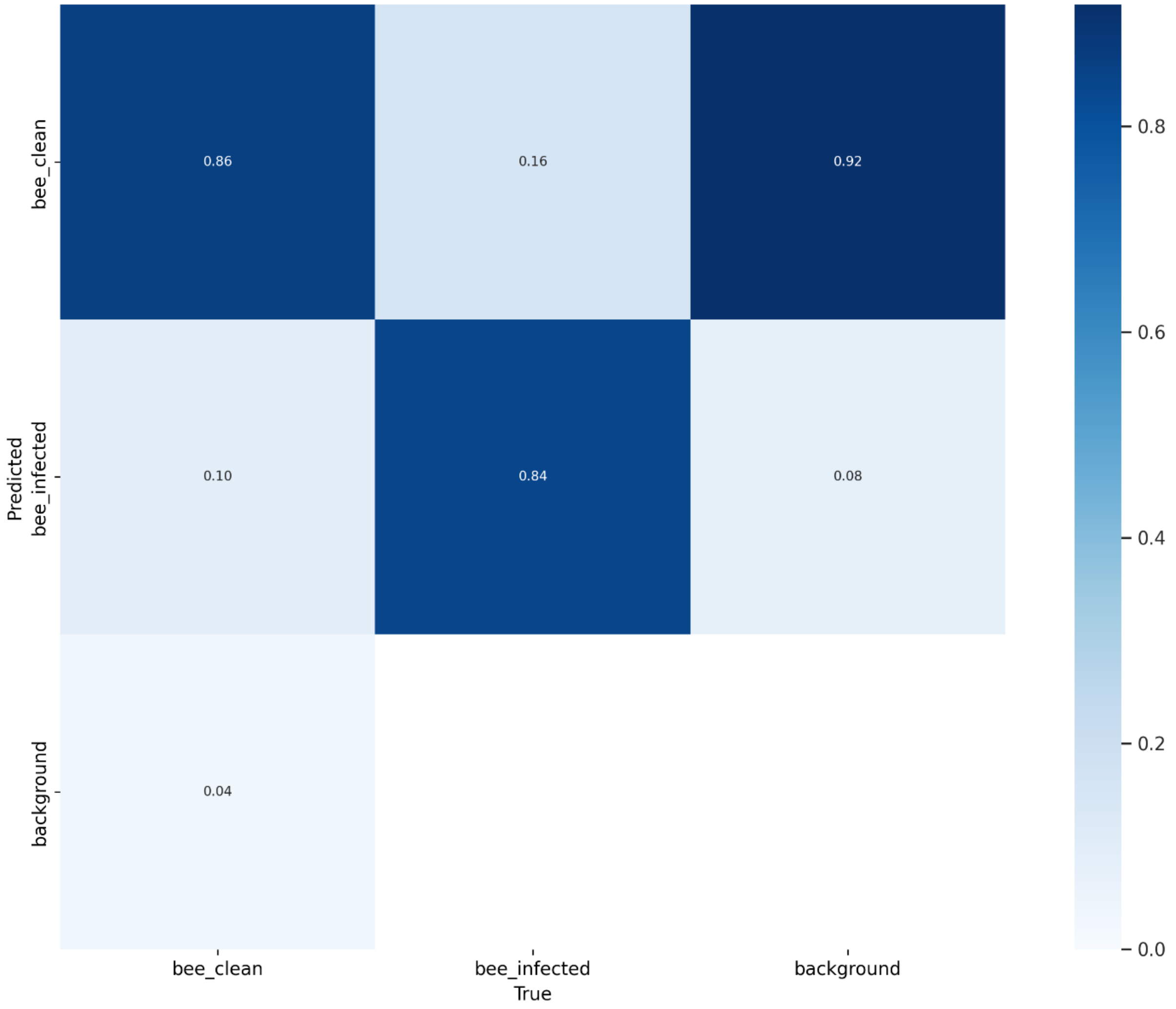

Figure 9. Normalized confusion matrix on test set

5.4. Relevant findings from participant observation and interview

This subchapter outlines findings derived from case study participant observations and interview as input for further development phases in design of robotic beehive. The case study partner describes their understanding of beekeeping with the following ideas. They believe generally that as experience of a beekeeper grows, so does the knowledge stored in muscle memory. The partner also confirms that, over the years, theoretical and analytical awareness tends to decrease as routine processes become established. From a scientific curiosity perspective, the aforementioned makes researching beekeeping procedures more challenging, as beekeepers working routines are difficult to recall by simply answering questions. Additionally, the case study partner admits that after years of experience with hundreds of beehives, one may say that beekeeping is simple – yet at the same time, it is highly complex, and no beekeeper is ever perfect. For instance, based on individual studies made by the case study partner, one beekeeper can earn 100 kg per beehive and another only 20 kg. In both cases procedures are made by book and relatively easy but results are different. The case study partner works in pairs when inspecting beehives in the apiary. During participant observations or other activities, it was noted several times that two professional beekeepers may hold different opinions on which decisions or actions should be taken. Nevertheless, both persons agreed that any of the chosen approaches would likely lead to the desired outcome.

To summarise the priorities within a beehive, the brood and adult honeybees must: a) be kept at a suitable temperature at all times; b) the queen must be alive and healthy; c) there must be sufficient space for brood and honey; d) within a single beehive body, brood frames should be kept in the middle, with frames containing food resources placed on the sides; e) food shortages should be compensated; f) *Varroa destructor* must be monitored and treated using oxalic acid; a beehive should be cleaned once per year by replacing and disinfecting hive bodies and frames; g) swarming must be prevented.

An interesting finding is that, despite several sources emphasizing that *Varroa destructor* has a tendency to develop resistance against chemicals when treated periodically without changing the approach, the case study partner does not follow this practice. Specifically, the case study partner uses only oxalic acid, following the production flow described in Figure 7. The case study partner shared statistics indicating that winter losses (the percentage of colonies that die during winter) remain between 2% and 10%, depending on the year. In addition, the case study partner does not know why one year is more successful than another.

A comparison between images taken with the imaging device and manually captured images of the removable bottom boards produced an interesting result. Among nearly 3000 frame images, only 73 *Varroa destructor* mites were found by manual inspection, while the same colonies showed thousands of mites when evaluated using the removable bottom boards. Considering that the highest number of mites found on a single frame by manual inspection was five, the difference amounts to several hundred times.

At the time of submitting this thesis, the experiment involving a neodymium magnet placed at the entrance of the one beehive had been running for over three months. During that time, no positive or negative effects from the strong magnetic field on the honeybees were confirmed when compared to other beehives in the test group. Based on that it was decided that in further development phases of robotic beehive magnetic tags attached on the backs of queens might be solution worth testing monitoring and localisation of the queen.

Other biological findings were as follows: a single colony may host two or even three queens without swarming. The case study partner keeps honeybee casualties to a minimum—under 50 per hive—during any activity throughout the season. The case study partner evaluated that winter losses must remain close to zero. However, it was also assessed that during summer, a strong colony can likely survive the loss of up to 500 honeybees every seven days. It must be considered, that young honeybees can not return back to hive when follen to ground or lost inide robotic compartment.

Records are kept at the beehive level and only when something highly abnormal occurs as too detailed notes wastes time of the case study partner. Notes are made using mobile phones and generally indicate which actions should be taken during the next visit. Parameters inspected on frames or within the hive are evaluated on the spot, and nothing is ever measured. Since beekeepers must manage hundreds of hives and thousands of frames, it becomes extremely difficult to memorise their previous states. As a result, beekeepers learn to make decisions on the spot, relying on experience and muscle memory. However, when asked to describe the ideal beekeeper, the representative of the case study partner replied: 'Sees everything and remembers everything. '

The case study partner confirmed theory that bee spaces must be maintained between 4 mm and 9 mm. It was also discussed and confirmed that honeybees are capable of building combs on both plastic and metal substrates which makes the design of the robotic beehive more flexible.

Different frame sizes and aspect ratios were discussed, and the case study partner confirmed that they see no risks even with an aspect ratio as low as 1:5. Despite this, sufficient surface area must still be maintained for brood and honey. Additionally, the case study partner recommends keeping the aspect ratio close to 1:1 to help retain warmth during winter.

During participant observation, the time required for the case study partner to inspect beehives was measured (in summer, during activity 7, shown in Figure 7). The results were discussed and evaluated, concluding that this activity typically takes around 20 minutes per hive. Additionally, another professional Estonian beekeeper was visited, and their practices were observed during spring activities. Based on these observations, activity 6 (Figure 7) took approximately 3 minutes per hive.

One of the most important actions in beekeeping is moving frames within a beehive body and between different beehive bodies. The first step involves using a hive tool to pry the first frame loose, as the frames are glued together by the honeybees. The case study partner usually begins from the sides, away from the brood and the probable location of the queen. It was observed that frames do not slide out of position easily. They are separated using both the hive tool and hands, and then carefully lifted out of the beehive body. When returning them, the frames are placed a few centimetres away from the neighbouring frame and pushed into position until physical contact is made. The last frame, however, must be inserted directly, as there is no space for sideways sliding. In some cases, significant force was required to move the first or last frame. For example, it was noted several times that a 100 kg man had to use his body weight to push the last frame back into the beehive body. Based on collected data, the concept of a robotic beehive will be composed as practical output of the work.

6. The Concept of robotic beehive

This chapter covers the activity nr. 9 from Table 3 which is formation of the concept of a robotic beehive. The following research questions are covered: How to automate the beehive based on the studied parameters and decisions? What requirements must a robotic beehive meet? The practical output of this thesis is the concept of smart frame, which detects movement of queen and locates her position between smart frames. The second practical output is mechanical concept of robotic beehive. The chapter ends with a discussion, which covers the limitations of the work and presents prospects on a practical and theoretical basis.

6.1. Localisation and monitoring of the queen bee

The queen must be kept unharmed during beehive inspections or management procedures. Designing a robot that can lift frames out of the beehive body as carefully as a human is a significant challenge. Accurate localization of the queen simplifies the mechanisms and sensor system responsible for sliding frames in and out of the beehive body. The queen can move between frames and hive bodies through gaps in the beehive structure, known as bee spaces (Figure 10 shows the frames in brown and indicates the bee spaces as 9 mm-wide gaps between the beehive bodies and frames.). Like most insects, the queen can move on surfaces regardless of angle or orientation. Scientific studies investigating the effect of bee space distance on honeybee behaviour are limited. However, empirical knowledge accumulated throughout the history of beekeeping has precisely defined bee space as follows: If the bee space is narrower than 6 mm, honeybees will likely seal it with propolis [76], [77], [78]. If it is greater than 9 mm, they will consistently fill it with burr comb [76], [77], [78]. The queen is indistinguishable from worker bees in radar or other sensor detection, which necessitates attaching a tag or reflector to her back. The queen's mass is 170 - 230 mg and recommendations suggest that a tag should not exceed 5% of the tagged insect's mass, thereby the tag should weigh no more than 12 mg [79]. For the concept of the robotic beehive, it has been decided that the tags/reflectors used should be round with a diameter no greater than 3 mm.

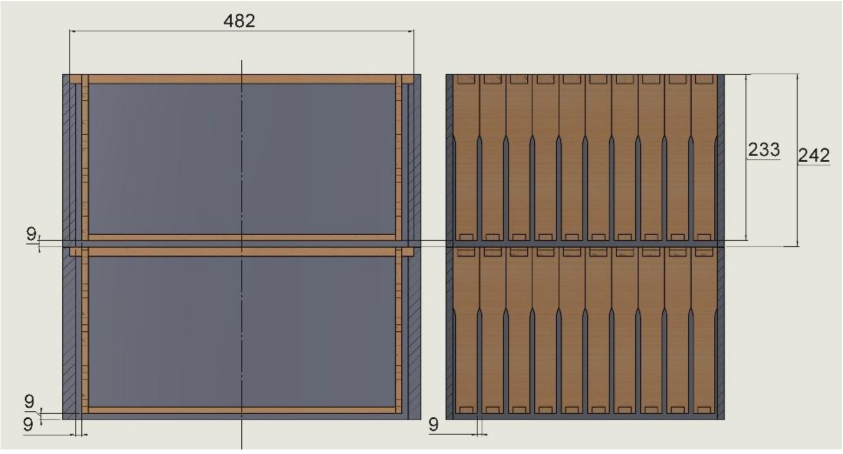

Figure 10. Bee spaces as pathways between frames and hive bodies

The queen's height for the robotic beehive concept is defined as follows. A maximum recommended bee space of 9 mm is used, which is then divided by two. Each tag, being geometrically symmetrical by nature, is positioned 4,5 mm above the surface the queen walks on, measured from the tag's centreline (Figure 11).

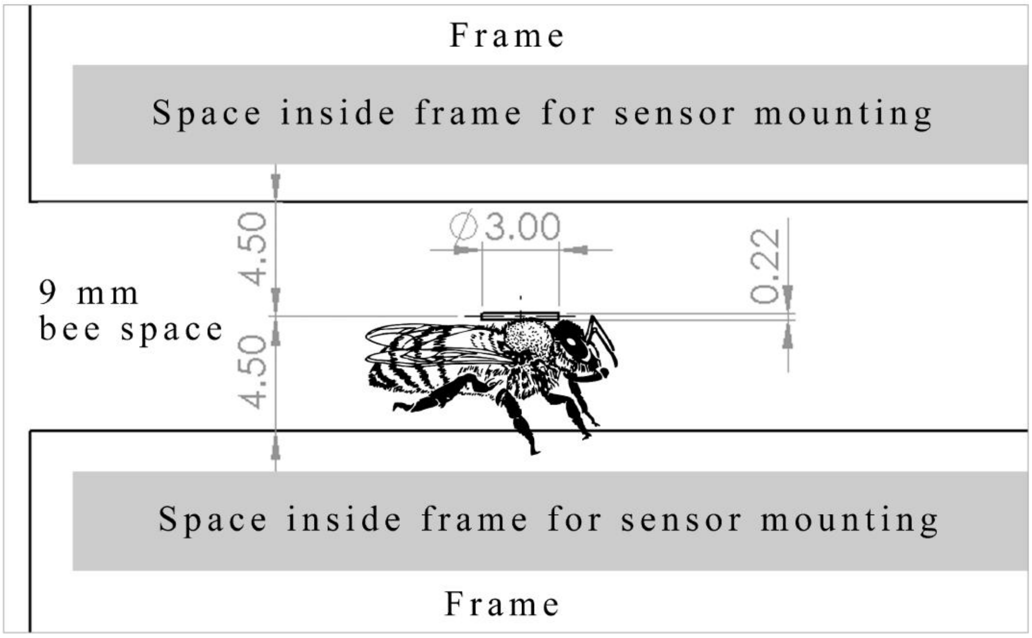

Figure 11. Queen tag position in bee spaces [80]

The following discussion explores reed switches, magnetic sensors and radars as potential technologies for detecting and monitoring the queen. Sensors may be placed around the frame or beehive to effectively track the queen's movement between frames and beehive bodies. One option is to use reed switches that are electrically connected in series and break the circuit when exposed to a certain magnetic field. It is recommended to surround the frame with two separate lines of reed switches to detect the direction of the queen's movement. This approach is highly efficient in terms of both computational performance and energy consumption. Since the maximum distance between the queen tag and the housed reed switches may range from 5 mm to 10 mm depending on the design, an N55 magnet, the strongest available permanent magnet, is proposed as the queen tag. [81]. Given that the density of an N55 magnet is 7.6 g/cm³, the tag's diameter is 3 mm, and the mass limit is 12 mg, the calculated thickness for the N55 magnetic tag is 0,223 mm [82], [83].

This means that, based on the aforementioned bee space and the queen's height estimation, the tag's estimated distance from the surface the honeybee walks on is 4.4 mm. The Intrinsic induction of this magnet is 1378 mT [67]. Considering the specifications, the flux density of this magnet is 2,29 mT at 5 mm, 0,32 mT at 10 mm, and 0.1 mT at 15 mm, respectively [68]. At the time of writing this thesis, the most sensitive reed switches available fell within the 5 AT to 10 AT range (AT stands for ampere-turn) [84]. As a starting point, it is recommended to use the rule that 0.1 mT per 1 AT is required for the reed switch to activate [85]. The production process of reed switches and magnets varies significantly, making real environment testing crucial alongside indicative calculations [85]. Based on this, one can estimate that the defined magnetic tag generates a magnetic field strong enough to activate a 5 AT reed switch at 0 mm to 10 mm. However, due to significant uncertainty in both magnet and reed switch specifications, testing is required to assess its usability in practical applications. The activation of reed switches depends on the orientation of the magnetic field around them. In this thesis, a simple experiment was conducted, which proved this fact, as 'blind spots' were indeed observed in certain positions.

However, these blind spots can be avoided by using different patterns in the reed switch row along with signal processing. There is a risk that chosen N55 tag might disturb magnetic senses of honeybees as they are able to sense fluctuations in Earth's magnetic field as small as 26 nT [69]. The chosen tag might be sensed by honeybees in 250 mm distance [68]. The effect of magnetic fields on larvae and pupae is not well understood, and further studies are recommended. The following benefits of reed switch technology justify further studies and testing: a lifespan of reed switch is millions of cycles, hermetic sealing and moisture resistance, and low cost [86].

Digital magnetic switches are a promising alternative to reed switches due to their potentially higher sensitivity, despite consuming more energy. There are digital sensors available that can detect the chosen N55 tag at 9,3 mm and are less dependent on the orientation of the magnetic field than reed switches [87].

Queen detection and monitoring can potentially be solved using radar technology. One of the most significant obstacles for radars is water, which strongly absorbs a wide spectrum of electromagnetic radiation. Its absorption level exceeds 90% across the frequency bands of 1.4 GHz – 63 GHz. [88]. Water is a component of honey and pollen, and it is a cellular compound in honeybees throughout every life stage. During wet seasons, the water content in honey can reach up to 29%, while in dry seasons, it typically ranges between 14% and 18% [89]. Pollen collected and stored by honeybees contains between 11% and 18% water [90]. Nectar contains between 75% and 80% water [91], [92]. Research on water content in honeybee bodies is very limited, although it has been confirmed that water constitutes 60% to 70% of an insect's body weight [93]. The behaviour of storing water in frame cells remains unclear. Some sources suggest that honeybees in temperate zones do not store water in cells, while others present opposing views [24], [94]. It has been said that a strong colony consumes over one Liter of water on a hot summer day [95]. The information gathered from literature and the case study partner is not sufficient for precise calculations of water content in the beehive body. Furthermore, due to the honeybees' natural ventilation behaviour, developed to regulate hive conditions during hot summer days, along with temperature and humidity fluctuations and their collective activity, water levels can only be estimated. Considering the percentages, one can estimate that the water presence in the brood beehive body may be high enough to interfere with radar systems using wavelengths that cannot penetrate water. The most promising frequency band, providing sufficiently high resolution, is X-band (8–12 GHz), which has been proven effective in practical use for tracking flying insects over open plains [96].

Based on previous research, the effect of electromagnetic radiation on the health of honeybees remains unclear. Many studies conclude the work with recommendations for further experiments, as existing studies bring out both negative and/or neutral effects of radiation. [97], [98], [99], [100], [101], [102], [103], [104], [105]

6.2. Development phases and requirements

In this thesis, it was decided that the design of the robotic beehive would be divided into four main phases, each lasting one to two seasons, with one season corresponding to the length of one iteration. The theoretical study, alongside the case study and related analysis, is focused on the first phase, which prioritises data collection and testing of mechanics. As the case study partner does not measure parameters within the beehive, the priority is to build a robotic beehive that conducts computer vision inspection for frames and removable bottom boards, measures temperature and humidity within the beehive. In the first phase, a user interface must be implemented for computer vision research and system calibration. Users must label images of frames until precise detection of all visual parameters is achieved. It is recommended to train the system in collaboration with beekeepers and engineers to ensure labeling precision. The user interface can be like existing labeling programs such as LabelStudio. Management strategies based on computer vision, temperature, and humidity must be delivered by the end of the first phase. In addition, mechanisms for moving frames between different beehive bodies must be tested during the first phase. It is recommended to use a 6 m shipping container to house all the systems, as it facilitates maintenance and testing by providing enough space for operations. As the next phases depend heavily on the data collected and the findings made, along with test results from the first phase, the descriptions of the following phases are intended to serve an indicative purpose.

The second phase utilizes the hardware built in the first phase, focusing on testing different management strategies that take digital images of frames and removable bottom boards, along with temperature and humidity measurements, as input. The system's deployment progresses as users train the computer vision, sound analysis, and temperature and humidity analysis systems to identify patterns that will inform the development of future management strategies. In second phase, additional research focuses on queen localization and monitoring to identify more efficient sensor systems or data analysis methods for ensuring her safety during mechanical operations in the beehive. The third phase requires a complete understanding of the analyzed parameters and discovered patterns to begin optimizing the hardware with the goal of making the robotic beehive smaller, lighter, and cheaper. The fourth phase serves the purpose of full automation, as all previous phases require users to conduct calibration and research activities. In fourth phase, the aim is to deliver a commercial solution that is small enough to enable safe transportation and requires considerably less effort for the initial setup compared to first phases.

Table 5 covers the requirements, which are sorted by type and linked with the phase numbers, as not all requirements are feasible or applicable in the first phase. Requirements are generally divided into functional (what to do?) and non-functional (how to do?) categories [106]. A great number of requirements will be defined and managed in the upcoming phases. For clarity in system design, the following types of requirements have been selected: functional, safety, structural, electronic, communication, data handling, power system, and user interface requirements. In the table, the significance of the requirements is divided into three categories as follows: **Crucial** (40 requirements) – inevitable for the development of the robotic beehive; **Secondary** (10 requirements) – requirements that may be considered once development has begun; **Potential** (1 requirement) – likely feasible in future iterations.

Table 5. Requirements for robotic beehive

ID	Type	Description	Quality
1.	Functional	Phase I; **Crucial**. Measurement of frame parameters using computer vision: presence of eggs, larvae, capped brood, empty cells, *Varroa destructor* on honeybees, burr comb, pollen, nectar, supersedure cells, swarm cells, and capped honey.	Quality will be determined in first and second iterations.
2.	Functional	Phase I; Secondary. The system may be capable of guiding honeybees back into the hive while removing the frame from the beehive body, allowing for frame measurements without bees present.	Will be determined in the next iterations.
3.	Functional	Phase I; **Crucial**. Counting of the (dead) *Varroa destructor* mites on the removable bottom board.	The bottom board must be made of a material that prevents organic matter from sticking to it. A mechanism must be in place to lift the bottom board in and out for measurement.
4.	Functional	Phase I or II; Secondary. A cleaning system may be implemented to clean the bottom board a few days before measurement.	Quality will determined in first and second iterations.
5.	Functional	Phase I; **Crucial**. Measurement of temperature in every beehive body.	Accuracy around 1°C.
6.	Functional	Phase I; **Crucial**. Measurement of humidity in every beehive body.	Accuracy around 2%.
7.	Functional	Phase I; **Crucial**. Regulation of temperature and humidity within a colony.	Quality will be determined in first and second iterations.
8.	Functional	Phase I; Secondary. Counting of the honeybees as they leave and return to the beehive.	Quality will be determined in first and second iterations.
9.	Functional	Phase I; Secondary. Measurement of sound signatures in beehive body.	Quality will be determined in first and second iterations.
10.	Functional	Phase I; **Crucial**. Movement of frames within a single beehive body or between different beehive bodies in the same colony.	Requirements nr. 18 and 19 must be maintained.
11.	Functional	Phase I; **Crucial**. Take the frame filled with honey from the beehive body. Move this frame to the storage compartment and return a new, empty frame to the beehive.	Requirement nr. 19 must be maintained.
12.	Functional	Phase I; **Crucial**. Managing multiple colonies using a single mechanism for measurements and production logistics.	Mechanism can change its location between different colonies.
13.	Functional	Phase I; **Crucial**. Opening and closing queen excluders between beehive bodies.	The movement must be slow enough to ensure compliance with requirement 18. The queen excluder must have three states: fully closed to seal the selected beehive bodies from the colony, open for both the queen and worker bees, and open only for worker bees.
14.	Functional	Phase I; **Crucial**. Applying oxalic acid vapor as a pest treatment for selected beehive(s).	IP68 for oxalic acid storage.
15.	Functional	Phase I; **Crucial**. The magnetic tag must be attached to the queen.	The cylindrical shape should have a diameter no greater than 3 mm and a mass no greater than 12 mg.
16.	Functional	Phase II; **Crucial**. The robot must measure CO_2 levels in beehive [22].	Quality will be determined in the next iterations.
17.	Functional	Phase II; **Crucial.** The robot must measure the amount of food in beehive.	Quality will be determined in the next iterations.
18.	Safety	Phase I; **Crucial**. The robot must ensure the safety of the queen in any possible action.	Queen must not die.
19.	Safety	Phase I; **Crucial**. When performing measurements and mechanical actions, the death of worker bees must be prevented.	Worker bee losses must be zero during winter. In summer, losses of up to 500 bees per week are considered acceptable.

20.	Safety	Phase I; **Crucial**. The entrance of the beehive must be completely closeable.	Serves security and follows requirement 7. Will be determined in the next iterations.
21.	Safety	Phase I; Secondary. Young honeybees that have not yet begun to fly must be kept safely inside the beehive. If they fall from the frame during visual inspection, they must be guided back into the hive.	Follows requirement 19.
22.	Safety	Phase I; **Crucial**. Electric shock and mechanical injuries must be prevented during robot maintenance to protect the technician.	It must be possible to manually switch off power.
23.	Safety	Phase II; **Crucial**. Beehive bodies must be either replaceable or easy to clean on-site, or the robot must include an onboard cleaning function.	Frames must withstand temperatures up to 100 °C or allow for chemical cleaning.
24.	Structural	Phase I; **Crucial**. If magnetic tag is attached to queen, frames and beehive bodies must not include ferromagnetic materials.	If ferromagnetic materials are still used, those must be inside construction far enough from the queen not to cause any harm.
25.	Structural	Phase I; **Crucial**. The honey storage compartment and sensitive electronics compartment must be sealed off from worker bees and other insects and moisture.	IP65 should be used for the compartment in general. If ventilation holes are used, filters that prevent insects from entering the honey compartment must be implemented.
26.	Electronic	Phase I; **Crucial**. Magnetic sensors must be implemented in the smart frames to detect the magnetic tag attached to the queen.	Follows requirement 15. Detection distance should be at least 4,5 mm.
27.	Electronic	Phase I; **Crucial**. The smart frames must operate as a hard real-time system for detection of magnetic tag [107].	Measurement frequency at least 10 Hz to ensure successful detection when the queen moves from one frame to another.
28.	Communication	Phase I; **Crucial**. Smart frames must report the queen's movement between frames as hard real-time system to hive controller.	There are two possible messages: 'Queen moved out' and 'Queen moved in.
29.	Communication	Phase I; **Crucial**. The hive controller must report the queen's up-to-date localization to the main controller of the robotic beehive.	Quality will be determined in the first iteration.
30.	Communication	Phase III; Secondary. Communication with the robotic beehive is established via wired internet, GSM connection, or satellite internet.	Slow internet for simple messages resulting from the automatic inspections of the beehive. Fast for real-time frame images evaluation and calibrations.
31.	Data handling	Phase I; **Crucial**. The hive controller must scan multiple smart frames to calculate the queen's movement.	Follows requirement 28. When the queen passes the sensors between two frames, those frames report queens movement. The reports must be compared to confirm the queen's movement.
32.	Data handling	Phase I; **Crucial**. Smart frames must calculate the queen's movement direction and store it in non-volatile memory.	Quality will be determined in the first iteration.
33.	Data handling	Phase I; **Crucial**. The hive controller must keep the queen's localization up to date in non-volatile memory.	Quality will be determined in the first iteration.
34.	Data handling	Phase I; **Crucial**. Images captured from smart frames must be stored in the robotic beehive and/or in the user's local system.	All raw images from each frame cycle must be stored to enable pattern analysis.
35.	Data handling	Phase I; **Crucial**. Smart frames and beehives must have unique IDs to track colony health and honey yield.	Quality will be determined in the first iteration.
36.	Power system	Phase I; **Crucial**. 230 V AC as power source.	Quality will be determined in the next iterations.

37.	Power system	Phase IV; Secondary. Solar panels as power source option.	Quality will be determined in the next iterations.
38.	User interface	Phase I; **Crucial**. Death of the queen must be reported to user.	Estimated time of death.
39.	User interface	Phase II; **Crucial**. Possibility to select between fully automated mode and semi-automated mode	Browser based GUI.
40.	User interface	Phase I; **Crucial**. The system must allow configuration of values for the following settings: changes in egg-laying intensity; patterns of capped brood, empty cells, and honey cells; the number of *Varroa destructor* mites on honeybees or removeable bottom board; temperature; humidity; and the number of honeybees entering and exiting the colony.	Quality will be determined in the first iterations.
41.	User interface	Phase I; **Crucial**. Adjusting the size of the beehive entrance based on external and internal temperature, humidity, season, or through manual control.	Follows requirement 20. Quality will be determined in the next iterations.
42.	User interface	Phase I; **Crucial**. Adjusting the heating system and active ventilation based on defined temperature and humidity ranges.	Follows requirement 7. Quality will be determined in the next iterations.
43.	User interface	Phase I; **Crucial**. Planning automatic chemical treatment for *Varroa destructor* based on manually selected colonies or the number of *Varroa destructor* mites detected on frames or bottom boards.	Follows requirement 14. Quality will be determined in the next iterations.
44.	User interface	Phase I; **Crucial**. Training the computer vision algorithm by visually labelling the following parameters on captured frame images: eggs, larvae, capped brood, empty cells, *Varroa destructor* on honeybees, burr comb, pollen, nectar, supersedure cells, swarm cells, and capped honey.	Follows requirement 1. Quality will be determined in the first iteration.
45.	User interface	Phase II; **Crucial**. Adjusting mechanical actions such as returning the frame to its original slot, swapping it with another frame in the same or a different beehive body, guiding honeybees back to the colony, or moving the frame to the honey storage compartment, based on the following parameters: presence of eggs, larvae, capped brood, empty cells, and capped honey.	Follows requirements 1, 2, 10 and 11. Quality will be determined in the next iterations.
46.	User interface	Phase I; **Crucial**. Remotely inspecting and moving the frames.	Follows requirements 1, 2, 10 and 11. Quality will be determined in the next iterations.
47.	User interface	Phase I; **Crucial**. Viewing the following alarms and notifications: duration of queen not being detected, maintenance alerts, and changes or triggers in all visual parameters on beehive frames.	Follows requirements 1 and 18. Quality will be determined in the next iterations.
48.	User interface	Phase II; Secondary. Viewing the history of frame or bottom board images, filtered by colony, beehive body, or frame.	Follows requirement 1. Switching from one image to another should be faster than 0,5 seconds.
49.	User interface	Phase III; Potential. Viewing the following beekeeping information: number of flights in and out of beehive, estimated number of honeybees, and *Varroa destructor* infection rate.	Quality will be determined in the next iterations.
50.	User interface	Phase III; Secondary. Viewing the following system statuses: health of the main batteries and smart frame batteries, precision of the computer vision system, and the number of frames in the honey compartment.	Quality will be determined in the next iterations.
51.	User interface	Phase III; **Crucial**. Adjusting the timing and interval of automatic visual inspections of frames.	Two main selections: frames with honeybees and frames without honeybees.
52.	User interface	Phase IV; Secondary. View a comparison of different robotic beehives.	Quality will be determined in the next iterations.

6.3. Critical technologies

Analysis of the procedures in beehives conducted by the case study partner for honey production led to two critical functionalities that must be further studied and developed when automating the beehive. The first functionality is the localization of the queen. When the robot moves the frame out of the beehive, following requirement 18 is crucial. Once the queen is localised, the frames can be manipulated safely.

The second critical functionality is mimicking the beekeepers' visual inspection using computer vision, namely capturing digital images from frames and analysing parameters that can then be translated into actions. In this thesis, the detection of *Varroa destructor* as one of these parameters was tested as a proof of concept.

These two functions together define a minimum viable automation layer that must be in place before more complex decision logic or autonomous control can be implemented.

6.4. Design and development of the first iteration of a robotic beehive

The queen's health, together with the colony's overall condition, remains a top priority for the case study partner, as established in earlier chapters. The analysis of existing robotic beehive concepts, combined with the observation that the case study partner does not measure any parameters within the beehive leads to the decision that multiple iterations are needed before full automation and system optimisation can be achieved. Before the full automation of the beehive, parameters, related patterns, and inter-parameter relations must be measured and documented. In parallel, it must be studied to what extent changes in parameters or related patterns reflect trends in the beehive colony. In the first development phase, the priority is to test frame movement mechanisms, temperature and humidity control, and the graphical user interface, which will allow users to calibrate AI-based visual and other inspection systems. Not all the requirements defined in Table 5 will be fulfilled in the first iteration; some will be considered in future development phases. The following description of the concept of the robotic beehive begins with a detailed description of the smart frame and then provides a more general overview of the architectural aspects of the proposed concept.

It was decided that in the first iterations, the use of a magnetic tag for queen localisation and monitoring should be tested due to its potential efficiency. The tag is attached to the queen and tracked using smart frames. Proposed smart frames are designed in a way that they detect the queen's movement direction when entering or leaving the gap between two frames, regardless of her body orientation or the angle of her movement relative to the sensor array. The advantages of this tagging technology include low energy consumption and low electromagnetic radiation. Based on the permanent magnet experiment conducted in this thesis, it is considered likely that the magnetic tag on the queen bee would not affect honeybee behaviour. However, there are limitations: ferromagnetic materials must be avoided inside the beehive bodies, and the system cannot pinpoint the queen's exact location with single-frame accuracy, as her position may fall between two frames or between a frame and the beehive wall. To illustrate the smart frame idea, an initial design model was created.

Figure 12 presents the mechanical model of the smart frame, where Nr. 1 mark the frame base for honeybees to build the comb. Nr. 2 indicates the frame controller housing for the controller, and Nr. 3 marks the housing cover, which is also used by the frame inspection and manipulation system to slide the smart frame out of the beehive and push it back in. Nr. 4 indicates the controller of the smart frame, while Nr. 5 shows the 146 magnetic sensors on each side of the smart frame, detecting the movement of the tagged queen.

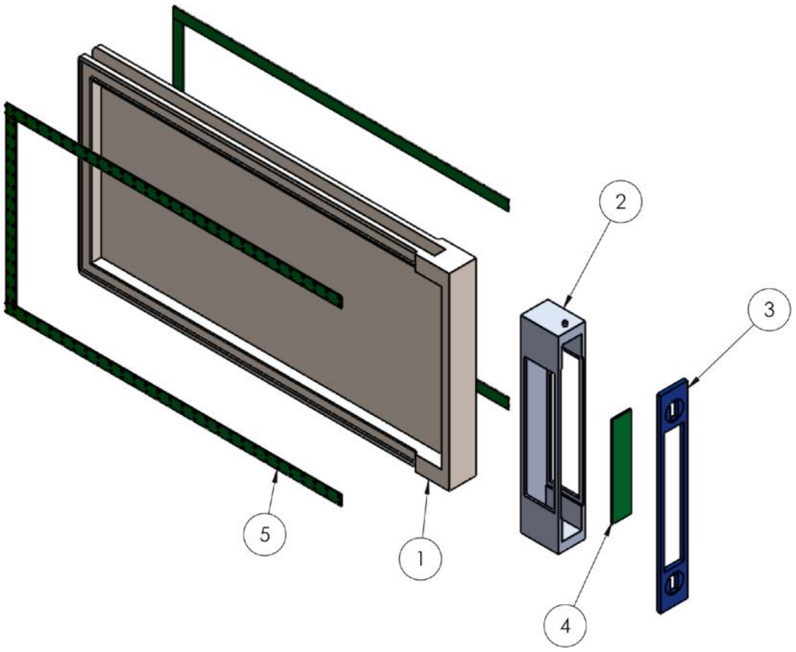

Figure 12. Mechanical concept of smart frame

In the proposed concept for the robotic beehive, there are 11 beehives, each housing 30 smart frames, making a total of 330 smart frames. Smart frame houses for example AFL006-10E magnetic sensors sensitive enough to detect the magnetic tag in 4 to 9 mm distance [108]. Measurement frequency of magnetic sensors must be at least 10 Hz to detect the queen and transfer her movement as hard real-time system. AFL006-10E consumes typically of current 0,063 mW (35μA at 1.8V) of power when operating which sums up to 18.4 mW as smart frame has 292 magnetic sensors combined. Each smart frame also has 1 to 2 digital temperature sensors [3], which measure temperature once per hour, making the power consumption negligible [109]. The same applies to the microcontroller, which operates in 32,768 kHz active mode, consuming 6,3 μW of power [110]. It can be estimated that a beehive housing 30 smart frames consumes roughly 0,5 W of power when taking measurements. In addition, each smart frame has a 1 W resistor for heating purposes during the winter, resulting in a total power consumption of 30 W for one beehive and 330 W for 11 beehives when heating of all frames is switched on (Power value is initial and must be tested).

Smart frames transmit/recieve the following data: unique ID (read only), address (including beehive ID and the address inside the beehive), direction of the queen's movement, temperature reading (read only), and heating element status (ON or OFF). When smart frames are relocated within a beehive body or moved to another beehive, the address is changed accordingly and stored in the smart frame non-volatile memory. If a smart frame is moved from the beehive to the honey storage compartment, the address of the beehive from which it was taken is stored in the smart frames non-volatile memory. Smart frames are electrically connected to the beehive for a 1.8 V power supply and wired communication.

Figure 13 illustrates the simplified components, along with the proposed interfaces for connection. All 30 smart frames in one beehive are simultaneously electrically connected to the same I2C line. When a smart frame wants to report the queen's movement, it grounds the interrupt line through a resistor. The smart frames function as slaves, while the beehive controller scans the line at a frequency of 3 to 5 Hz. When the queen passes the sensor lines between two smart frames, both frames will report. The hive controller listens for the reports and stores the queen's current location in its non-volatile memory. If the main controller of the robotic beehive wants to perform a frame inspection or move frames, it requests the queen's location from the hive controller. Based on this information, only those frames are moved where the queen is confirmed not to be present. The proposed smart frame system has a 'blind spot,' meaning that if the queen is moving on top of the smart frames (between two beehive bodies for instance), the last report from the smart frames will indicate that the queen has moved out. When the queen moves between two smart frames again, she will be detected and located, respectively. This status can be referred to as 'unlocated'. If the unlocated status persists for too long, it must be reported and investigated. However, further research is needed regarding queen localization.

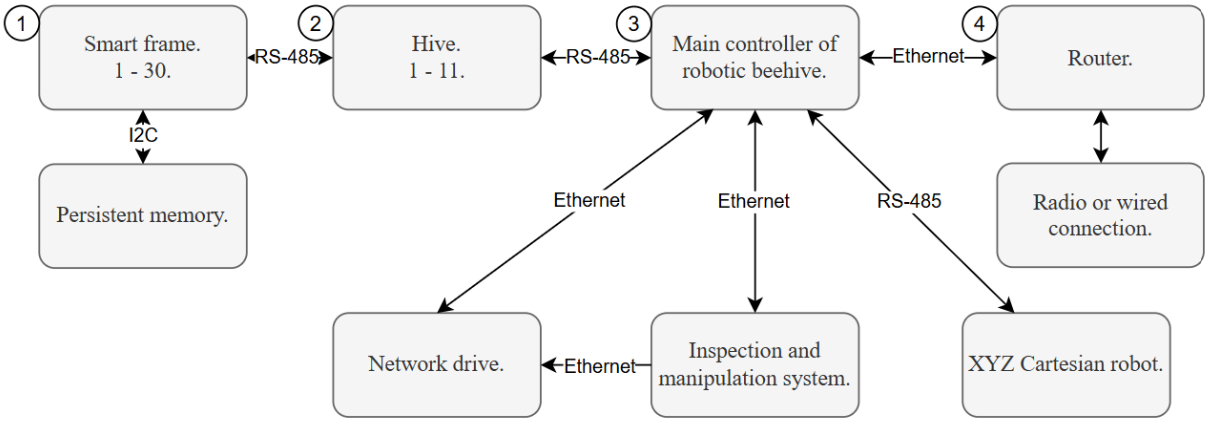

Figure 13. Data flow overview of robotic beehive

The first phase in further developments is envisioned to utilize a 6 m shipping container to store the robotic beehive and protect it against weather conditions. In the first development phase it should be tested how multiple beehives can perform in close distance to each other. In addition, the container provides space for humans to operate inside.

Figure 14 illustrates the mechanical part of the robotic beehive concept. **Nr. 1** represents one beehive out of the total 11 beehives, each housing 30 smart frames, as indicated by **nr. 2.** Each beehive has a hive entrance and queen excluder, which can be opened or closed via the hive controller. The hives also have holes for ventilation and a removable bottom board mechanism. **Nr. 3** is the honey storage compartment, which is also used to store empty smart frames or smart frames containing bee bread. **Nr. 4** is the frame inspection and manipulation system, which removes smart frames from the beehive bodies, performs imaging, and then puts them back into the initial slot or relocates them inside the beehive robot. **Nr. 5** is the XYZ Cartesian robot system, which moves the frame inspection and manipulation system within the beehive robot. To locate the correct smart frame and retrieve it precisely, belt drives, linear drives and ball screw drives are used. **Nr. 6** is the panel, which houses the main controller of the robotic beehive, the power supply (including batteries if solar panels are used), network storage for images, and the communication systems. **Nr. 7** illustrates the ventilation system. Air conditioner use is needed based on updated requirements after the first iteration. **Nr. 8** is a standard 6-meter shipping container for effective testing, development, and transportation. Appendix D provides a more detailed view of the mechanical models.

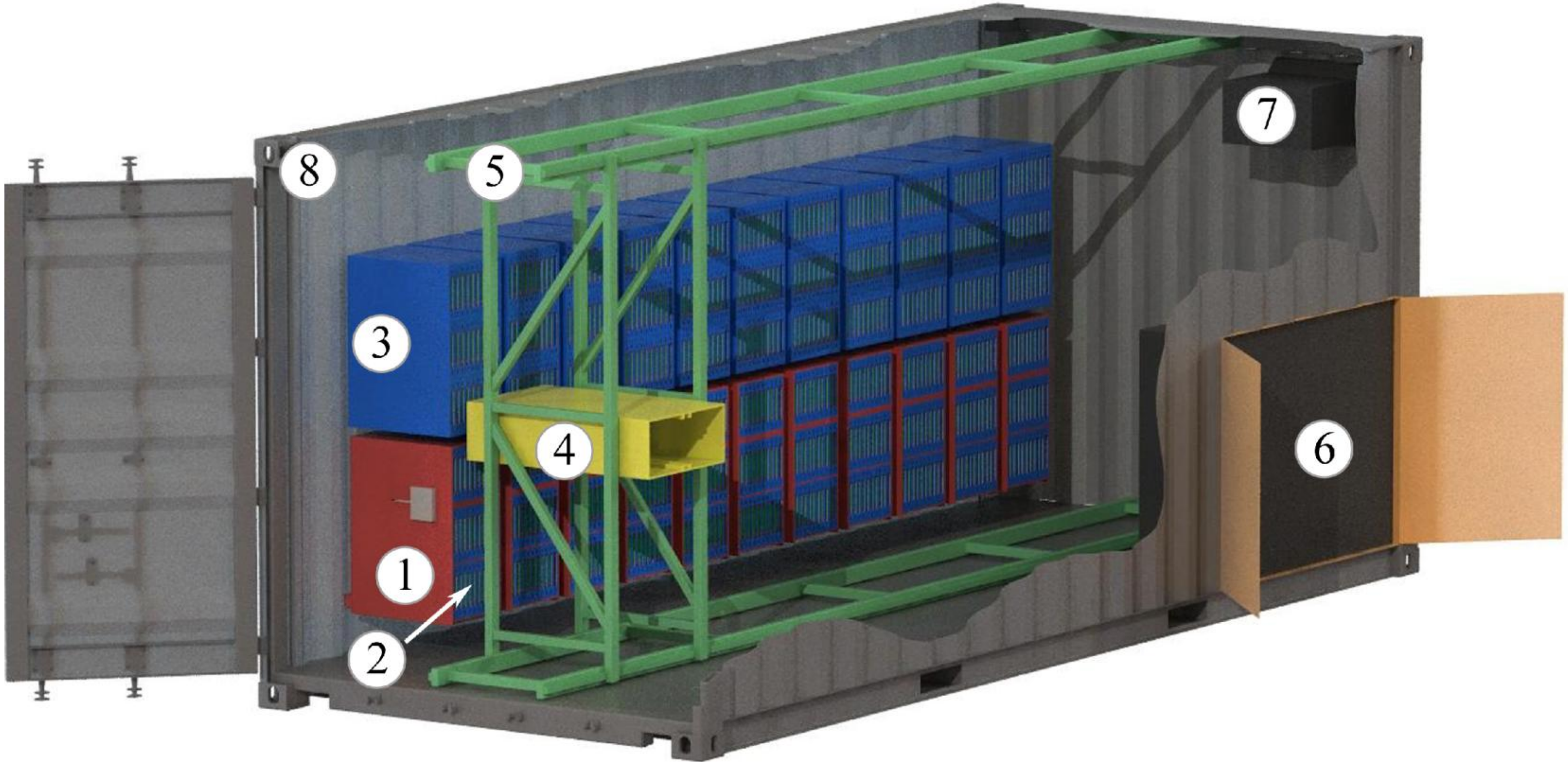

Figure 14. Mechanical concept of the first iteration of the robotic beehive

7. Discussion

This subchapter covers activity No. 10 from Table 3, which discusses the conducted work and results, along with recommendations for future development and research. This discussion reflects on the main findings derived from practical fieldwork, image analysis, and collaboration with the case study partner. While experienced beekeeping relies on intuitive decision-making, automation poses a fundamentally different set of challenges that demand systematised measurements and engineering solutions.

Although experienced beekeeping may seem straightforward, this is largely due to the beekeeper's ability to intuitively respond to hive dynamics. Honeybees often compensate for minor errors, masking the biological complexity behind effective hive management. Automating this process requires translating intuitive practices into measurable parameters and structured system logic, supported by both qualitative and quantitative data.

Fieldwork, including observation, interviews, and collaboration with the case study partner, revealed that successful automation relies on close cooperation between beekeepers and engineers to define requirements and adapt solutions to real-world practice.

In this thesis, qualitative research methods proved especially effective and are recommended for early stages of automation, where key parameters and decision processes must first be understood through human interaction and contextual insight. A particularly significant finding was that the professional beekeeper does not rely on any formal measurements when making management decisions. Instead, all actions are guided by visual assessment and experience-based interpretation of hive conditions.

This presents a core challenge for automation: beekeeping decisions often stem not from objective sensor data, but from pattern recognition, behavioural cues, and intuitive judgement. Consequently, future robotic hives must go beyond basic measurement and evolve toward interpreting complex, dynamic conditions in a way that emulates human expertise. Designing such systems will require integrating both quantitative data and qualitative context into the automation logic.

Like the case study partner Artocarpus OÜ, this thesis focuses on honey production. Other aspects of beekeeping, such as the pollination business and queen rearing, are not covered in this thesis. The most advanced project aiming for full beehive automation, found during this thesis, focuses on the pollination business, highlighting the importance of automation. The case study partner contacted the company Beewise but did not receive a reply. This might suggest that the company is still in the development phase.

While a thorough financial analysis would be needed, it is out of the scope of this thesis and would be left for future iterations. Initial development will be rather expensive, but once ready, the robotic beehives could help honey production companies scale up and grow the market.

In parallel with the development of the robotic beehive concept introduced in this thesis, it is recommended to leverage valuable data from existing developments, to open two new business lines in the pollination and queen rearing sectors.

The staged development phases defined in subsection 6.2 provide a roadmap for implementing robotic features progressively, which is necessary given the interdisciplinary and evolving nature of beekeeping. In the first iterations, it is recommended to develop systems for *Varroa destructor* treatment using oxalic acid. Additionally, this thesis does not propose systems for managing supersedure cells, which are important for the prevention of swarming. A specific mechanism or energy-based manipulation should be developed to manage supersedure cells.

This thesis proposes magnetic tag technology for the localisation and monitoring of the queen, measured by smart frames, which are very efficient in terms of power consumption. A small experiment was conducted with a strong permanent magnet at the entrance of the beehive, which supports the idea that the magnetic field might not be harmful to honeybees. However, both this thesis and other experiments remain inconclusive, and further research is recommended.

The following experiments are proposed as part of the robotic beehive in the first iterations.

- How to make calculated decisions based on the visual inspection of frames.
- Effect of magnetic field on honeybees.
- The maximum mass of the tag that the queen can carry without affecting her activities.
- Varroa mite treatment using temperature changes.
- Making decisions and taking actions based on measurements of sound and/or temperature patterns.

At the time of writing this thesis, the patents and marketing documents of Beewise appeared promising, although the actual functionality of their robotic beehive remained unclear. Based on the analysis of the theoretical background of beekeeping, the previously mentioned robotics company, as well as the conducted case study, participant observation and experiments, it was concluded that automating the beehive is a challenging but relevant vision. It was concluded that, based on the analysis of Beewise and the conducted case study, temperature control, frame inspection (using computer vision), and mechanisms for frame manipulation are the minimum required functions of a robotic beehive. Additionally, the case study partner prioritises honey production, whereas Beewise focuses on the pollination business. Based on participant observation and interview, it is also important to evaluate or measure the queen’s location to prevent her from being injured during the physical movement of frames. In addition, automation of the beehive brings possibilities to conduct procedures around the clock, increasing the scalability of beekeeping compared to human labour.

In conclusion, this thesis has shown that while traditional beekeeping relies heavily on visual and experience-based decision-making, the automation of beehive management requires a rethinking of how such intuitive processes can be automated through measurement of parameters. The absence of measured parameters in the case study partner's workflow reveals that automation cannot merely replicate manual data collection but must interpret patterns in a way that reflects expert intuition. This insight significantly shapes the direction of future development phases. Robotic beehives must therefore be designed not only to collect data but to reason with it meaningfully. Early collaboration of beekeepers and engineers is crucial. The findings in this thesis offer a foundation for building such reasoning through a combination of image-based pattern recognition, qualitative parameter mapping, and collaborative design with beekeepers.

8. Summary

This thesis explores the research questions:

- Which parameters in the beehive are inspected by beekeepers to make decisions?
- How to automate the beehive based on the studied parameters and decisions?

This thesis investigates the potential for automating beehive management through the development of a robotic beehive concept, with an emphasis on real-world practicality. The research focused on two main questions: Which parameters do beekeepers monitor to make decisions? How can these be automated within a functional system?

A case study approach was used in collaboration with a professional Estonian beekeeper. Methods included participant observation, a semi-structured interview, field imaging of over 3000 Langstroth frames, and YOLO-based computer vision testing for *Varroa destructor* detection. A prototype concept of a robotic beehive, including smart frames capable of tracking the queen bee, was also proposed.

Key findings highlight that while some beekeeping actions are based on measurable parameters (e.g., brood pattern, *Varroa* count), many are driven by experience and qualitative evaluation. The study successfully mapped key decisions and the production flow within the beehive. The results show that computer vision demonstrates promising accuracy in detecting *Varroa destructor*. The use of embedded magnet-based queen tracking with a magnetic tag warrants further study and development trials. However, further experiments must be conducted to ensure that the magnetic tag does not have any negative effects on the queen or honeybees in general.

Notably, the case study revealed that the professional beekeeper, despite long-term success and a high level of skill, does not rely on formal measurements when making decisions. Instead, actions are based on qualitative evaluations of parameters, experience, and visual cues. This finding underscores a critical challenge in automating beehive management: successful decision-making in practice often depends on tacit knowledge rather than quantified parameters, making observational research essential in designing automated beehive.

The thesis proposes a modular robotic hive design that automates inspection, parameter tracking, and frame handling. A staged control system is presented, based on conditional logic for internal hive actions. Although financial analysis and extensive biological validation were not within scope, the concept lays the groundwork for future development.

Recommendations for future work include refining magnetic tag design and safety, validating sensor arrays under varying conditions, integrating automated oxalic acid treatment, and expanding the model to cover other beekeeping business lines such as pollination and queen rearing.

This work contributes a practical, multidisciplinary foundation for automating apiary management and highlights the importance of blending observational data with system design in early-stage development. The requirements mapped in this thesis provide a foundation for scalable and testable development.

In conclusion, future research should continue focusing on measurable parameters and their patterns, alongside financial analysis to support commercialisation. During the early development phases of robotic beehives, close collaboration between beekeepers and engineers is essential.

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Appendixes

Appendix A – Interview questions for semi-structured interview

Research question	ID of interview question	Interview question
Which parameters in beehive are assessed by beekeepers to make decisions?	1	What factors do you consider when making decisions in the beehive?
	2	To what extent do you rely on your sense of sight when making decisions in the beehive?
	3	To what extent do you rely on your sense of hearing or smell when making decisions in the beehive?
	4	List all the parameters you assess in the beehive when making decisions and acting (If the case study partner does not mention the parameters outlined in the theoretical overview of beekeeping in subchapter 2.2, the missing parameters must be discussed).
	5	Based on which parameters do you evaluate the queen's health?
	6	List all the possible actions you make in the beehive.
How to automate the beehive based on the studied parameters and decisions?	7	How do you monitor *Varroa destructor* and other pests in beehive?
	8	How do weather conditions affect your activities in the apiary?
	9	How do you monitor the food resources in the beehive?
	10	How do you monitor swarming?
	11	How do you decide when to requeen?
	12	How do you evaluate the adequacy of honey and pollen stores within the hive?
	13	How do you decide when to add or remove hive bodies?
	14	How do you decide when to add, remove, or reposition frames?
	15	How do you decide when to add or remove the queen excluder?
	16	Describe the maintenance of the beehive and its components.
	17	Explain how you keep records of your beehives.
	18	How do you use records to make decisions?

	19	Describe any unique procedures and routines you have implemented into your practice.
	20	Describe how you detect and remove burr comb.
	21	Describe how you harvest pollen.
	22	How do you monitor supersedure cells, and what steps do you take to manage them?
	23	With the above discussion in mind, let's now map out the specific procedures you perform in direct contact with the honeybees and beehives each month throughout the season. All assessed parameters, decisions made, and actions taken should be discussed in detail for each corresponding month.
	24	Imagine you remove a frame from the beehive body very slowly, maintaining a constant speed, and then return it to the beehive body in the same manner, taking 60 seconds for each cycle. How do you think this process affects the honeybees?
	25	Imagine a situation where two frames are stuck together by propolis and wax. The technology implemented into the frames heats the contact surfaces between the two frames, for example, to 70°C over a period of 5 seconds. How do you think this may affect the honeybees?
What requirements must a robotic beehive meet?	26	Now that we have mapped all the parameters you assess on frames, let's review 32 digital images and precisely mark each parameter. Additionally, let's take notes on quality aspects such as colours, patterns, etc.
	27	Evaluate the shape and surface area of the frames. Assess the risks and possibilities of changing the frame's surface area or aspect ratio. (To aid evaluation, visual geometric examples should be presented to the case study partner.)
	28	How important do you think stable temperature and humidity are for honeybees?
	29	How do you ensure the safety of the bees when harvesting honey?
	30	How do you ensure the bees' safety when relocating frames?
	31	How do you ensure safety of the queen when relocating frames?
	32	Estimate how many bees can be lost during each inspection while keeping the hive sustainable. Are there seasonal differences?

	33	How long do you think it takes to inspect a beehive? Also, evaluate how long a beehive can remain open while still maintaining its sustainability.
	34	How long do you think it takes to remove a stuck frame from the beehive body?
	35	Under what conditions do you avoid opening a beehive?
	36	How often do you think it is acceptable to open a beehive for inspection?
	37	Why are frames made of wood, and what other materials could be used in their construction?
	38	What effects have you observed on bees from cell phones or other technologies, such as transmission lines, transformers, solar panels, or wind turbines?
	39	What methods or technologies do you think could be used to enhance honey yield?
	40	How do you think it affects honeybees when the distance between frames is increased to 50 mm or decreased to 9 mm?
	41	How many beehives can you manage?
	42	How often do you replace frames? How to decide?
	43	Describe the ideal beekeeper. What are their key capabilities?

Appendix B – Images of beekeeping

Figure B1. Supersedure cells, swarm cells, drone cells and empty cells

Figure B2. Tagged queens

Figure B3. Moldy comb

Appendix C – YOLO testing

Labelling and model training for the detection of Varroa destructor was performed in Ubuntu Linux. The source code for training the YOLO model is stored in Github together with the following components:

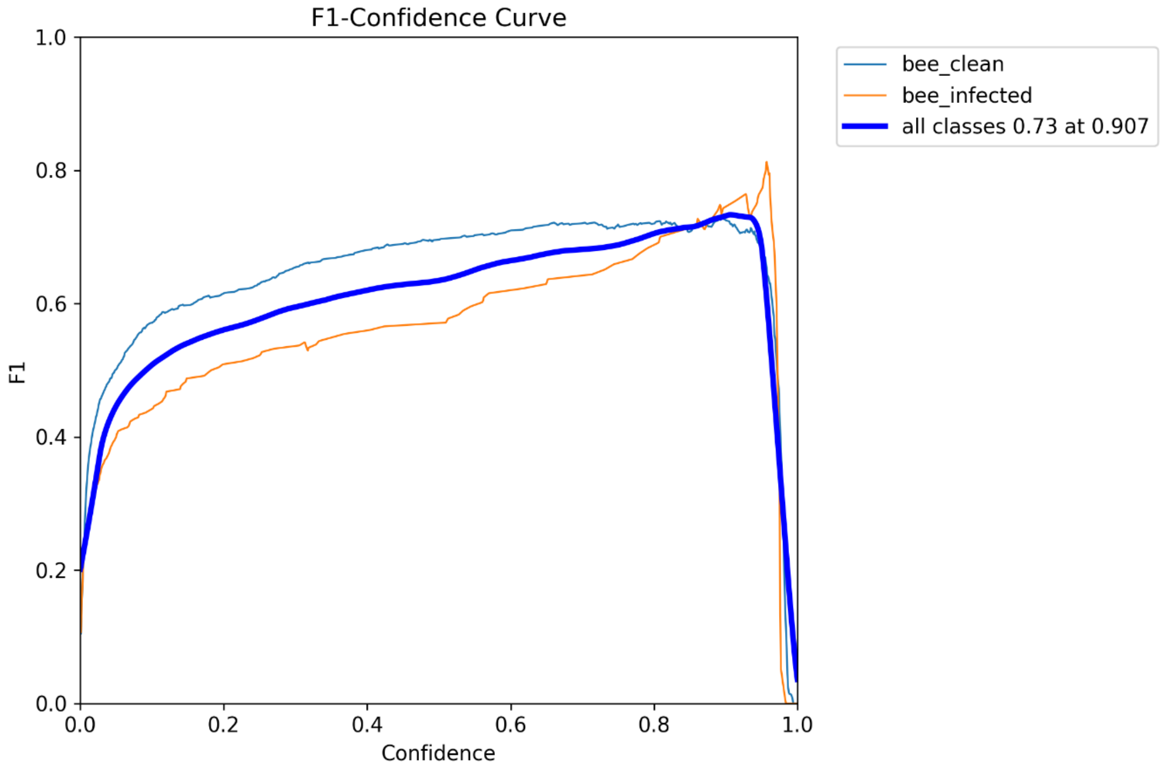
- environment.yml – Conda environment defining Python packages for running the code.
- run_labeller.sh – Script for starting Label Studio.
- train_data.yaml – Defines data sets for training, validation and testing.
- varroa_detector.py – Python code for training and evaluation of the model.
- datasets/mesilastaru_yolo – Placeholders for directory tree of training and validation data. Labelled images are not stored in Github due to their large size.

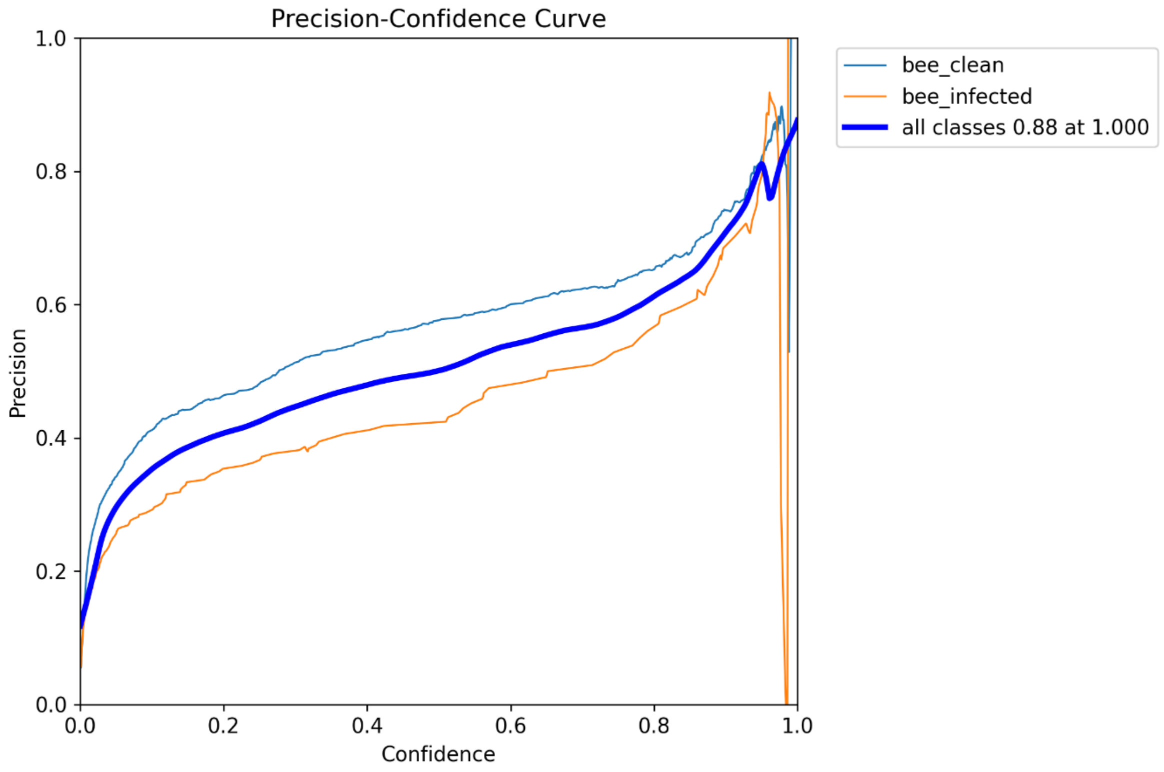
Link of Github repository: https://github.com/mihkel-valjaots/mesilastaru_yolo

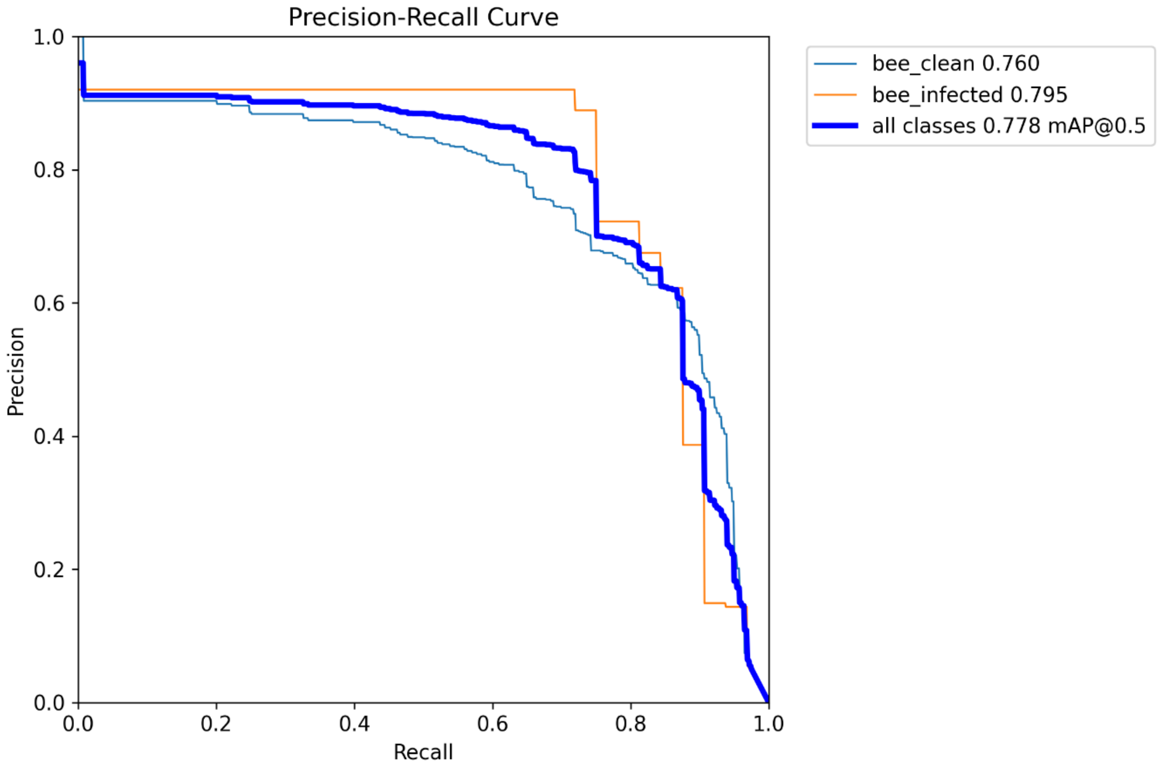
The following code was used for YOLO implementation and testing:

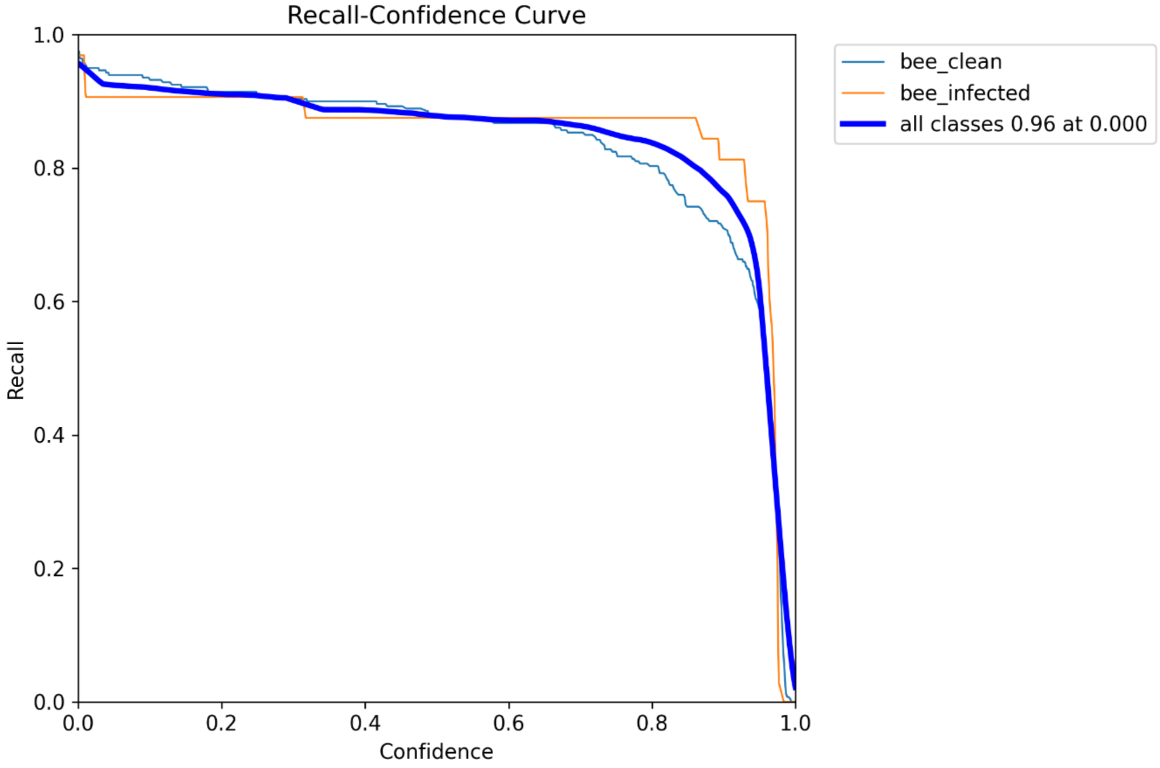
```
from ultralytics import YOLO

model = YOLO("yolo11x.pt")

results = model.train(data="train_data.yaml", epochs=200)
```

The following figures present the YOLO model evaluation results on testing dataset.



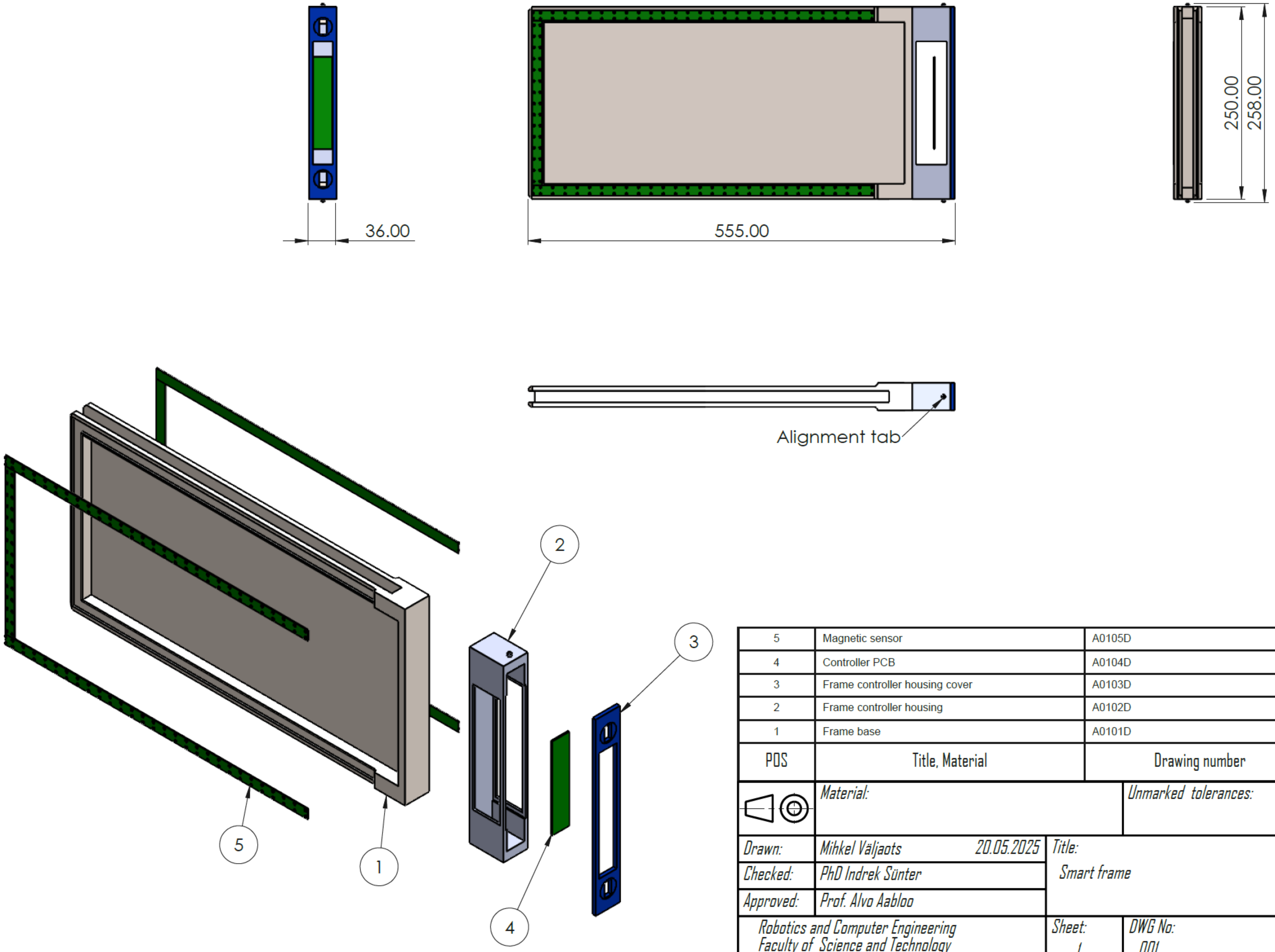



Precision-Recall Curve
Precision
Recall
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
bee_clean 0.760
bee_infected 0.795
all classes 0.778 mAP@0.5


Recall-Confidence Curve
Recall
Confidence
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
bee_clean
bee_infected
all classes 0.96 at 0.000

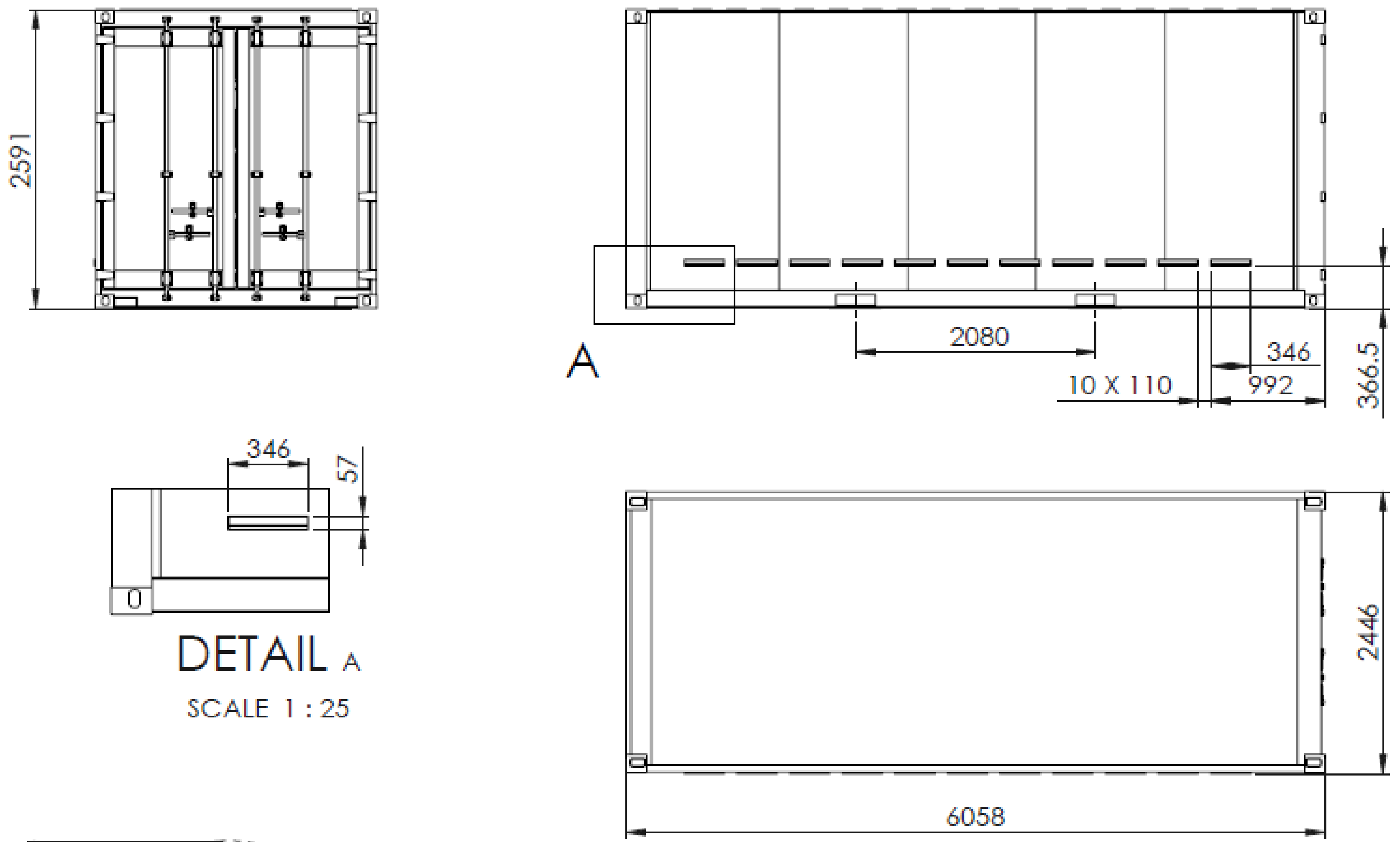
Appendix D – Technical drawings of the proposed concept for the robotic beehive

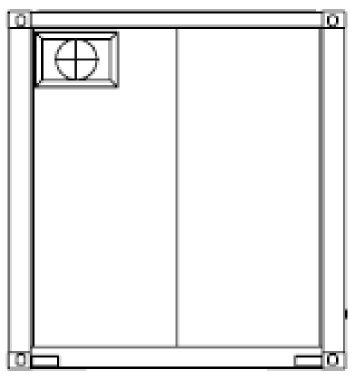
The following drawings illustrate the smart frame and the general concept of the robotic beehive. Drawings are shown on next three pages.

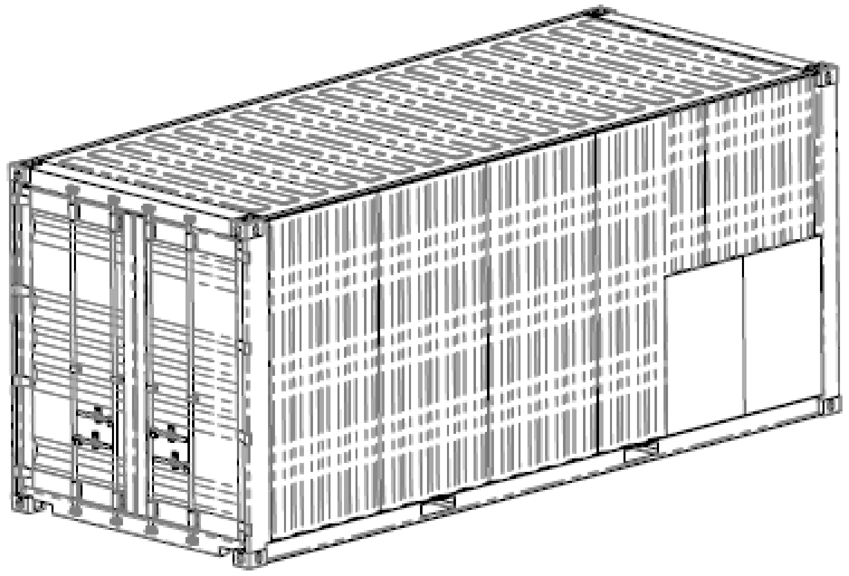


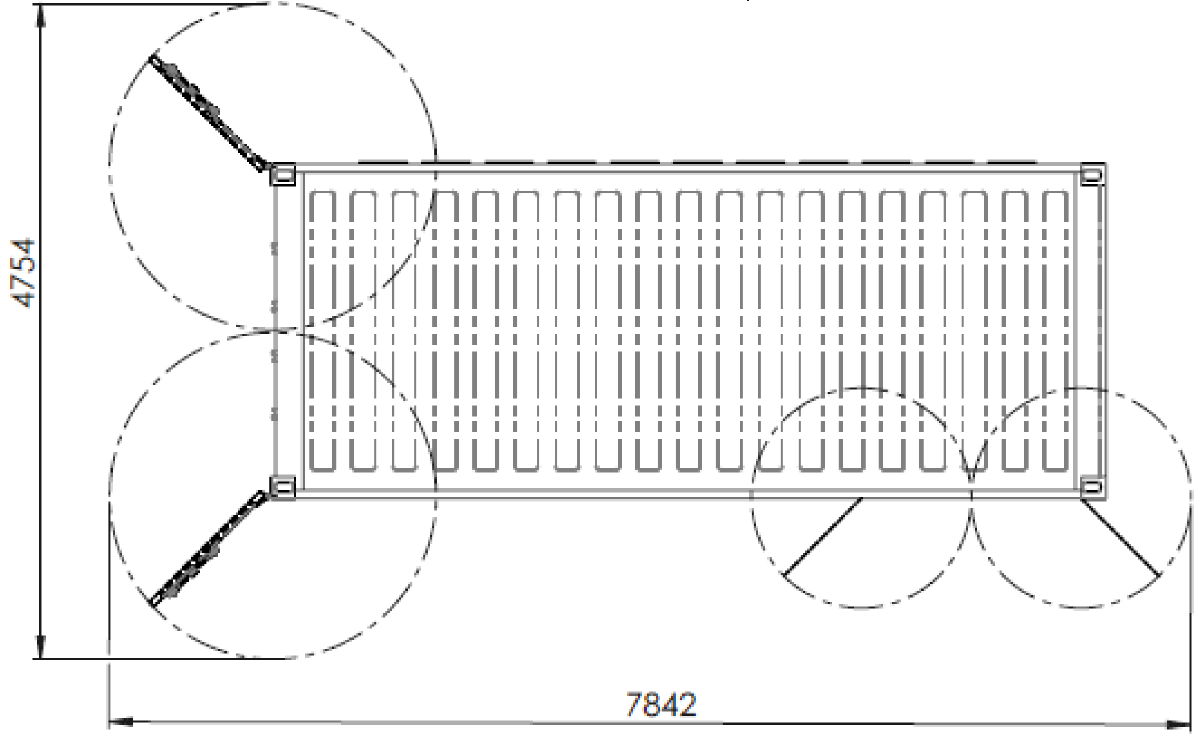
POS	Title, Material	Drawing number	QTY	Comment
5	Magnetic sensor	A0105D	2	
4	Controller PCB	A0104D	1	
3	Frame controller housing cover	A0103D	1	
2	Frame controller housing	A0102D	1	
1	Frame base	A0101D	1	

Material:
Unmarked tolerances:
Mass: 4.28 Kg
Scale: 1:5
Drawn: Mihkel Väljaots 20.05.2025
Checked: PhD Indrek Sünter
Approved: Prof. Alvo Aabloo
Title: Smart frame
File name: Smart frame
Robotics and Computer Engineering
Faculty of Science and Technology
University of Tartu
Sheet: 1
DWG No: 001
Format: A3

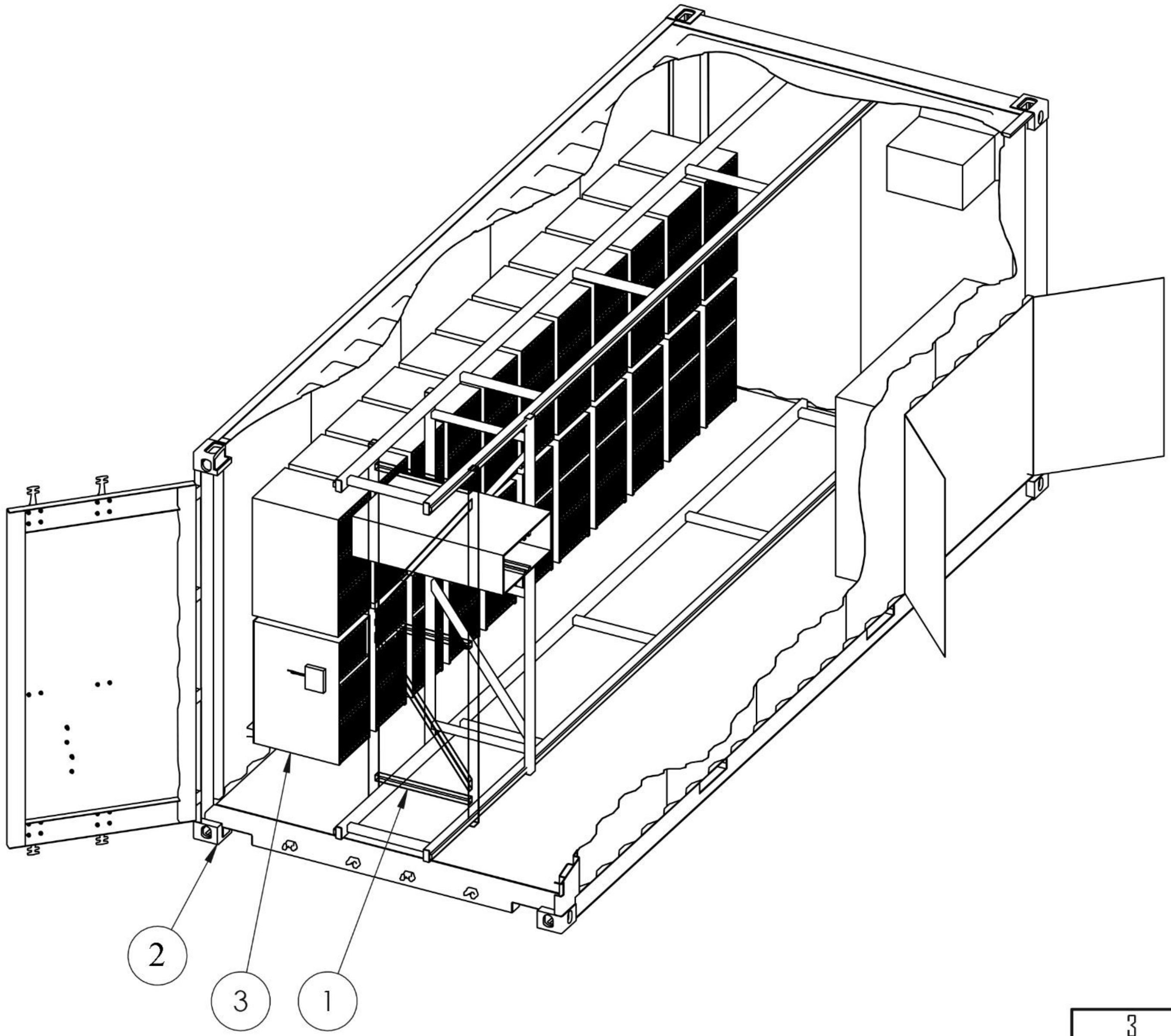








	Material:		Unmarked tolerances:	Mass:
Drawn:	Mihkel Väljaots 20.05.2025	Title: Automated beehive	Scale: 1:50	File name: Main Asm
Checked:	PhD Indrek Sünter			
Approved:	Prof. Alvo Aabloo			
Robotics and Computer Engineering Faculty of Science and Technology University of Tartu		Sheet: 1	DWG No: K00	Format: A3



3	Beehive - Storage		1	
2	Container		1	
1	Cartesian Robot		1	
POS	Title, Material	Drawing number	QTY.	Comment

Material:

Unmarked tolerances:

Mass:

Scale: *1:35*

Drawn: *Mihkel Väljaots* *20.05.2025*
Checked: *PhD Indrek Sünter*
Approved: *Prof. Alvo Aabloo*

Title: *Automated beehive*

File name: *Main Asm*

Robotics and Computer Engineering
Faculty of Science and Technology
University of Tartu

Sheet: *2*

DWG No: *K00*

Format: *A3*

Appendix E – Frame movement illustration

Figure 1. Mechanism starts movement in the middle of the robotic beehive

Figure 2. Mechanism has arrived and aligned to first beehive

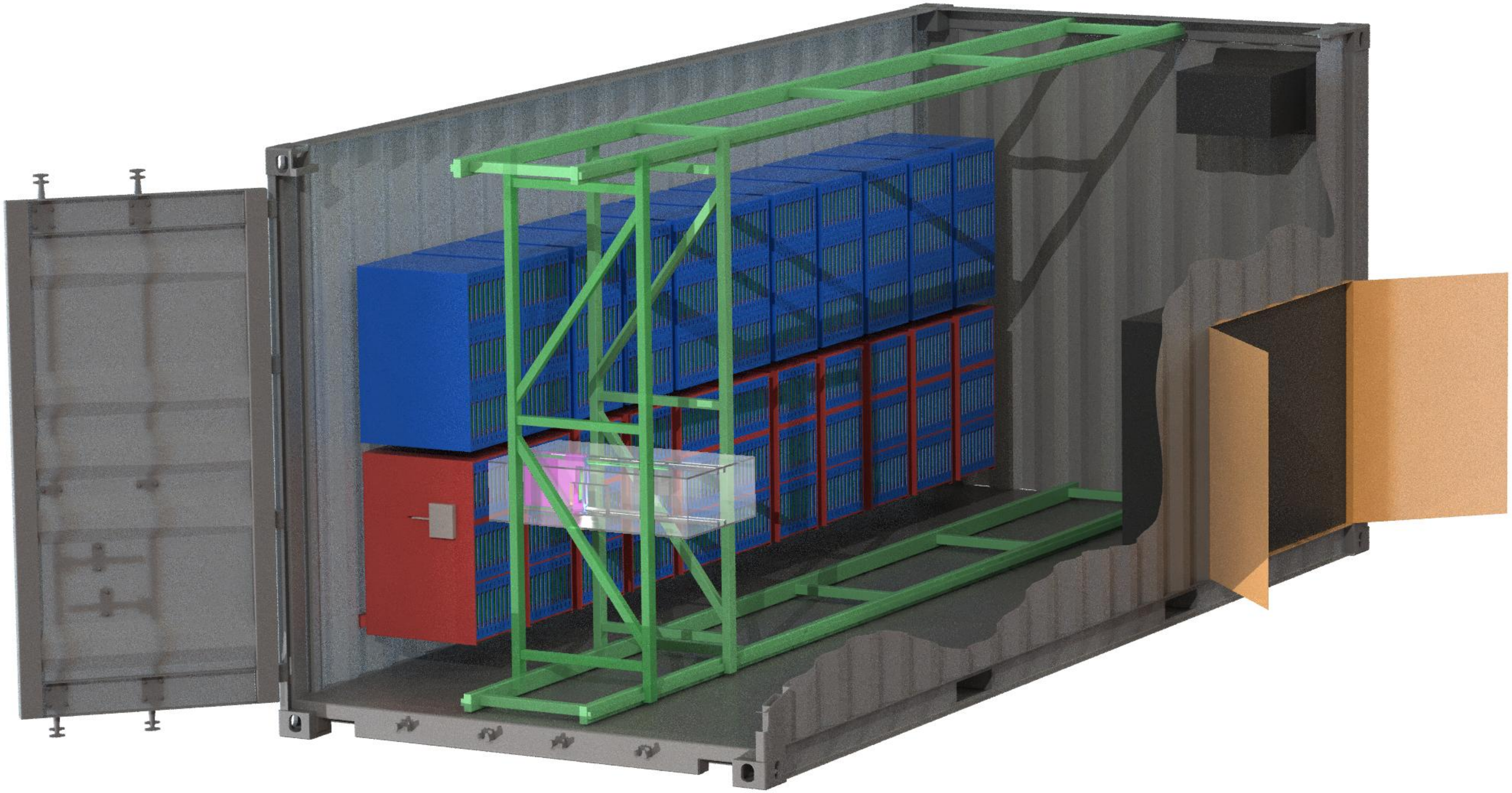


Figure 3. Mechanism takes smart frame out of the first beehive

Figure 4. Mechanism moves to temporary storage of smart frames

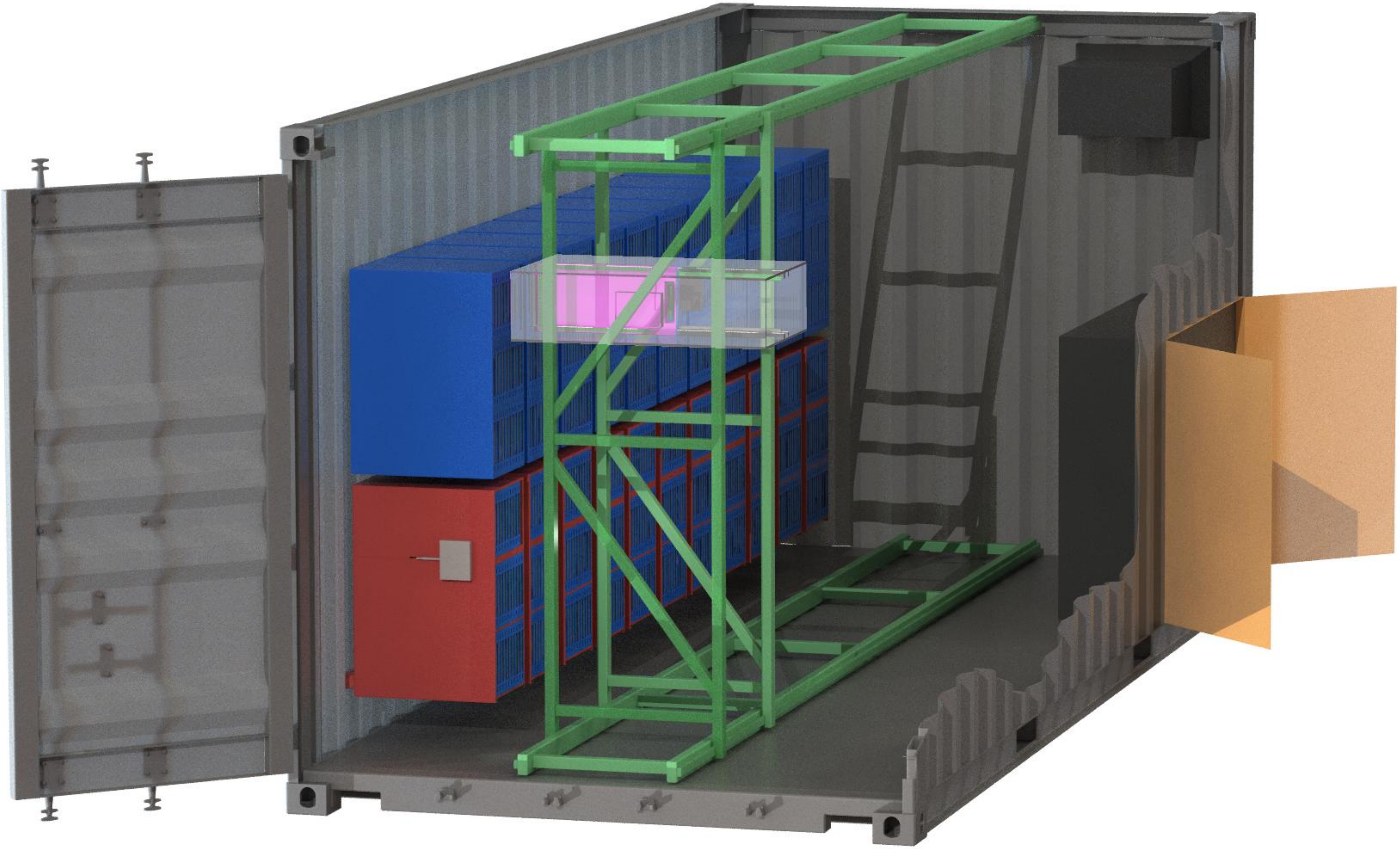


Figure 5. Mechanis is aligned to the temporary storage of smart frames

Figure 6. Mechanism slides smart frame into temporary storage of smart frames

Figure 7. Mechanism moves to the second beehive

Figure 8. Mechanism takes smart frame out of second beehive

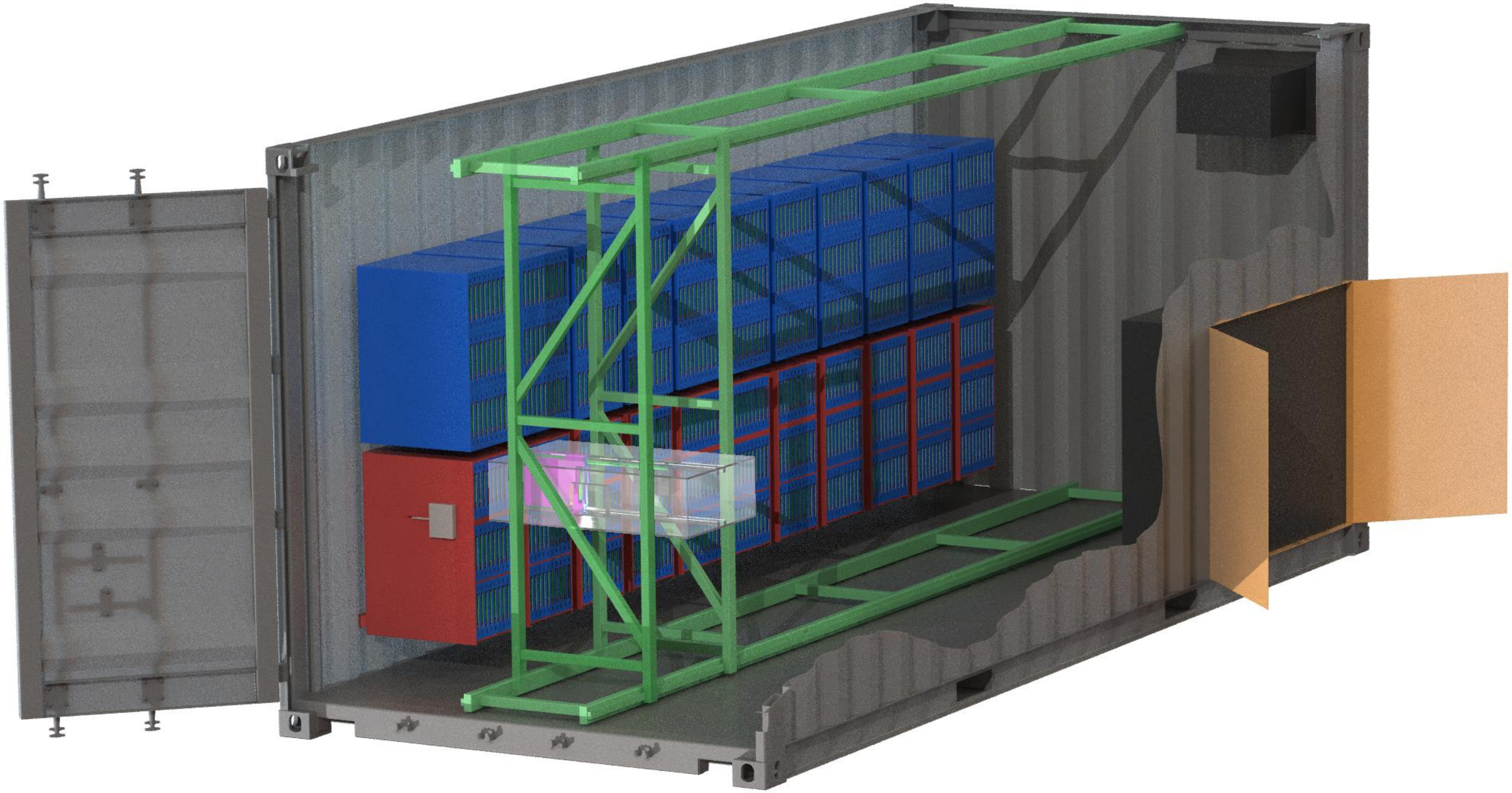


Figure 9. Mechanism moves back to the first beehive and aligns with it

Figure 10. End of the cycle. Smart frame is moved from the second beehive to the first beehive (frame initially taken from the first beehive is stored in the temporary storage of smart frames

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