BEN-GURION UNIVERSITY OF THE NEGEV
FACULTY OF ENGINEERING SCIENCES
DEPARTMENT OF INDUSTRIAL ENGINEERING & MANAGEMENT

Analysis of Human-Robot Harvesting Operations in Sweet Pepper Greenhouses

THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE M.Sc DEGREE

By: Zohar Melamed (Elkoby)

June, 2016

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Supervised by: Yael Edan
Bert van 't Ooster

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Chairman of Graduate Studies Committee: ______________ Date: ______________

June, 2016

Abstract

Major problems limiting greenhouse horticulture production are lack of human resources and the high cost of human labor. A proposed solution is the development of a harvesting robot. The introduction of robotics into the harvesting process creates the need to explore and simulate the sweet pepper harvest for its optimal integration into the system. As the robot's performance is limited, this thesis proposes to combine the robot into the production processes in parallel to human workers. This thesis aims to evaluate and analyze different human-robot combinations for efficient sweet pepper harvesting taking into account economic analyses of the proposed systems.

A simulation model was developed to simulate different work scenarios of robotic and manual harvesting in a sweet pepper greenhouse. The simulation model was based on concepts and elements from an existing GWorkS simulation model that was developed originally for evaluating and improving logistic processes in rose cultivation systems in the Netherlands. The simulation model developed in this thesis was implemented in Matlab using Simulink and SimEvents. Verification was conducted with manual harvesting data from a greenhouse in the Netherland with 92% accuracy of average harvest time in a path.

Using the simulation model, different human-robot combinations for completing the harvesting throughout the season were tested. Basic evaluations were conducted in a 4.3 hectare greenhouse with basic robot capabilities (detection success: R_{DET}=70%, harvest success: R_{REPEAT}=100% and arm acceleration: R_{ACC}=0.2 m/s^2). Extended analyses were conducted for different greenhouse sizes (1, 8.6, 10, 15 and 20 hectares), extreme pepper amounts and different robot capabilities (R_{DET}=50%, 70%, 90%; R_{REPEAT}=70%, 100%; R_{ACC}=0.1, 0.2, 1 m/s^2) in order to assess future changes in the greenhouse structure and the composition of resources for the harvesting season.

Economic analysis of all human-robot combined solutions was conducted using an economic model built based on a previous EU project (cRoPs - evaluation of economic viability of agricultural robotic systems, Ref: C0399). Annual costs of each human-robot combined solution were compared to harvesting conducted solely by human workers.

Results indicate that for a 4.3 hectares greenhouse for robots with basic capabilities (R_{DET}=70%, R_{REPEAT}=100% and R_{ACC}=0.2 m/s^2), the human-robot combined solutions should include 3-6 workers with 4-1 robots accordingly. The maximum price for each robot with these capabilities is 53,880€. When the capabilities improve to 90% detection and arm acceleration of 1 m per s^2, the price can increase to about 79,870€. According to the results, the most significant improvement can be achieved (when R_{REPEAT}=100%) by shortening the harvest times (increasing R_{ACC}), an improvement that can increase the maximum price per robot in average by 12,900€.

Keywords: Agriculture work methods, Data Analysis, Simulation, Pepper harvesting, Robotic harvester, Human-robot collaboration, Economic analysis

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List of Abbreviations

- **DST:** Days Since Transplanting
- **GWorkS:** Greenhouse Work Simulation
- **HC:** Harvest Cycle
- **R_{DET}:** Robot detection accuracy
- **R_{ACC}:** Robot's harvester arm acceleration
- **R_{RETRY}:** Robot repetitive cycles success rate

1. Introduction

1.1 Description of the problem

Major problems in greenhouse horticulture production are lack of human resources and the high cost of human labor (Bechar, Edan, & Krause, 2005; van 't Ooster, Bontsema, Henten, & Hemming, 2012). Labor costs in Dutch greenhouse horticulture, for instance, constitute 29% of the production costs (Bac, Henten, Hemming, & Edan, 2014) and in Israel 25% (*Israeli Central Bureau of Statistics*). A possible solution to this problem is improving labor efficiency. Work methods analysis is a commonly employed technique to improve production, operations management and increase efficiency (Globerson, 2002). In addition and as a complementary tool, simulation can be used to assess for cost-effectiveness, the effect of changing existing processes or the introduction of new processes in an actual system (Law, 2008).

Advanced research has been applied to improve work methods in greenhouse horticulture for different crops such as sweet pepper (Bechar et al., 2005), tomato (Bechar, Yosef, Netanyahu, & Edan, 2007), Gypsophila flowers (Bechar, Lanir, Ruhrberg, & Edan, 2009) and cut-rose (van 't Ooster et al., 2012) using work methods analyses and simulation.

The harvesting crop operation is the most time consuming and labor intensive process in a greenhouse (Bac et al., 2014). According to Israel's Ministry of Agriculture and Rural development (July 2010), harvesting takes about 54% of the work time spent in a greenhouse. Therefore, another solution for the lack of manpower is to replace operations by advanced automation such as harvesting robots (Bac et al., 2014). At the moment, even though it is technically feasible to develop such a harvesting robot, it is already known that 100% replacement of human labor by this robot is far ahead, and not sure if it can be economically justified (Bac et al., 2014). Since agriculture is expected to grow significantly there will be an increased need for agricultural operations. Therefore, different automation solutions will be required to compensate for the lack of labour (Pedersen, Fountas, Have, & Blackmore, 2006). However, it might be more effective to have the automation solutions perform only some of the operations while humans are integrated into other operations or work simultaneously. Hence, analysis of different combinations of the human-automation collaboration should be investigated. This thesis aims to answer an important question related to how to operate the robots and humans in concert from the logistics perspective for the different greenhouse harvest processes, and specifically-

- What is the robot's needed capability?
- How many robots are needed per unit area greenhouse?
- How should the work be divided between the robots and the humans?

When analysing human-robotic combined operations it is important to investigate the economic feasibility. In the thesis, a discrete event simulation model of the crop handling processes inside a greenhouse was built based on the GWorkS model (van't Ooster, Bontsema, Henten, & Hemming, 2015). GWorkS is a model that was originally built to analyze logistics in Dutch rose greenhouses for multiple crop operations and was later on adapted for sweet pepper greenhouses (Aantjes, 2014; Elkoby, van’t Ooster, & Edan, 2014) and other crops.

This study focuses on developing best-fit work-methods for economically feasible human-robot combined solutions applied to the harvest process of sweet peppers produced in greenhouses. For this purpose, the performance of each individual “resource” (i.e., human and robot) was analysed based on existing data of harvesting capabilities of the human and estimated data of the robot.

1.2 Objectives

The main objective of this master thesis study is to evaluate the “logistics” of the integration of humans and robots for harvesting sweet peppers in greenhouses. Specifically to:

1. Find best-fit logistic human-robot combinations for harvesting in a greenhouse;
2. Perform economic analysis of the human-robot combined solutions suggested; and
3. Test whether humans and robots should work in parallel on separate tasks.

In order to realise these objectives a simulation model for evaluating robotic harvest operations was developed.

In this research, the robots have predefined capabilities such as capacity, timing of actions and success rate. Since there is lack of data available on the robot's current performance (Hemming et al., 2014), sensitivity analyses were performed for some of the capabilities. The robot capability parameters are not optimized in this research, rather we explore the logistical decisions for given robot capabilities. The model developed provides insights related to the needed numbers of robots and workers and their economic viability for specific robot capabilities.

This thesis aims to address the following research questions:

- How many fixed workers are needed to harvest sweet peppers in a greenhouse when workers are the sole resource?
- How many robots are needed for a greenhouse with a known number of fixed workers?
- How many workers are needed to complete the harvest started by robots incapable of 100% harvest efficiency?
- How do potential resources needed and financial savings depend on robot performance such as accuracy rate and harvest rate?
- With given robot capabilities, what are the maximum costs of a harvesting robot a grower will be willing to pay without exceeding existing costs of the harvest operation by human labor alone?
- When robot capabilities and price are defined, what will be the selected logistic solution (i.e., what are the required number of workers and robots)?

1.3 Thesis structure

Chapter 2 presents the literature review including description of the process of sweet pepper harvesting, simulation models and integration of robotic systems. The research methodology is described in chapter 1 followed by detailed explanation of each part of the method with corresponding results in chapters 4-7. In chapter 4, the data sources used and analyzed in the thesis are described. The simulation model developed is presented in chapter 5 followed by human-robot combined solutions explored using the simulation model in chapter 6. Chapter 7 describes the economic analysis of the combined solutions. The thesis is summarized with conclusions, discussion and future work presented in chapter 8.

2. Literature review

2.1 Work methods in agriculture

Several researchers investigated different methods to improve work methods in greenhouse horticulture, mainly in Israel (Bechar et al., 2005; Bechar et al., 2009; Bechar & Vitner, 2011; Bechar et al., 2007) and the Netherlands (van 't Ooster et al., 2012; van 't Ooster, Bontsema, Henten, & Hemming, 2014; van't Ooster, Bontsema, Henten, & Hemming, 2013).

The studies included improvement of work processes for different crops and operations such as for the harvesting and trellising processes in tomato greenhouse production (Bechar et al., 2005; Bechar et al., 2007), packing house operations in three types of green ornamentals (Pittosporum, Aralia and Aspidistra) greenhouse (Bechar & Vitner, 2011), harvesting, packing and conveying operation in Gypsophila Arrosti greenhouses (Bechar et al., 2009), assessment of re-designed horticultural crop production systems and work scenarios on labor and machine performance before implementation in roses greenhouses (van 't Ooster et al., 2012). In addition, several final BSc projects have been conducted at Ben-Gurion University (Table 1) aiming to improve work methods by focusing on different crops and applying different improvement methods. For each research, performance measures were specifically predefined as cycle time per plant and percentage of labor savings (Bechar & Vitner, 2011; Bechar et al., 2007), revenue (Bechar & Vitner, 2011), worker yield, proportion of the total process time allocated to conveying time and yield quality (Bechar et al., 2009) and total working time (Bechar et al., 2005). The research methods included data collection and characterization of work methods (Bechar et al., 2005; Bechar & Vitner, 2011; Bechar et al., 2007), statistical analyses of the work-study data (Bechar et al., 2007; van 't Ooster et al., 2012) and development of simulation models in ARENA, Microsoft Excel Visual Basic and MATLAB for comparing different work methods as alternatives to the existing state (Bechar et al., 2005; Bechar et al., 2009; Bechar et al., 2007) finding an optimal work plan (Bechar & Vitner, 2011) and creating a tool for assessment of work scenarios and resources performance (van 't Ooster et al., 2012). Results shows that using work methods and simulation techniques can lead to major improvements in the greenhouse operations leading to reductions of 32% in manual labor (Bechar et al., 2007), improvement of processing time by 19% - 47% (Bechar & Vitner, 2011), reduction of trellising time by 11% and harvesting time by 25% (Bechar et al., 2005). In addition, specific recommendations were made for the working processes of tomatoes (Bechar et al., 2007): batch harvested fruits, working both sides of path at once instead of only a single side. For sweet pepper harvesting specifically recommendations include (Bechar et al., 2005): increasing the number of containers, use of rails inside the row and uploading the pepper inside the greenhouse. Some of the simulation models built can be used daily as a decision support tool for different objective functions- improved allocation of workers to the various tasks, increased production, and reduced time and manual labor (Bechar et al., 2009; van 't Ooster et al., 2012).

All of the studies above proved the usefulness of applying advanced industrial engineering techniques such as work method analysis and simulation to the improvement of horticultural production and operation management. Furthermore, the work indicates that simulating work scenarios can help find work methods to reduce manual labor substantially.

2.1.1 Work method analysis in IDEF3

The IDEF3 process description method was created specifically to capture descriptions of sequences of activities (Dorador & Young, 2000). Among the main advantages of this methodology are its simplicity and descriptive power (Dorador & Young, 2000). An IDEF3 model provides: stage description that specifies each activity, structure of underlying stages and flow of objects and their relationship (Huang & Kusiak, 1998).

The graphical elements that comprise process schematics include: Unit of Behavior (UOB) boxes, precedence links and junctions (Figure 1). A UOB captures information on a process, action, decision or other procedure performed in the system. Junctions in IDEF3 provide a mechanism specifying a logical branching of UOBs and introduce the timing and sequencing of multiple processes. Links connect UOBs or junctions (Jeong, Cho, & Phillips, 2008). Multiple process paths are classified as fan-in or fan-out corresponding to converging and diverging paths, respectively. The relative timing of process paths that converge or diverge at a junction are classified as synchronous or asynchronous (Huang & Kusiak, 1998). Detailed information about junctions in IDEF3 is presented in Figure 2.

Table 1: Final projects conducted at BGU on agricultural work methods improvement

Crops, work processes	Methods	Main Recommendations	Reference
Tomatoes- harvesting, trellising	• Work analysis • Simulation	Two bottlenecks were found in the manual work stages- manual dilution and harvest. Suggestions for improvement: usage of ancillary instrument for dilution in specific cases and construction of equipment warehouse in a central area.	Improvement of work methods in tomato greenhouses (Levi & Kessler, 2002)
Cherry Tomatoes- harvesting, cut off the leaves and secondary branches	• Work study: direct measurement and multi observational study • Simulation	Specific recommendations on how to move between rows, how to harvest, location of the trolley and allocation of assignments in the harvesting process.	Improvement of Work Methods in Cherry Tomato Greenhouses Using Simulation (Avigdor & Israels, 2003)
Sweet peppers- harvesting, trellising	• Work study: direct measurement • Statistical analyzes • Simulation • Development of economic model	Recommended work methods: Harvesting- working on tracks with distribution of boxes at the beginning of the day and collection of full boxes at the end of the day. Trellising- signing a line after each trellising finishes to reduce the searching time.	Improving processes and developing economic model for greenhouse peppers work methods using simulation (Shahaf & Biton, 2004)
Tomatoes- packing, sorting	• Work analysis • Simulation • Optimization	Different allocation of workers in the packing house and changing some work processes.	Improving efficiency of work processes integrating optimization in tomato packing-house (Mukomolov & Cohen, 2005)
Basil- harvesting, sorting, packing	• Data collection using handheld computer (IPAQ) • Statistical analyzes • Simulation	Recommendations with no additional costs: Changes in work procedures of weighing, sorting and packing processes, refrigerator for the harvested Basil, changing the growth and harvesting system.	Improvement of work methods of harvesting, sorting and packing processes in basil greenhouses (Yerushalmi & Libadro, 2009)
Grapes- manual dilution, harvesting	• Work analysis • Simulation	Recommended work methods: Harvesting- Construction of equipment warehouse in a central area. Dilution- using a dedicated auxiliary device, that will perform the dilution.	Improvement of work methods in a vineyard (Cahana, 2010)
Strawberry- leaves removal, harvesting, packing	• Work analysis • MOST • Simulation	Recommended work methods: Harvesting- boxes distribution and using an ergonomic carrier during the process. Packing- using packaging with structured labels	Improvement of work methods in ‘hanging strawberry’ greenhouses (Benin & Moyal, 2011)

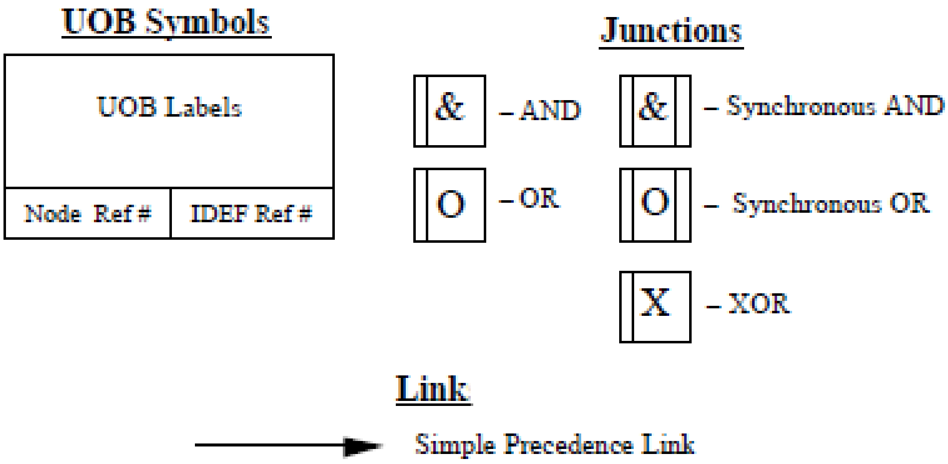


Figure 1: Process Schematic Symbols of IDEF3 (Mayer et al., 1995)

Junction	Name	Meaning in *Fan-in	Meaning in *Fan-out
&	Asynchronous AND	All preceding processes must be complete.	All following processes must start.
&	Synchronous AND	All preceding processes complete simultaneously.	All following processes start simultaneously.
O	Asynchronous OR	One or more preceding processes must be completed.	One or more following processes must start.
O	Synchronous OR	One or more preceding processes complete simultaneously.	One or more following processes start simultaneously.
X	XOR (Exclusive OR)	Exactly one preceding process completes.	Exactly one following process starts.

*Fan-in means convergence
*Fan-out means divergence

Figure 2: Junctions used in the IDEF3 process models (Mayer et al., 1995)

2.2 Sweet peppers

Sweet peppers can be grown in almost any climate; they are grown on all continents except Antarctica. Growth can be perennial or annual, open field or inside net houses or greenhouses (Hickman, 1998).

2.2.1 Crop operations

Growing sweet peppers lasts throughout the year with several main phases in each cycle throughout the period (Hickman, 1998):

- **Seeding:** one/twice a year.
- **Trellising:** wrapping of the main stems and wiring them in upward direction. Performed about every week.
- **Pruning:** removing fruits, flowers and foliage that are damaged or not growing in accordance with the cultivation system and consumes resources from the plant. Performed during the growth period.
- **Harvesting:** according to crop development stage and fruit ripeness.

This thesis will focus on the harvesting operation which is the most time consuming and labor intensive process in sweet pepper greenhouses: in Israel, according to Israel's Ministry of Agriculture and Rural development (July 2010), out of 1,346 working days in 13 different types of crops and work methods, the harvesting takes about 54% of the work time spent in sweet pepper growing operations (Table 2). In the Netherlands, according to the data derived from a databased based on 215 working days acquired from a Dutch grower between 2011-2013 (September), harvesting was also found the most time consuming and stands about 39% of the workers time (Figure 3).

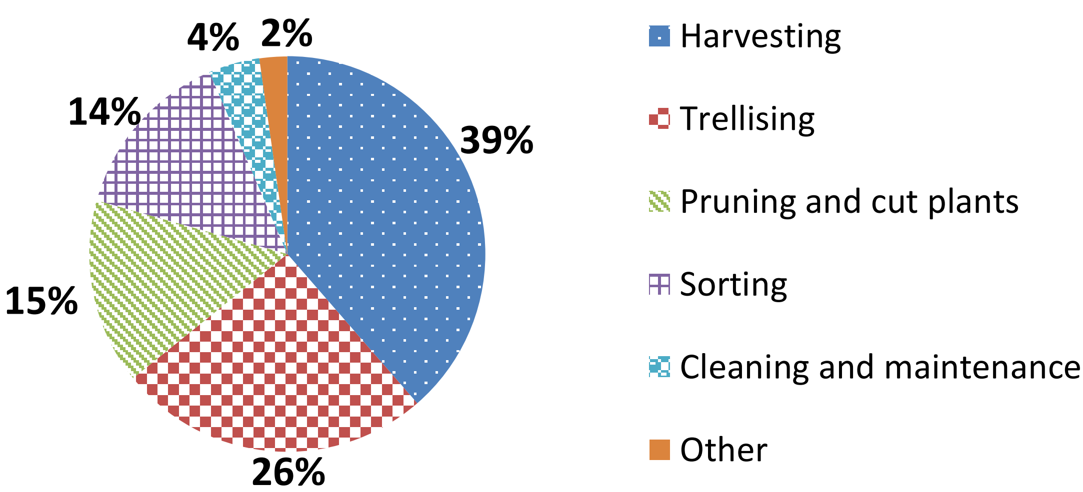


Figure 3: Time division in the Dutch greenhouse under study

Table 2: Amount of working days by operations for sweet peppers growing in Israel (Israel Ministry of Agriculture and Rural Development, July 2010)

Type of crop	Trellising	Harvesting management	Harvesting	Sorting and package	Other operations	Total days	Percentage of harvesting
Middle "Arava" pepper	-	2.6	37	13.2	17.7	70.5	56.17%
Dutch cultivation pepper- cooled greenhouse	6.2	3.7	52.2	18.6	19.9	100.6	55.57%
Dutch cultivation pepper- cooled greenhouse for export	3.7	3.7	52.2	18.6	22.4	100.6	55.57%
Dutch cultivation pepper- cooled and heated greenhouse	12.1	3.1	44	15.7	72.9	147.8	31.87%
Spanish cultivation pepper greenhouse- August	2.7	2.7	37.4	13.4	15.9	72.1	55.62%
Pepper greenhouse for domestic market	2	2	27.5	9.8	11.4	52.7	55.98%
Pepper	0.9	0.9	12.5	4.5	5.7	24.5	54.69%
Organic pepper greenhouse- Dutch export	2.9	6.1	86	30.7	38.9	164.6	55.95%
Oganic pepper greenhouse	2.6	5.6	78.7	28.1	35.7	150.7	55.94%
Pepper greenhouse: Arromro, Tinklbl, Switbl and Switbiot	6.9	6.9	97.1	34.7	41.7	187.3	55.53%
Pepper net houses for export	2.8	2.8	38.6	13.8	16.4	74.4	55.65%
Organic pepper net houses for export	2.5	5.4	75.1	26.8	33.9	143.7	56.02%
Organic pepper net houses for domestic market	1.4	2.1	29.8	10.7	12.8	56.8	56.16%
						Average:	53.90%

2.2.2 Cultivation systems for growing sweet pepper

There are two types of common cultivation systems (Jovicich, Cantliffe, & Stoffella, 2004): the "Dutch" and the "Spanish" trellis system, which both are widely used in greenhouses growing pepper crops. In both systems the plants are planted along the lines. In the "Dutch" system plants grow to a height of about 3-4 meters while in the "Spanish" system plants grow horizontally, so the plants height is only 1.5-2 meters. Each system has its own features and involves different amounts of labor for pruning and "training" of the plant canopy (Jovicich et al., 2004):

- The **"Dutch" trellis system** is also called "V" trellis system. It consists of forming a two-stem plant by removing one of the two shoots that develop at each node. Stems are supported vertically with twine wound around the stems (Figure 4). The "V" trellis system is used mostly by Dutch and Canadian growers.

- In plants trellised to the **"Spanish" trellis system**, the stems and lateral branches are not pruned, allowing the plant to develop a canopy with two-four main stems with lateral branches in the mature plant. In the "Spanish" trellis system, the plant canopies are supported vertically from both sides by horizontal twines tied to poles distributed along the rows of the plants (Figure 4). This trellis system is mostly used by Spanish and Israeli growers.

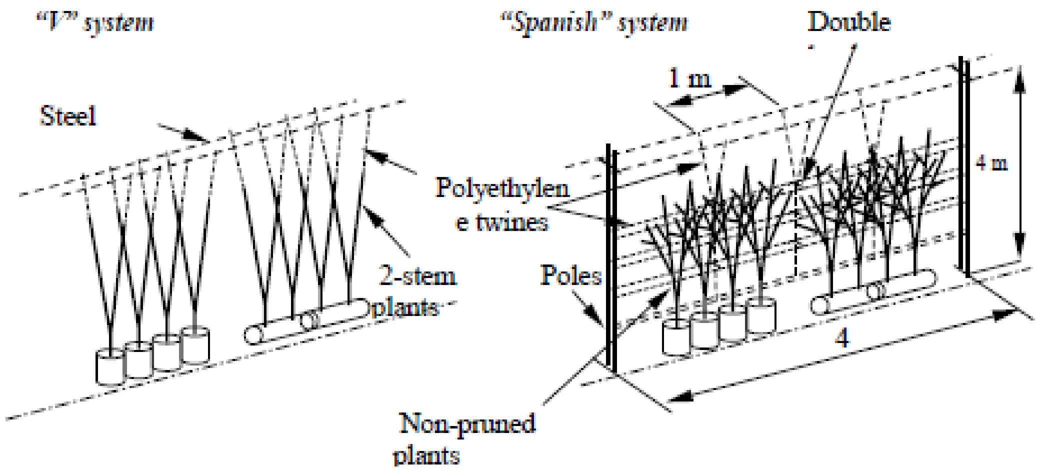


Figure 4: Pepper plants grown in pots and bags, trellised to the "Dutch"/ "V" trellis system (left) and to the "Spanish" trellis system (right)
(Jovicich, Cantliffe, & Stoffella, 2002)

2.2.3 Growth analysis

Several models have been developed to characterize the sweet pepper growth for different environmental conditions; this includes measurements of fruit growth and quantification of the growth over time (Wubs, Ma, Heuvelink, Hemerik, & Marcelis, 2012). Results indicate that the growth of fruit like tomato and sweet pepper normally follows a sigmoid growth curve (Marcelis & Baan Hofman-Eijer, 1995). The logistic, Gompertz, and other functions are often used to describe fruit growth over time (Charlo et al., 2011; Marcelis & Baan Hofman-Eijer, 1995; Wubs et al., 2012). In Marcelis et al. research (Marcelis & Baan Hofman-Eijer, 1995), the growth of sweet pepper fruits (Capsicum annuum L.) was measured throughout their development and the relative contributions of different fruit parts to the growth of the fruit were quantified. Three experiments were conducted, with different light and weather conditions, humidity level, dates of flowers anthesis and other factors. It was found that the growth curve of the fresh fruits weight followed sigmoid growth curves (Figure 5).

The growth curve of sweet pepper (Eppo hybrid type) cultivated in pots containing ferti-irrigated coconut fiber in greenhouse cultivation was evaluated by Charlo et al. (2011). In order to evaluate the growth curve of the sweet pepper as a function of days after transplanting, the height of the plant and number of fruits, flowers and leaves were determined. According to the results there was continuous accumulation of dry mass plant (DMP) over the entire cultivation cycle (Figure 6). The accumulation of total dry mass of fruits (TDMFt or DMFt) was continuous over the cultivation cycle (Figure 7). Both DMP and DMFt where fitted to the logistic function with high accuracy.

The sigmoid functions used to model fruit growth along time have different properties with respect to their shapes, and should be adjusted specifically to the greenhouse and environmental conditions (Wubs et al., 2012). Parameters such as temperature and assimilate supply may affect the growth curves, and there may be varietal differences and therefore these effects must be quantified (Wubs et al., 2012). Although many factors may influence the growth rate, the type of sigmoid growth curves presented in the research is likely to be general. Therefore, comparison of different parameters of the sigmoid functions should be done to assure the most appropriate one is used for the needed greenhouse (Wubs et al., 2012).

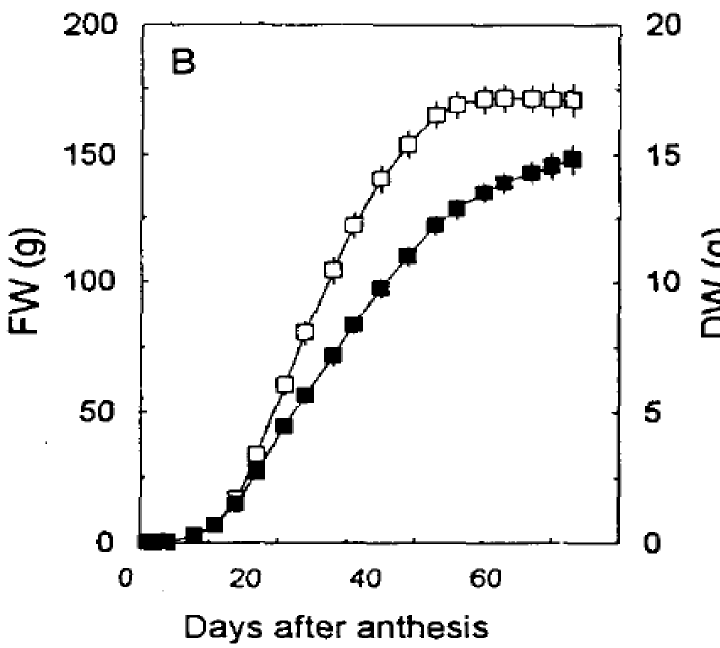


**Figure 5: Estimated fresh weight (▫) and estimated dry weight (▪) of a fruit as a function of time after anthesis at 20°C. Data are means of 15 fruits;
vertical bars represent standard errors of means (Marcelis & Hofman-Eijer, 1995)**

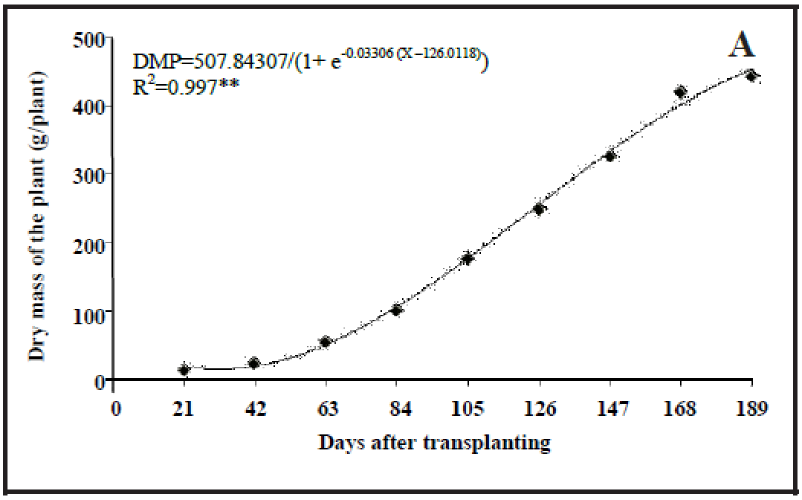


Figure 6: Dry mass of plant [g/pl.] as a function of days after transplanting (Charlo et al., 2011)

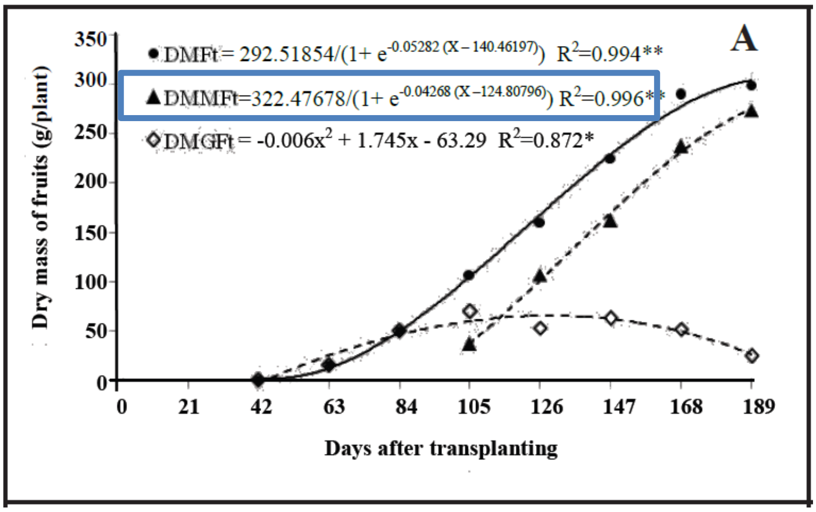


Figure 7: Dry mass of mature fruits DMMFt [g/pl.] as a function of days after transplanting (Charlo et al., 2011)

2.3 Integration of robotic systems into production processes

2.3.1 Robotic system pre-implementation evaluation

The major goal in automation is to improve or optimize a process. To employ robots effectively in automation, they must first be evaluated to ensure that the automation can be used at its full potential (Edan & Nof, 1996). The implementation of a manufacturing robotic system is commonly more expensive and difficult than initially planned (Rubinovitz, 1999). Robotic systems are expensive to purchase, install, and operate and in some cases are less efficient and effective than expected (Rubinovitz, 1999).

The capabilities and performance of a particular robot are affected by the robot's design, its motions and the work cell set-up (Edan & Nof, 1996). Therefore, important decisions must be made such as which manipulator to select (Goldenberg & Emami, 1999; Warnecke, Schraft, Hagele, Barth, & Schmierer, 1999), where to place the manipulator and tools (Tanie, 1999), whether to select a mobile robot (Schempf, 1999) and how to design the robot's workspace.

Using operations research techniques for planning, design and operation of robotic systems can be valuable due to the complexity of the planning problems that arise in robotic systems (Hall, 1999). Simulation is usually used to estimate correctly the performance, throughput and how to get the robotics up and running efficiently pre-implementation, the robot's abilities and tasks (Rubinovitz, 1999). The simulation enables to examine several options and decide which is the most efficient for the specific scenario.

The following phases of activity are important for implementation of a robotic system (Hall, 1999):

1. **System planning-** including feasibility study, consideration of several alternatives, preliminary system design and economic evaluations.
2. **System design-** including deciding which operations will be performed by the robotic system in question, selecting equipment and configuration decisions. This stage is critical to the eventual performance of the system.
3. **System operation-** should include operating the system in an efficient way that satisfies the production targets with minimum disruption to ongoing processes. In addition, the performance of the system should be evaluated and in case needed, a new iteration of step 2 can be performed and the system may be modified, upgraded or expanded.

For justification of a robotic system, it is not sufficient to judge a solution solely based on traditional economic criteria. It is important to select other measurements of the systems strategic and long term benefits (Mills, Stevencs, Huff, & Presley, 1999). When a robotic technology is properly selected and defined, it can offer substantial potential for cost savings, flexibility, improved quality, product consistency and improved throughput (Mills et al., 1999).

When choosing an operations research technique, the level of complexity should be according to the necessity type: deterministic or probabilistic modelling, a static or dynamic modelling (Hall, 1999).

In Table 3, according to each phase, important issues and requirements, performance measures are suggested as well as compatible operations research techniques that can be useful for the decisions to be made (Hall, 1999).

An example for robot integration in agriculture was applied for the usage of an automatic milking system on a dairy farm. Economic and logistical consequences of using an automatic milking system was explored using a discrete simulation model (Cooper & Parsons, 1999). In addition, the optimal robotic milking barn was designed using simulation (Halachmi, 2000; Halachmi, Metz, Maltz, Dijkhuizen, & Speelman, 2000). The target of the above studies was to explore and find the correct and most efficient manner to use those automatic systems and implement it on the farms. In Cooper & Parsons research (1999), a simulation model was built and combined with an economic analysis for a range of real dairy farms and sensitivity analysis was conducted. Their model is able to simulate the milking process and provide the optimal decision for a specific herd size: how many robots and milking stalls should be used with little or no human intervention. In Halachmi et al. (Halachmi, 2000; Halachmi, Adan, Van Der Wal, Van Beek, & Heesterbeek, 2003) a behavior-based simulation model was developed as a design tool to derive the optimal layout for a robotic milking barn, considering all the relevant factors such as cow behavior, welfare needs, and facility utilization for a specific farm or site.

All of the mentioned studies demonstrate the necessity of research prior to implementation of a robotic system. In agriculture the need is even greater due to the large diversity and variances between environments and growers (Edan, Engel, & Miles, 1993). The optimal layout and usage of robotics is 'site dependent'. The introduction of simulation into agricultural systems provides the ability to compare several alternatives under predefined, controlled conditions that are independent of the growing season, without the need for repeated field experiments (Edan & Miles, 1994). The influence of differences between and within cultivars can be examined with a computerized model of the system (Edan, Flash, Shmulevich, Sarig, & Peiper, 1990), and statistical comparisons can be made among the various possible combinations of all crop parameters, such as the geometry of the crop and of the fruit distribution (Edan & Simon, 1997). Finding the optimal solution for a given operational situation is a classic industrial engineering problem (Taha, 2003). The use of optimization in agricultural operations is complicated because of the high variability and low accuracy of the operational, marketing and environmental parameters (Vitner, Giller, & Pat, 2006). Hence, even in industrial settings where all is defined a-priori and constant, researchers also strengthen the importance of simulation in that field (e.g. (Edan & Nof, 1996), as presented at the beginning of the section (Rubinovitz, 1999).

Table 3: Summary of suggested approaches for implementation of a robotic system

Phase	Issues and requirements	Performance measure	Operations research techniques
1. System planning	- Definition of management objectives - Location and layout of the robotic system - Selection of operations and equipment to be automated - Resource requirement for the robotic system	- Amount of investment - Return on investment - Flexibility	- Linear programming - Analytic hierarchy process for making comparisons between several options - Heuristics in cases optimality is hard to achieve - Location and layout of facilities
2. System design	- Equipment layout - Cell design- by product or by process - Material-handling equipment - Accessories- if necessary	- Throughput rate - Throughput time - Work-in-process inventory - Equipment utilization - System reliability	- Group technology and cell formation - Queuing models- single robot system or multiple robot system or even extension to queuing networks - Simulation - Reliability and maintenance according to the reliability theory
3. System operation	- Batch sizes - Scheduling - Disruptions - Maintenance	Same as the “System design” phase but with greater detail and precision and the decisions are aimed to the short-term operating	- Batching of jobs - Scheduling algorithms for robotic cells or other configurations - Hierarchical production planning

2.3.2 Agricultural robots - state-of-the-art

Extensive research has been conducted in agriculture for exploring robotic solutions for advanced automation: autonomous vehicles in agriculture for cultivation, seeding, fertilizers (Pedersen et al., 2006), robotic weeding in organic farming (Sørensen, Madsen, & Jacobsen, 2005) and harvesting (Edan, Rogozin, Flash, & Miles, 2000; Kitamura & Oka, 2005). Several studies proved economic feasibility of implementing some innovative technologies (Edan, 1995; Edan et al., 2000; Hayashi et al., 2010). The results showed that the benefit gained from new technologies is affected directly from the system capacity, efficiency and initial price of the equipment.

Harvesting robots have been developed along the last 30 years of research (Grift, Zhang, Kondo, & Ting, 2008; B. Li, Vigneault, & Wang, 2010; P. Li, Lee, & Hsu, 2011; Sarig, 1990) and the current state is still far from mature. Harvesting is still performed manually due to the limited performance of current robots (Bac et al., 2014; B. Li et al., 2010; P. Li et al., 2011; Sarig, 1990). According to Bac et al. (2014), in a recent study summarizing the state-of-the-art in the field of harvesting robots, "*although performance of harvesting robots did not improve over the last three decades; there is an expectation for a positive trend in performance*".

For successful implementation of a harvesting robot in practice, the solution must be technically capable to perform the task, economically feasible, safe, fit the logistics process and must be accepted by growers and society (Bac et al., 2014). The main reasons limiting implementation of a harvesting robot are low success rates due to diversity of plant properties, slow operational speeds, and high costs associated with the seasonal affect (Edan, Han, & Kondo, 2009). At the moment, based on the technical feasibility of over 50 projects reported of harvesting robots for different crops, 100% of human labor replacement does not seem technically or economic feasible (Bac et al., 2014). For example, the success rate for an orange harvesting robot according to (Plebe & Grasso, 2001) was 52-85% depending on the weather conditions; a cucumber harvesting robot reached an average of 74% harvesting success in a research conducted in The Netherlands, with localization success of 95% (Henten et al., 2002; Henten et al., 2003); for mushrooms, a research was conducted in UK resulting in 76% harvesting success (Reed, Miles, Butler, Baldwin, & Noble, 2001). One of the highest harvesting success rates of these projects resulted from a research conducted for melon harvesting in Israel and USA with a success rate of 86% for a sample of 400 melons and with high fruit localization success and detachment success of 94% and 92% respectively (Edan, 1995; Edan et al., 2000). According to Blackmore et al., (2001) in order for the robot to be economically feasible it must be able to detect more than 95% of the targets successfully.

Due to these low harvesting success rates, and the need for higher success rates, an emerging R&D direction is to investigate a human-robot collaboration solution in order to maximize the detection rate which is the main limiting factor (Adamides et al., 2013; Adamides, Berenstein, Ben-Halevi, Hadzilacos, & Edan, 2014; Bechar & Edan, 2003; Bechar, Meyer, & Edan, 2009; Blackmore, Have, & Fountas, 2002; Edan & Miles, 1994; Oren, Bechar, & Edan, 2012; Tkach, Bechar, & Edan, 2011).

An alternative proposed in this thesis is to incorporate humans and robots working in parallel. The needed logistical decisions for these combinations were explored in this thesis.

2.3.3 Economic analysis

"The adoption of advanced technologies such as robotics and flexible manufacturing systems is widely seen as a key to continued competitiveness in the world market" (Mills et al., 1999). When defining and selecting correctly the technology, it has substantial potential for cost savings, flexibility, product consistency, and improved throughput (Mills et al., 1999). Many factors can influence the speed of adoption and the extent of a new technology (Dijkhuizen, Huirne, Harsh, & Gardner, 1997). One of the key factors influencing the adoption process is the economic profits that producers will gain from new technology (Dijkhuizen et al., 1997). Without knowing the economic consequences of adopting a new technology, managers will not cooperate with implementing it (Dijkhuizen et al., 1997). There are mainly two factors to consider when determining the economic desirability of a robot installation (Mills et al., 1999): 1-The cost of the robotic installation (capital investment); 2-Estimated (calculated) changes in costs resulting from the robot installation.

An important point that must be made early in the justification of any robotic system is that the objective of any robotic system project is not to emulate existing methods and systems, simply replacing human with robots, but to develop a new, integrated system providing strategic, operational, and financial benefits such as decreased labor costs (Mills et al., 1999). Although investment in robotic systems project is similar to other capitalized equipment projects there are some major differences that lead to operational benefits that include: flexibility, increased productivity, reduced operation costs, increased product quality, elimination of health and safety hazards, and the ability to run longer shifts (Mills et al., 1999).

A few studies performed economic analysis to test different robotic applications in agriculture (Clary et al., 2007; Edan et al., 1990; Pedersen et al., 2006; Tillett, 1993). These studies examined the profitability of a robotic system by analyzing costs and potential savings. The following factors were considered: harvester initial costs and investments, interest rate and economic life cycle (Clary et al., 2007), changes in labor costs, change in speed, daily working hours, energy consumption, control and surveillance costs (Pedersen et al., 2006; Tillett, 1993). According to Tillett (1993), the savings in labor costs is the product of the hourly rate, the difference in productivity relative to manual labor and the number of hours, assuming similar supervisory costs. Robots do not require meal breaks or sleep, enabling them to work longer hours and 6-7-days a week. Other benefits, which cannot be quantified at this stage, are likely to include accuracy, consistency, better hygiene and improved management information through linking computers (Tillett, 1993). Other costs to consider are the cost of robot's operation includes the labor necessary to operate the harvester and robot's maintenance costs (Clary et al., 2007). Technical data and costs of robotic systems, when not existed were estimated (Clary et al., 2007; Tillett, 1993) and based on recommendations from other research groups and experts as well (Pedersen et al., 2006). The economic figures such as period of depreciation, real interest rate and maintenance costs were based on assumptions (Pedersen et al., 2006). In all studies, the costs were compared to conventional practices and systems. Results of economic analysis can vary depending on the state and knowledge on the robotic system pre-research and the research objectives, for example- when a research deals with wide range of applications, the results of economic analysis can indicate type of application with most potential for cost reduction (Tillett, 1993); when the robotic system is yet not fully defined but application is known, economic research can lead to the needed capabilities and guidelines to make a system profitable (Clary et al., 2007); and when enough knowledge exist on the robotic application, results can indicate that the robotic system is economically feasible compared to conventional systems (Pedersen et al., 2006).

According to Tillett (1993), the cost of horticultural robots is difficult to judge, due to the special qualities the robot should have such as sophisticated sensing techniques and high accuracy rate including tolerance to various target orientations which increases the cost in compare to regular industrial machines. However, benefits are beyond the transfer of technology (e.g., improved quality, additional tasks) so these must be analyzed also as noted by Nof (1999).

2.4 Simulation models

2.4.1 ODD protocol

The simulation model built for the research will be described by the 'ODD' - Overview, Design concepts, and Details protocol. The ODD protocol was first published in 2006 (Grimm et al., 2006) to standardize the published descriptions of individual-based and agent-based models (ABMs). The primary objectives of ODD are to make model descriptions more understandable and complete, thereby making models less subject to criticism for being irreproducible. On 2010 (Grimm et al., 2010) the ODD protocol was revised to clarify aspects of the original version and improve the standardization of ABM descriptions. The differences between the versions of the protocol are presented in Table 4.

Although the protocol was designed for ABMs, it can help with documenting any large, complex model, alleviating some general objections against such models. Therefore, this protocol was chosen to assist and serve as a guideline for describing the discrete event simulation (DES) model of this research.

Table 4: The seven elements of the original and updated ODD protocol

	Elements of the original ODD protocol (Grimm et al., 2006)	Elements of the updated ODD protocol (Grimm et al., 2010)
Overview	1. Purpose 2. State variables and scales 3. Process overview and scheduling	1. Purpose 2. State variables and scales 3. Process overview and scheduling
Design concepts	4. Design concepts • Emergence • Adaptation • Fitness • Prediction • Sensing • Interaction • Stochasticity • Collectives • Observation	4. Design concepts • Basic principles • Emergence • Adaptation • Objectives • Learning • Prediction • Sensing • Interaction • Stochasticity • Collectives • Observation
Details	5. Initialization 6. Input 7. Submodels	5. Initialization 6. Input 7. Submodels

2.4.2 Discrete event systems

Discrete Event Systems (DES) are discrete-state, event-driven systems so that its state evolution depends entirely on the occurrence of asynchronous discrete events over time (Borshchev & Filippov, 2004). The DES modeling approach is based on the concept of entities, resources and block charts describing entity flow and resource sharing (Borshchev & Filippov, 2004). Entities are service-requesting objects that move within the system between service points, servers, while they compete for the use of resources (van 't Ooster et al., 2012). An entity may interact with other entities or be affected by external environmental factors (Grimm et al., 2006; Grimm et al., 2010).

The states of the entities used in the simulation model built in the research were implemented using the Matlab Stateflow chart. State-flow charts can contain sequential decision logic based on state machines (Mathworks documentation, 2015). A finite state machine is a representation of an event-driven (reactive) system. In an event-driven system, the system makes a transition from one state (mode) to another, if the condition defining the change is true (Mathworks documentation, 2015).

2.4.3 Verification, calibration and validation of simulation models

The stages in evaluation of modelled systems are: verification, calibration and validation (Sargent, 2005). These terms are often mixed and assign with different meanings by different researchers (Rykiel, 1996). Especially 'verify' and 'validate' which are synonyms in ordinary language, must be assign with conclusive meanings to distinguish them for modelling purposes. A modelled system can be classified into two types: "Observable System" and "Non-observable System" where observable means it is possible to collect data on the operational behavior of the system (Sargent, 2005). The stages in model evaluation are: verification, calibration and validation can be classified differently for each type of system.

In this research, the evaluation of the simulation model was performed using the following definitions:

1. **Verification** is a demonstration that the modeling formalism is correct (Rykiel, 1996). This process does not require any external data but the model itself and therefore can be performed for both system types (Sargent, 2005).
2. **Calibration** is the estimation and adjustment of model parameters and constants to improve the agreement between model output and a data set (Rykiel, 1996).
3. **Validation** is a demonstration that a model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model (Rykiel, 1996).

Both calibration and validation are stages that require actual data to compare to, with calculations of accuracy levels and therefore cannot be applied for a "Non-observable System" (Sargent, 2005).

2.5 GWorkS - Greenhouse Work Simulation

2.5.1 Background and purpose

The GWorkS model was developed in order to evaluate and improve labor and logistics processes in greenhouse production systems (van 't Ooster et al., 2012). The GWorkS model simulates the internal logistic processes inside a greenhouse production site and enables assessment of the efficiency of crop operations under different scenarios with increasing automation (van 't Ooster et al., 2012). The model uses parameters in time and space on labor and crop properties for realistic simulation and estimates the time used for different jobs. The model is able to produce a detailed level of information about the subdivision of work time, throughput of product, in-core action time, cycle time of a greenhouse path, transport (or walk) time, wait time, time overlap between transport and core action time and utilization of resources.

The GWorkS model was developed by Bert van ’t Ooster, Wageningen University and Research center (WUR, (van't Ooster, 2015). GWorkS was implemented in the Matlab environment using Simulink and SimEvents aiming to quantify effects of production system changes by means of a flexible and generic model approach.

The model was developed in steps. The first step aimed at modelling tomato production operations to obtain the general framework and develop a job planner (not published in papers). The second and third steps modelled harvesting processes in mobile (van 't Ooster et al., 2012) and static rose cultivation systems (van't Ooster et al., 2013); the static rose cultivation system was analysed for one or two workers (van 't Ooster et al., 2014; van't Ooster et al., 2013; van't Ooster et al., 2015). The fourth step, which this thesis is part of, was to expand the model for more crop operations, functioning for a variety of crops and an unlimited number of workers (Aantjes, 2014; Elkoby et al., 2014).

2.5.2 Status of the GWorkS model

Since the GWorkS model was created, several studies were published on the subject by Bert van ’t Ooster and in MSc & BSc theses conducted at WUR. Table 5, describes relevant previous research for this project and their contribution to the model.

2.5.3 GWorkS model description

2.5.3.1 Model type and Definitions

GWorkS is a Discrete Event System (DES) simulation model. In the GWorkS model entities are all system components that contribute to required actions in servers. The main entities are jobs. A job is a set of planned crop handling operations at a planned location called node using planned workers and facilities (resources). Normally a job entity allocates one worker. If more workers are needed in a node, the job entity splits off into operation entity (called atomic job-entity in GWorkS). For each node of interest (i.e., a node that was selected to be simulated), a job is generated with node number and operations to be executed on the current day as primary attributes of a job-entity. A process will only be executed if node and resources are simultaneously available at a server (van 't Ooster et al., 2012). The work plan for the simulated greenhouse is determined by the job planner that creates a work schedule for each day. In GWorkS-core (DES) this schedule is translated into job-entities. The job planner defines the daily workload in the greenhouse based on numbered jobs and job-frequency information and assigns nodes and subnodes to resources (e.g., assigns operators with trolleys). Terms such as entity, job, node, subnode, resource and action represent the abstract level of the model, whereas terms like harvest, greenhouse path, side of a path, harvester\ worker, trolley, and 'harvest pepper' represent the physical system (van 't Ooster et al., 2014).

Table 5: Published articles on the GWorkS model

Title	GWorkS status prior to research	Objectives	Contribution to GWorkS model	Reference
GWorkS - A discrete event simulation model on crop handling processes in a mobile rose cultivation system	No model available for simulation of crop operations	An assessment of re-designed horticultural crop production systems and work scenarios on labor and machine performance before implementation. To attain this goal, GWorkS-rose model is built for a mobile rose cultivation system. The modelling will quantify effects of production system changes. Validation and testing of the model will be performed.	• GWorkS-rose model is built for a mobile rose cultivation system. • Validation of the harvesting sub model with high accuracy rates. • The model can be used for studies on design and management of this kind of production systems.	(van 't Ooster et al., 2012)
Simulation of harvest operations in a static rose cultivation system	The model is developed for a mobile rose production system, but not yet for static rose growing system.	• Demonstration of the model flexibility by adapting the existing model to a model for a static rose growing system. • Validation of the adapted model for the harvest process. • Simulation of work scenarios to examine effects of skill, equipment, and harvest management.	• The GWorkS model was adapted to simulate a static growing system for cut-rose without altering the generic model structure. • Description of the adaptation process. • Validation of the model. • The work scenario study showed that worker skill affected labor performance considerably. • Some sensitivity analysis was made, to demonstrate the model as a decision support tool.	(van 't Ooster et al., 2014)

Title	GWorkS status prior to research	Objectives	Contribution to GWorkS model	Reference
Sensitivity analysis of a stochastic discrete event simulation model of harvest operations in a static rose cultivation system	The model is developed and active for both mobile and static rose production systems. Updated model version not (yet) validated for mobile rose production system.	• Identify parameters with strong influence on labor performance as well as the effect of uncertainty in input parameters on key performance indicators. • Identify growing system features that could guide designer and grower to an improved system design.	• Extensive sensitivity analysis of harvest operations in static rose cultivation system was made. • Results were tested for model linearity and superposability and verified using the robust Monte Carlo analysis method. • The research has found the most affecting factors on 'harvested stems per second', which is the preferred metric for labor performance.	(van't Ooster et al., 2013)
Model-based analysis of skill oriented labour management in a multi-operations and multi-worker static cut rose cultivation system	The model is developed and validated for the harvesting action in mobile and static rose production system. Disbudding and Bending were not yet added.	• ranking simulated labor management scenarios in a multi-operations and multi-worker static cut-rose cultivation system	• The model was prepared for simulation of disbudding and bending in addition to harvest • Different workers skills were tested and it was found that working with low skilled, low paid workers is not effective	(van't Ooster et al., 2015)

Table 6: WUR theses on the GWorkS model

Title	GWorkS status prior to research	Objectives	Contribution to GWorkS model	Reference
Analysis and modelling of crop handling processes in conventional and mobile rose production systems	The model was built and tested for a mobile rose cultivation system. The harvest and disbudding operation is modeled for a conventional rose production greenhouse but was not yet tested.	Identify labor demand affecting factors in current crop production processes in both conventional and mobile rose production systems. Main focus was on data analysis.	Comparison of the yield and labor requirement for both systems.	(Khunmuang, 2011)
Verification of the GWorkS-rose model for a stationary rose production system Data acquisition and model study	Same as in the (Khunmuang,2011) project.	Get precise information of harvesting, disbudding and bending for conventional rose production system and also to verify the GWorkS-rose model with reality on a daily basis. Verification was done for harvest and axillary bud removal (disbudding).	• Model input parameters were defined based on video observation. Labor registration data were analyzed and used for model verification. • Process flow diagram (IDEF3) was used to define the process flow of harvest, disbudding and bending operations. • Accuracy of model output was measured.	(Rahman,2011)
Simulation of workflows and internal logistics on crop handling operations other than harvest in a conventional growing system for cut-rose	For conventional and mobile rose greenhouse production, only the harvesting operations are modelled and validated completely. Other operations are not worked out to the desired level of detail yet.	The GWorkS model will be extended for a main labor operation other than harvesting in conventional rose production. For the model, all relevant crop handling processes need to be modelled and tested. Data analysis on all crop operations, focus in simulation on bending non-productive shoots.	The contribution of this thesis is a development of the service station Bending in SimEvents.	(Straver, 2013)

2.5.3.2 The main model structure

The main structure of the GWorkS model is given in Figure 8. The outline structure is a job routing system based on sub-models of the tasks in the greenhouse which are called service stations in this model. The main task, which this research is going to focus on, is the harvest task. Model adaptations for this research stage were done at WUR in collaboration with the developer of GWorkS (as mentioned at the end of section 2.5.2, describing the status of the model).

The model generates objects like *Greenhouse Layout* and *Growing system* based on the *model inputs P* which includes details about the greenhouse simulated. The user needs to define input parameters such as size of the greenhouse and the crop system (the inputs of the model is detailed in Appendix A) and also define run settings including the time series to simulate paths of interest, i.e. the paths the user would like to see simulated and obtain results for.

Run initiation section defines the input for the *job planner*. The *Job planner* plans and generates jobs which must be performed based on job frequency input from the excel workbook and job history. This job is an entity, which follows the entity path in Figure 8. After the job has completed and is reported, the entity is destroyed in the *Job sink*. The *job completion status* checks if job was finished and returns status to *job planner*. Detailed process output per day and cumulative performance indicators are created such as amount of peppers harvested including from which path, cycle time for a path, average time for a worker and utility of resources (workers and trolleys).

The details of the GWorkS model's inputs and outputs are described in Appendix A and Appendix B.

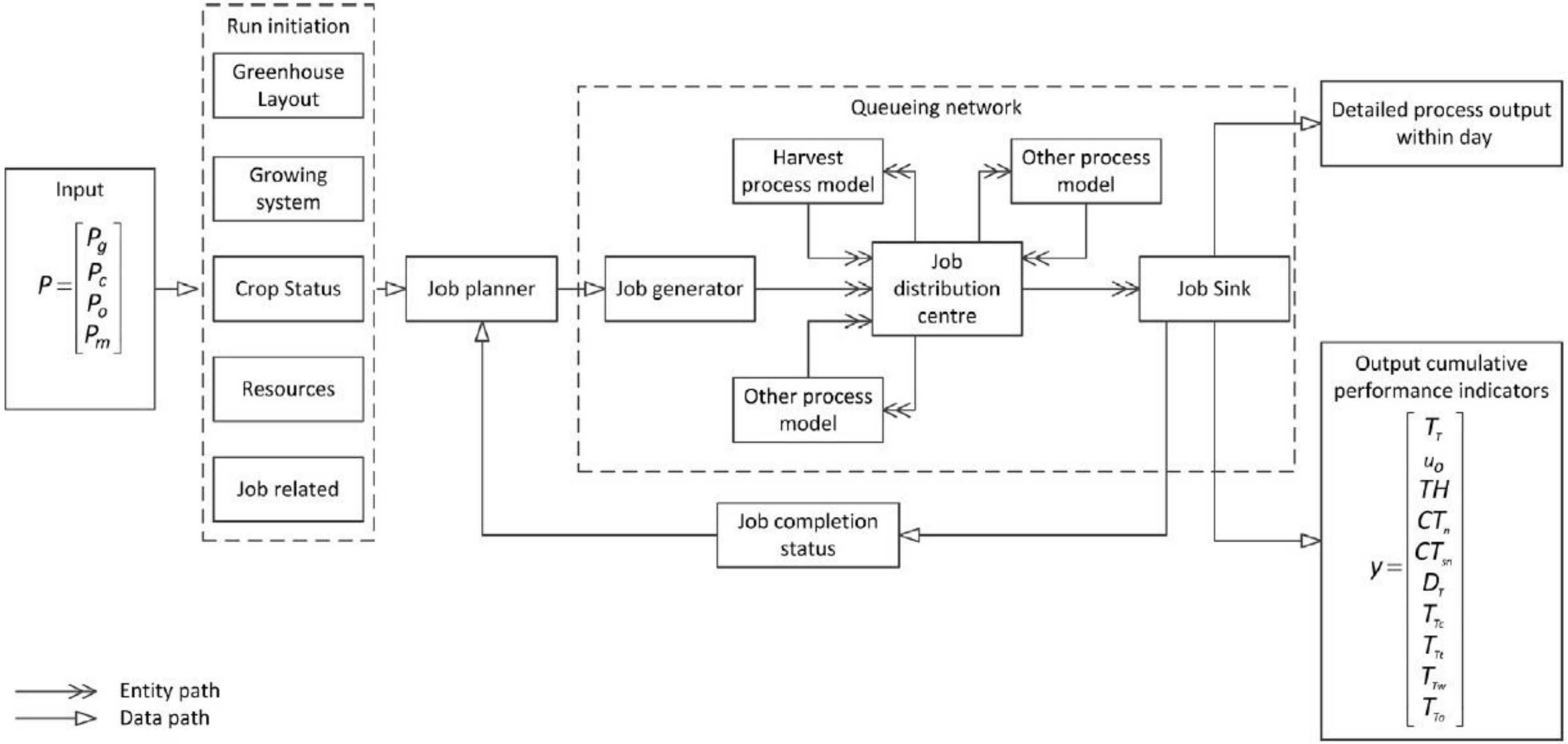


Figure 8: Main structure of the model GWorkS-Roses
(van't Ooster et al., 2013)
The same structure is used for the model GWorkS-Peppers (Aantjes, 2014; Elkoby et al., 2014)

3. Methodology

3.1 Overview

A simulation model aiming to evaluate how many resources are needed for the sweet pepper harvesting process was developed in Matlab based on GWorkS. The simulation was used to examine the number of human workers and robots (defined as human-robot combination) required to complete the harvest along the entire harvesting season.

The parameters for the simulation model were based on data collected from two greenhouses, one in the Netherlands and one in Israel. All simulations were analyzed for a 4.3 hectare sized greenhouse (which was equal to half of the NL greenhouse). The resulting combinations were also translated to 8.6, 10, 15 and 20 hectares. These human-robot combinations differ in number of workers and robots, in robot capabilities and the resulting harvest division between the robots and workers.

Economic analysis was performed by comparing annual costs of each solution found in the simulations and the annual costs of solutions with harvesting by human resource only. The annual savings were found to determine the maximum initial investment to justify a robot (i.e., the robot cost).

3.2 Data collection

All data for the research was collected from two commercial sweet pepper growing houses, one in The Netherlands (NL) and one in Israel (IL). The data includes the following information:

- **Production site:** growing house dimensions and layout, number of paths and their dimensions.
- **Human workers harvesting performance:** the sequences and times of sub-actions comprising the harvesting action.
- **Yield information:** harvested amounts at each harvest date, the height of the peppers harvested and its weight all along the season.

Most of the data used in the research analyses was based on the NL greenhouse due to the detailed level of data collected there. This included data for simulation inputs and the different scenarios tested. The IL data was taken from a net house and was used for sensitivity analysis of the yield model (one of the simulation's inputs) that was derived from the NL data (4.3).

The data analysis of the NL greenhouse included:

- Examining the effects of the factors: harvest date, path harvested and worker on the harvest time by calculating averages and standard deviation of harvest times. Welch test (also known as "unpaired" t test) was used in case a factor shows low std., for verification that the factor has no effect over the harvest time.

- Characterization of the harvesting season of 2012 for defining input parameters to the simulation model regarding the season's features as: harvest cycle (HC) duration, number of days between HC, number of HCs throughout the season etc.
- Creation of additional yield data sets for simulation model inputs (changing parameters of a literature based yield model).

3.3 Robot performance assumptions

The following performance parameters were assumed for the modelling of the robots:

1. Unlike the human, the robot does not harvest 100% of the peppers in a path. The harvest detection rate (R_{DET}) and harvest success in each attempt to harvest (R_{RETRY}) are provided as inputs to the model.
2. R_{DET} and R_{RETRY} are constants for each attempt and for each pass through a path.
3. When a robot harvests a second/third/or consecutive harvest in a path (can happen if all the workers are occupied or not currently in the greenhouse), the R_{DET} rate is calculated based on the remaining amount of peppers in the path until there are less than 5% peppers of the original peppers amount.
4. The cycle times depends only on the motion time (the time it takes the robot to move between two locations), there is no extra time calculated for the peppers detection which is assumed to be executed in parallel.
5. The robot's gripper movement to the pepper for a harvest is calculated by the shortest distance between the pepper and the initial gripper position.
6. The logistics inside the paths, the harvest sequence (one side of the path after another) and movements of the robot are identical to the human worker, but with different speeds.
7. The robot can work 20 hours per day, 7 days a week.

3.4 Simulation model

A simulation model was developed to simulate different work scenarios in a sweet pepper greenhouse, which included different human-robot combinations (number of human workers and harvesting robots and their capabilities) in order to complete the harvest in a greenhouse. The model was built based on concepts and elements from the existing GWorkS simulation model (van't Ooster et al., 2015) and was implemented in the Matlab version R2014a environment using Simulink and SimEvents. Even though the GWorkS model can simulate sweet pepper greenhouse logistic operations, and was validated (Aantjes, 2014; Elkoby et al., 2014), a new model was built in this thesis with focus on combined work of robotic and human harvest operations in the greenhouse. Conceptually, it is possible to simulate a robot as one category of a 'worker' resource in the GWorkS model with different capabilities but several changes related to current worker capabilities should be made to enable that; for example the robots' incomplete harvest in a path (the robot is not able to detect and harvest all fruit) and as a result- harvest repetitions to complete a non-completed harvested path, a different method for timing of ‘limb’ movement in the harvesting actions based on calculated time rather than randomized time sampled from a known probability density function. In addition, once another type of resource is entered into the simulation model both "compete" on the same harvesting operations and therefore there should be proper assignment of different priority to worker versus robot on a first or second harvest in a path and this changes the operations resource allocation of the model.

All of these features require changes to the GWorks model. These changes require expertise to incorporate them directly into the GWorkS model which is a generic model.

Therefore, a new model was built in the research, in a smaller scale focusing only on the harvesting action of a greenhouse with two resource types: worker and robot, each with its own capabilities enabling different behaviors (i.e. incomplete/complete harvest in a path, movement and harvest timing) that can work either each separately or with pre-defined work division (combined work).

3.5 Human-robot combined solutions

3.5.1 Description

Simulation runs were designed to find the needed number of resources to complete the harvest, by examining the effect of different robot capabilities and different combinations of humans and robots on the ability to complete the harvest of the entire season. A human-robot combined solution is a suggested number of resources in which the harvesting task in the greenhouse is divided between the two resource types. As shown in Figure 9, after defining the number of workers required and specific robot capabilities, the simulation returns the required number of robots and a human-robot combination is created. A path will first be harvested by a robot when available. Since the robots are not capable in harvesting all fruits (i.e., their harvest is incomplete) each path is then completed by a human worker (the human harvests the peppers that the robot did not harvest). Nevertheless, for increased utilization, in some cases a worker can harvest a new un-harvested path (and complete the harvest at once) or a robot can complete the harvest in an incomplete path. The assignment of robots/humans to paths was performed so there will be no possible situation of available resource in idle state while harvesting tasks are waiting (Figure 10; the harvesting tasks are always in one of the resources queues). Harvest completion is achieved when the assigned resources manage to harvest all the paths of the greenhouse within a defined time window in every harvest cycle (HC) conducted along the season. When the criterion of harvest completion is met for the whole season, the solution is logistically feasible. The time window defines the amount of days the harvest in a HC normally lasts.

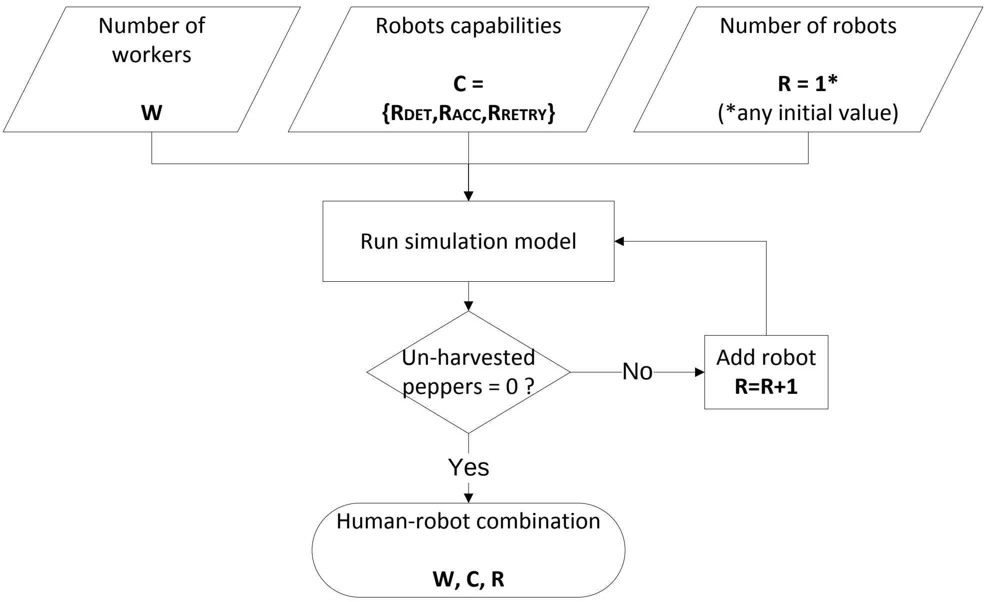


Figure 9: Flowchart describing the process of determining the human-robot combinations for the simulation analyses

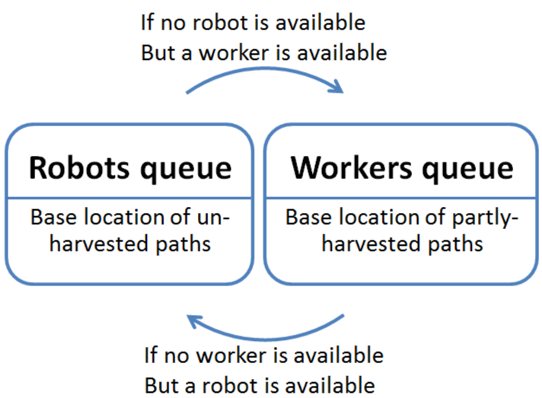


Figure 10: Human-robot combined work allocation diagram

Due to the length of simulation runs[1] when simulating the entire season, it was decided to run only part of each harvest cycle comprising the season. If for example the HC's time window is X days, then in the simulation only one day was simulated with the objective to harvest $\left[\frac{1}{x}\right]$ of the greenhouse. As a result the runtimes of simulations are shortened and the number of resources needed is the same as if the run was executed for the entire harvest cycle.

In the first stage, the starting point of a solution is a fixed number of workers that are not sufficient to complete the harvest alone. To complete the harvest, robots are added to the greenhouse with the following harvesting capabilities: robot detection accuracy (R_{DET}) of 70%, robot's harvester arm acceleration (R_{ACC}) of 0.2 m/s^2 and robot repetitive cycles success rate (R_{RETRY}) of 100%. For all harvesting tasks in the greenhouse, the priority of an un-harvested path is allocated to the robots, unless a worker is available and the priority of a partially harvested path (after one or more harvests by robots) is the workers, unless a robot is available. To determine the number of required robots, a series of simulation runs was performed simulating the peak of the season[2] for each solution. In each run the number of robots increases until the harvest is completed within the required time window. After determining the human-robot combination (i.e. the number of robots for the given number of human workers) an additional simulation run is performed for the entire season to verify if the resources are indeed sufficient for the entire season and to analyze the resources utilization.

In the second stage, the starting point for a feasible solution is a fixed number of robots below the maximum number of robots determined in the previous stage. For each fixed number of robots, the harvesting season was examined for the required number of workers to complete the harvest. The number of robots remains constant while unlike the first stage, the number of workers can be changed along the season.

3.5.2 Sensitivity analysis

Sensitivity of the solutions of the human-robot combinations to changes in the robot harvesting capabilities (5.1.4) and yield was tested.

Robot harvesting capabilities- sensitivity of changes in the following parameters (Table 7):

- **Robot detection accuracy (R_{DET}):** different robot detection rates were tested: 100%, 90%, 70% and 50%.

---

[1] One run of the whole greenhouse for the entire season with 6 resources lasted 172,800 seconds on a Samsung computer- Intel® Core™ i5-3230M CPU 2.6GHz, 8.00 GB RAM, 64-bit Operating System

[2] The yield of sweet peppers along the season changes depending on days from harvest; it was found that in the basic yield scenario, between 223 and 273 days since transplanting the yield is maximal and therefore the resources that completes the harvest there will complete the harvest the entire season

- **Robot's harvester arm acceleration (R_{ACC}):** the acceleration of the robotic arm has direct influence on the robot's cycle time. Therefore, in order to test the effect of the harvesting time on the number of robots, different accelerations were tested: 0.1 m/s^2, 0.2 m/s^2 and 1 m/s^2.
- **Robot repetitive cycles success rate (R_{RETRY}):** the success rate for harvesting a detected pepper in (two) potential repetitions of harvest actions (N_{RETRY}=2) was tested, each with a success rate of 70%.

The total success rate for each R_{DET} combination with R_{RETRY} is presented in Table 13.

Table 7: Summary of the robot capability parameters analyzed in the research

Parameter	Description	Baseline	Sensitivity
R_{DET}	Robot detection rate for peppers [%]	70	50, 90, 100
R_{ACC}	Robot's harvester arm acceleration [m/s^2]	0.2	0.1, 1
R_{RETRY}	Robot success rate for harvesting [%], equal in each repetition	100	70
N_{RETRY}	Maximum repetitions [Times]	1	2

Yield- the sensitivity to yield changes was analyzed. When using yield level as an input for making decisions about the resources needed in the greenhouse, it is important not only to use the paths with average yield patterns, but to check also the outliers.

Therefore, high and low yields were examined in addition to average yield that served as the basis for all simulation runs. The parameters used for yield creation were based on the yield mathematical model (detailed in section 4.4.3.3). When using low yields model parameters, the total yield decreased in 43% from the average yield of the entire season (total yield per year: 18.11 kg/m^2/y) and when using high yield parameters, the total yield increased by 25% (total yield per year: 35.51 kg/m^2/y).

3.6 Economic analysis

Economic analysis of the human-robot combined solutions was performed based on the methodology applied in CROPS (a FP7 EU project dealing with development of a sweet pepper harvesting robot - evaluation of economic viability of agricultural robotic systems, Ref: C0399). This evaluation examined the costs of human workers and robots as separate resources and the maximum cost to invest in the robots as a function of the annual savings when replacing the workers defined as the *maximum cost per robot*. In this model, the number of resources needed for the costs calculations was originally determined from the estimated average time per pepper of each resource. Modifications to this economic model in this thesis included enabling costs calculations of combined human-robot work solutions rather than each resource working separately and deriving the number of resources needed from the simulation results instead of the less realistic calculation based on average times (it is not guaranteed that the average amount of workers/robots will be sufficient for the peak of the season).

The annual cost of the workers as a sole resource was used as the basis for comparing all other solutions (current state). In this thesis economic analysis, similar to the CROPS model, each solution including robots as a resource was calculated for the equivalent annual cost without the robots investment and maintenance costs that are yet unknown; the solution was compared to the current state annual cost. Using the annual costs gap between the solution and current state, combined with the fixed costs parameters for robots, the willingness to invest in robots was calculated.

The economic analysis includes three parts for all examined solutions with different robot capabilities to determine the *maximum cost per robot*:

1. **The tested greenhouse-** fixed greenhouse size of 4.3 hectares with identical yield in all solutions derived from the yield model (based on average yield of the NL greenhouse).
2. **Greenhouse with** low and high yields.
3. **Greenhouses of** different sizes: 1, 4.3, 8.6, 10, 15, 20 hectares.

4. Data sources

4.1 Overview

The data for the simulation model was based on two sources:

1. **Data collected in commercial growing houses-**
   - **The Dutch greenhouse:** "Van der Harg van Winden" greenhouse located in Bemmel in the east of the Netherlands. The production area is separated into two different greenhouses with a total of 8.6 hectares of red peppers. The sorting and packing lines are located in between the two greenhouses (Figure 11). Each greenhouse has a main aisle with crops on both sides, organized within paths. The span width is 4.8 m with 4 crop rows in each span. A single trellis girder spans two spans widths and is called a base or greenhouse section.
   - **The Israeli net house:** "Kochav" net house located in Camhin in the south-west of Israel. Its production area is approximately two hectares of red peppers separated into two one hectare different growing areas. One area is dedicated to growing peppers in the “Spanish” cultivation system and the other includes pepper growth in “Dutch” cultivation system (the Spanish system is not evaluated in this study). In this research the focus will be on the “Dutch” cultivation part. The net house has a main aisle with crops on both sides, organized within paths.
2. **Yield data based on models from the literature-**

   Additional yield data was delivered based on simple more generic sweet pepper yield growth models (section 2.2.3). New data sets were derived by finding the number of peppers as a function of time from transplanting. These data sets are literature based instead of data measurements from a single greenhouse and therefore considered to have more generic value.

The processed data served as the database for all analysis.

4.2 Data from commercial growing houses

This section includes description and data characterization of both growing houses.

4.2.1 The Dutch greenhouse

4.2.1.1 Description of yield, workforce and equipment

The growing procedure is a cycle according to the following general time table: October-planting, from November to January maintaining the crop with no product to harvest yet. First fruits are harvested in February (green fruits) with increasing yield until April; the main production and yield occur between April and September. From September to October is continuing harvesting with decreasing production. In week 44 (in October) the crop is removed from the greenhouse.

During summer time there are about 3.5 workers per hectare for all crop operations and in the winter the number goes down to 2.5 workers approximately. The workers are partly Dutch and partly Polish. Some of the workers work only in the summer and some only in the winter. Not all workers are qualified to perform all tasks. In the harvest season, there are five working days a week most of the time. Along peaks, harvesting is performed along weekends as well.

The company has 36 electrically-driven trolleys (Figure 12) used to transport the harvester and buffer the peppers until arrival at the processing hall. The trolley has an adjustable height and it moves along the main aisles autonomously. Within a path, the trolley runs along a pipe rail system which is also used as heating system. After cutting, the peppers are placed in a container mounted on the trolley. Once the path is completed, the trolley passes through an induction line automatically to the processing hall (Figure 12); there the peppers are weighted, sorted and packed. Sometimes, the trolley returns only when container is full and not after each path. The maximum capacity of a container is 290kg.

Figure 11: The Dutch greenhouse (right-google earth 2013, left-picture of the greenhouse)

Figure 12: A convoy of trolleys with containers returns to the processing hall automatically

4.2.1.2 Data collection

The grower uses a SDF labor registration system (LRS). The main use of the LRS is recording of work hours, work planning and tracking and tracing (monitoring workers and quality) to analyze labor operations. The LRS also registers the yield in each path when the container holds the yield of one path or a weighted average yield when the container holds the yield of more paths. At the beginning of each path there is an RFID that recognizes the trolley's entrance and exit and transmits it to a receiver located on the greenhouse's ceiling (Figure 13) combined with trolley number and path number. The workers have badges or code numbers which they log, when they start each of their tasks and finish it. All actions are registered automatically by the software .An automatic report on every task done by the workers, frequency of tasks and time required for each task every day can be easily generated.

Figure 13: Registration system of the Dutch greenhouse
(The red marking is enlargement of the RFID on the floor (left) and the receiver on the ceiling (right))

Each of the two greenhouses has four sectors and each sector has 72-80 paths (Figure 14). The paths are numbered from the center of the company (the sorting and packing area) heading out towards the end of the greenhouse.

Data was collected for both greenhouses and detailed for each path and action, between the first week of 2012 (January 1st) and week 38 of 2013 (September 19th). For the model, only the first greenhouse with 304 paths (left in Figure 14) was simulated because it provides sufficient information for testing and validation. Hence, only the information about the first greenhouse (paths 101-472) was used for the simulation model input and validation.

Figure 14: The Dutch greenhouse structure

The information collected and used includes:

- **For each day:** what operations were performed, how many employees were involved, what is the total time invested and the amount of units/paths processed.
- **For each harvesting action performed:** path, employee, trolley and amount of peppers in kg.
- **For each employee:** how many hours invested in each operation per year.
- **Total time** invested in each operation during the whole period, including the number of employees performed the operation.

In addition, the grower provided information about the average pepper weight and crop height for each week of the year. The weight is calculated as an average from the weighing action of boxes after sorting and by counting the number of peppers. The height is measured independently on each Friday for 6-7 plants and an average is calculated. The height is measured from the plant's bed till the top of the plant (Figure 15).

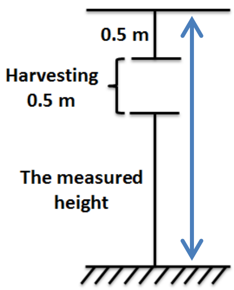


Figure 15: Harvesting height

For completing the data necessary for the simulation model's input and validation, more detailed information about the harvesting process is required. This needed level of detail for the model cannot be obtained with the labor registration system. Therefore, additional data was acquired and analyzed as a part of a B.Sc. thesis in WUR (Aantjes, 2014) and included:

- Subdivision of actions within each harvesting operation: cut of the pepper, place pepper in the container and change the path side when each side finishes. Each is a random variable from a probability density function with calculated expectancy and variance.
- The average velocity of the trolley with the worker on it within the paths: 0.22 m s^{-1}.

This data was calculated for a different greenhouse in the Netherlands but the preliminary assumption is that this data roughly fits the greenhouse in this research due to the similarity in the work processes between the greenhouses. This assumption was examined and verified as a part of the calibration process (section 5.2.2.1).

4.2.2 The Israeli net house

4.2.2.1 Description of yield, workforce and equipment

The growing procedure is a cycle according to this general time table: April- seeding and planting, from May to July maintaining the crop by pruning and trellising operations with no product to harvest yet. The main production and yield occur between July and October; From October to March continuous harvesting with decreasing production.

The number of workers varies along the season: from planting to the start of harvesting there are about 5-8 workers per hectare for all crop operations, from the start of harvesting till the end of October about 10 workers per hectare and between November and March down to 2 workers per hectare approx. For comparison to the other side of the net house (the "Spanish" cultivation) the numbers are 3, 5 and 2 workers respectively. According to the grower the main reason for that difference lies in the difference between the crop maintaining operations that are more demanding in the "Dutch" cultivation system. All the workers of the company are Thais.

In the harvest season, there are six working days a week most of the time, when usually the day off is Saturday, but it can change according to the company needs. The company has 20 hand-pushed trolleys (Figure 16) used to buffer the peppers harvested to the main aisle. During the harvesting, the worker walks with the trolley in the path. On the trolley, plastic boxes are placed- usually six but in extreme cases 7-8 and each box can contain about 10 kg of peppers. In case the harvesting should be made for a pepper positioned higher than the harvester's reach, he climbs on the trolley or even on the boxes. In order to move the boxes into the processing room, there is a tractor with a wagon, on which the full boxes are placed for transport in the main aisle. The wagon can be filled with 300 boxes. Once it's filled, one of the workers drives the wagon to the processing room. When the harvesting is completed for the day, all the workers continue to the processing room and there each pepper is weighed, sorted to weight classes, and packed in a box containing that weight class.

Figure 16: The main isle of the Israeli net house with a manual trolley at the front and tractor with a wagon at the end

4.2.2.2 Data collection

The data from the Israeli net house includes two parts. The first part includes excel files with aggregative information received from the grower and the second part was acquired by video recordings analysed as a part of a B.Sc. final project (Melman & Dotan, 2014).

The data from the grower is mainly collected manually and stored in excel tables, that summarize all the information about the yield and workers of the net house. Therefore, it is not possible to obtain specific and detailed information for each path.

Each part of the net house has two sections and each section includes 6-7 gables (Figure 17). Each gable is enclosed by two poles, and contains 7 paths, each 48 m long. The data was collected for the entire net house between the first harvest in the season of 2013 (July 13th) and week 11 of 2014 (March 10th). The main information collected and used includes:

- Estimated workers demand for the entire company including all actions made by the net house's manager. The number of workers needed per day for the relevant harvesting sections is evaluated based on that information.
- For several dates during the season: number of workers and work hours for harvesting in a section.

- For each harvesting day in the season of 2013-2014: the amount of boxes harvested from each section, the total weight of the peppers harvested and their average weight as measured at the sorting machine.

The second part of the data, including sub actions of the harvesting process as taken from the BSc final project conducted at BGU (Melman & Dotan, 2014). The data was obtained by analysis of video material taken in the net house during January 2014 and processed with the help of the behavioral research software "Noldus Observer XT". The Observer is an event recorder to collect, analyze and present activities, movements and positions of subjects (the workers). The data includes:

- Subdivision of actions within each harvesting operation: grab and cut of the pepper, place pepper in the container, arrange the boxes during the harvesting and turn around when each path is finished. Each is a random variable from a distribution with calculated expectancy and variance.
- The average velocity of the worker holding the trolley within the paths: 0.33 m s^{-1}.
- The average velocity to climb up and down from a box in the paths: 0.39 m s^{-1} up and 0.19 m s^{-1} down.

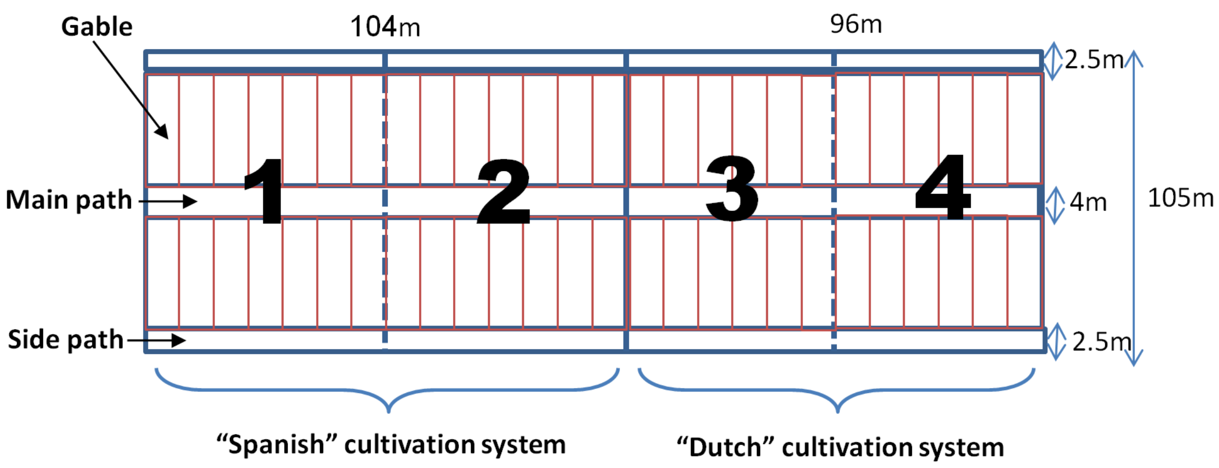


Figure 17: The Israeli net house structure

4.3 Sweet pepper yield data

The data used in this research, includes information of sweet pepper harvested yield as registered in the NL greenhouse. The data is detailed to the level of kg of pepper harvested per path per date. Since the collected data is very limited and the harvested sweet pepper amounts recorded are highly dependent on the environmental conditions of the recorded season (e.g. low yields due to extreme weather) and management decisions (e.g. day off to the workers) made in the Dutch greenhouse, more flexible yield data was needed. It is needed that in every simulated HC, all paths will be "filled" with yield to harvest. But the data as collected from the greenhouse, does not deliver that because in practice not in every HC all paths are harvested and the separation between HC in reality is not always clear. Therefore, additional data was delivered based on simple more generic sweet pepper yield models (section 2.2.3). New data sets were derived by finding the cumulative yield of peppers per path (kg m^{-2}) as a function of time from transplanting.

The sweet pepper growth and yield is affected by many factors as light, temperature, humidity, water status, time since transplanting, development stage, crop operations and other factors (Wubs, Yun, Heuvelink, Hemerik and Marcelis, 2012). Since it is not in the scope of this research to evaluate the crop production, the focus was to obtain a realistic number of peppers as a function of time since transplanting.

The new data sets were created using mathematical models from the literature (section 2.2.3). These models were used as a black box. According to Charlo et al. (2011), the description of sweet pepper growth by its dry mass of fruit is presented by a curve from the type:

$$Y = \frac{b_1}{1+exp(-b_2*(X-b_3))} \tag{1}$$

This curve shape is based on: $DMMFt = 322.47678/(1 + e^{-0.04268(X-124.80796)})$ from Charlo et al. (Charlo, Hamilton César de O et al., 2011). The equation represents the accumulated DMMFt- Dry Mass of Mature Fruits (Y in the general form of equation (1)) as a function of days since transplanting X. This curve's shape can be used also to represent accumulated fruit fresh weight under the assumption that the dry mass is proportional to the pepper's weight in kg. Therefore, the presented equation (1) will be used for its curve and shape, but the parameters (b_1, b_2 and b_3) will be fitted specifically to the data of harvested peppers weight the NL greenhouse, rather than being translated by using proportionality of the dry mass to fresh fruit weight.

4.3.1 Usage of the yield model in the simulation

The curve shape and the parameters found are entered into the simulation model as inputs for the accumulated yield per m^2 in kg. In the simulation, using this curve, the yield is assigned to the paths on a daily basis in the following steps:

1. According to the simulated day (X_1) and information about day of previous harvest (X_2), the accumulated kg per m^2 between these days is calculated:

   $$(2) \qquad YieldModel(b_1, b_2, b_3, X_1) - YieldModel(b_1, b_2, b_3, X_2)$$

2. In order to find the average amount of peppers in kg per path, the accumulated kg per m^2 selected is multiplied with the area of a path in m^2.
3. A lognormal distribution was used to predict the number of ripe peppers per path. Parameters for the distribution were the kg of peppers per m^2 calculated in 1,2 and standard deviation according to the average std. of kg per m^2 between the paths from all the season's past data.
4. Each path's kg peppers is divided by the average pepper weight in kg suitable for the harvest week.
5. The peppers in each path are distributed within the path, each with unique value (x,y,z) as explained in the model inputs of the simulation model (5.1.8).

4.3.2 Sensitivity analysis

After fitting the growth equation to the NL greenhouse data using all the paths in the greenhouse, two steps were performed to test the sensitivity of the yield model parameters (b_1, b_2, b_3) to other data sets:

1. **The IL net house-** different parameters for the same yield curve shape were matched based on the IL net house data.
2. **Extreme yields in the NL greenhouse-** different parameters for the growth model were found using the highest and lowest yield paths in the NL greenhouse.

4.4 Data analysis results

The following analysis results were performed based on NL greenhouse data.

4.4.1 Influencing factors on the harvesting time

The harvest time per pepper calculated from the collected data is influenced by many factors. In order to use this data for simulation model calibration and validation, it was analyzed to derive the variance between different factors including: harvesting day, the harvested path and the worker perform the harvest.

1. **Harvesting day**: the harvesting season of 2012 took place between the dates March 12th and October 29th. For each date in the harvesting season, the average time for harvest pepper, average time to complete a path and the average amount of peppers harvested were calculated. Then, the average of all dates and the standard deviation between the dates was calculated to measure the impact of the date on these averages. The results:
   - The average of harvesting time per pepper for all dates is 3.67 seconds with standard deviation of 0.864 seconds between the dates.
   - The average time to complete a path is 2061.1 seconds with standard deviation of 567.9 seconds between the dates.
   - The average amount of pepper harvested in a path is 585.2 peppers with standard deviation of 219.5 peppers between the dates.

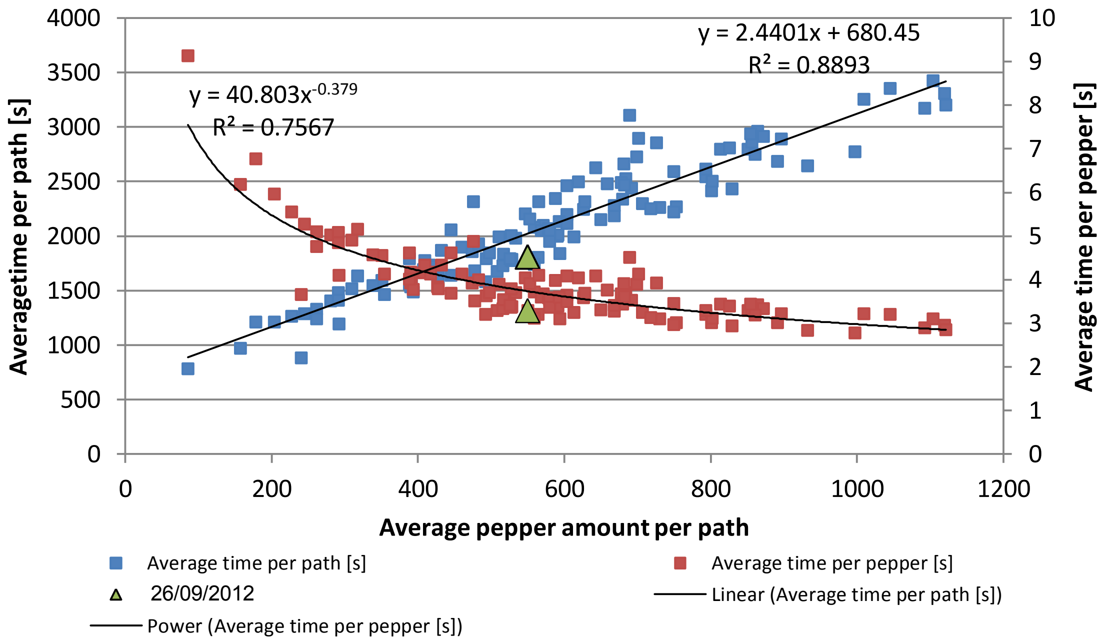
The deviation between the dates average harvest times may be explained by the large difference in amount of peppers harvested at each date. This is probably due to changes in the peppers growth throughout the season as explained in section 2.2.3.

In Figure 18, the average time per path and per pepper are presented as a function of average pepper amount per path for each of the dates- each point on a graph represents the average time per date (similar graph was created for all harvests without averaging result per day in Appendix C). A trend line was fitted for each average with R^2 of 0.756 for the average time per pepper and R^2 of 0.889 for the average time per path (the same was performed in Appendix C with R^2=0.436 for time per pepper and R^2=0.657 for time per path). According to the trend lines it is possible to see that as more peppers are harvested in a path, the time to complete the path is longer and the gross time to harvest each pepper is shorter. The same behavior of harvest times is expected to appear in the simulation model's results.

Another important conclusion arising from Figure 18 (and Appendix C) is that the date selected for the simulation model calibration: September 26th is slightly faster than the average expected (in Figure 18, this date is represented by a green triangle). The average amount of peppers per path in September 26th is: 550, the time per path is 1810 seconds (upper triangle) and the time per pepper is 3.29 seconds (lower triangle). According to the trend lines:

- The average time per path for the same pepper amount per path is 2022 seconds which is 12% higher than the actual September 26th average (and according to results of Appendix C, around 1996 second, 10% higher).
- The time per pepper is around 3.73 seconds which is 13% higher than the actual September 26th average (and according to results of Appendix C, around 3.64 second, 11% higher).

As a result, when performing the calibration of the simulation model the goal is to achieve high accuracy rates but slightly "slower" than the actual September 26th average, to yield calibration closer to the actual averages.



** The '△' in the graph represents the data point of 26/09/2012. The upper triangle is for average time in a path and the lower is the average time per pepper.

Figure 18: Average harvest time per path and per pepper for each harvesting date in the season of 2012

2. **Path harvested**: the greenhouse is composed of 304 paths. For each path, the average time to harvest a pepper, average time to complete the path and the average amount of peppers harvested were calculated. Then, the average of all paths and the standard deviation between the paths was calculated to measure the impact of the path on these averages. The results:

   - The average of harvesting time per pepper for all paths is 3.67 seconds with standard deviation of 0.164 seconds between the paths.

- The average time to complete a path is 2061.1 seconds with standard deviation of 121.2 seconds between the paths.
- The average amount of pepper harvested in a path is 562.1 peppers with standard deviation of 32.8 peppers between the paths.

The standard deviations for the "path harvested factor" are lower than the standard deviations for the "harvesting day factor" and are approximately 5% from the average value in each calculated category. Due to the low std., it is possible that the path has no influence over the harvesting times (i.e. there is no distinct difference in the harvesting times between the paths). To verify this, the Welch statistical test was conducted.

The selected paths to be examined were 110 paths corresponding to the harvested paths on the calibration date- September 26th (paths 1-61 and 153-205) - denoted as "group calibration" against all other 192 paths (paths 62-152 and 206-304) - denoted as "other group". The data about the two groups of paths selected was taken from all dates along the season of 2012.

Two tests were performed, one examines whether the mean time per path of group calibration is the same as the mean time per path of other groups and the other examines the mean time per pepper. The results (Table 8) showed that there is no distinct difference between both groups of paths tested in the time per path (t_{stat}: -0.0217, P_{value}: 0.9827) but there is difference in the time per pepper (t_{stat}: 5.9751, P_{value}: 1.20E-08) though very small (the interval is close to zero). Hence, it is likely that the simulation model calibration results which are performed on the "group calibration" paths can be referred for other paths as well (but before using these results on other paths it is tested in a calibration test).

Table 8: Welch test for testing hypothesis that two groups of different paths have equal harvest time means

	Measure	"Group calibration" parameters n_1=110	"Other group" parameters n_2=192	*Difference interval (alpha=0.05)	Test conclusion
1	Time per path [s]	Average: 2060.6 Std.: 132.7	Average: 2060.9 Std.: 114.8	(-30.134,29.511)	Equal means
2	Time per pepper [s]	Average: 3.746 Std.: 0.181	Average: 3.627 Std.: 0.137	(0.079,0.158)	Non-equal means

* The difference interval was calculated by adding and subtracting from the average difference between the two groups the value: $t_{1-\frac{\alpha}{2},f} \cdot \sqrt{\frac{S_1{}^2}{n_1} + \frac{S_2{}^2}{n_2}}$, where S_1, S_2 and n_1, n_2 are the standard deviation and the sizes of samples from groups 1 and 2 respectively and 'f' is the degree of freedom calculated by Welch test equation (Appendix D).

3. **Workers**: the greenhouse was harvested in the season of 2012 by 35 different workers. While the simulation model treats all workers as equal, it is clear that there are differences between the workers. For each worker, the average time for harvesting pepper, average time to complete a path and the total amount of peppers harvested by a worker were calculated. Then, the average of all workers and the standard deviation between the workers was calculated to measure the impact of the worker on these averages. The results:
   - The average of harvesting time per pepper for all workers is 3.67 seconds with standard deviation of 1.664 seconds between the workers.
   - The average time to complete a path is 2061.1 seconds with standard deviation of 559.3 seconds between the workers.

   The standard deviation of harvest time per pepper is higher by 1.93 and by 10.14 than the standard deviation of harvest time per pepper between days and between paths respectively. Therefore, the average time per pepper was examined against the total pepper amount each of the workers harvested. Results indicate (Figure 19-left) that there are several workers that harvested only a small amount of peppers each (less than 50,000 peppers all season), and their average time per pepper is scattered along different times (Y axis in Figure 19). This information can be used if there will be major differences between the simulation and the real data of some dates, due to this group of workers. If these workers are disregarded from the analysis (Figure 19-right), the scatter is around an average of 3.7 seconds/pepper with a small decrease of the harvest time per pepper when the total amount of peppers increases. This may be explained by the experience level of workers- the more peppers they harvest the more experience they get and hence the harvest cycle time reduced. In this research the worker resources for the simulation was taken as the average worker and not individual workers capabilities. The reason is that the main focus of this thesis was to analyze performance for different robot capabilities and not different worker capabilities.

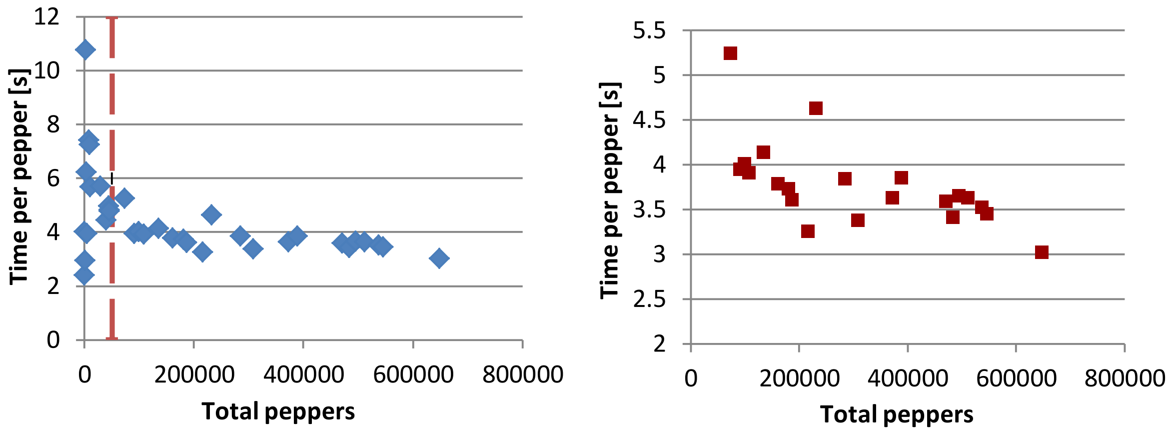


Figure 19: Average time per pepper as a function of total peppers harvested by each worker
Left: presented all workers of the greenhouse
Right: only workers that harvested more than 50,000 peppers all season

4.4.2 Harvesting season analysis

The NL greenhouse's 2012 harvesting season was analyzed in order to derive data about the season's features for simulation inputs. During the season, the greenhouse paths are harvested repeatedly. Every time a harvest of the entire greenhouse in performed, a harvest cycle is made (HC). Two definitions for the duration of a harvest cycle:

- **Time window:** amount of days the harvest in a HC normally lasts.
- **Days since last harvest:** amount of days between the beginning of two sequential harvest operations in one path.

These terms are not identical since between two sequential HC, there are normally some additional days that are used for other crop operations in the greenhouse such as trellising the plants or harvesting a different section of the greenhouse.

In order to define a complete harvest season, the following HC features must be derived from the data: how many HC occur during the harvesting season, HC time window and days since last harvest.

The harvest information of a specific season recorded in the greenhouse is affected by many different factors such as the peppers growth throughout the season, workers availability and experience, weekends/holidays and management decisions. Therefore, in most cases not all paths are harvested in one HC but there are parts of the greenhouse missing (instead they are harvested twice in the next HC), sometimes the workers harvest faster/ slower than the intended time window or there are holidays that extend the amount of days between two HC. Hence, some of the above features could not be found explicitly at the greenhouse level in the data collected in the greenhouse, but therefore, had to be concluded.

To separate between different HC, the data of the NL greenhouse was analyzed manually by visual inspection of the harvested paths in each date. After separating to HCs- the amount of HCs, time window in each HC and days since last harvest between every two sequential HC was calculated (all HC details of the season of 2012 are in Appendix K).

Analyses of the results indicate the following findings:

1. In the season of 2012, 41 harvest cycles were made.
2. The average time window to harvest the paths is three days.
3. Excluding the first two harvest cycles, the average days between two sequential harvests is five days. This implies that after three harvest days there are two days for other crop operations or rest.

To strengthen the third result from the visual inspection of data at the greenhouse level, 80 paths from the greenhouse (one section of the greenhouse) were analyzed individually to find the days since last harvest parameter according to each path harvest dates. Figure 20 shows the results per path (each path is in different color). The results indicate that the average number of days since last harvest is 5.251 days which is similar to the visual inspection that resulted in an average of 5.138 days (this was rounded to 5 for simulation purposes). The standard deviation of the number of days average is 2.4741 which is compatible with Figure 20 in which it's possible to see that the number of days is distributed between 1-8 days and not concentrated around the value of 5 days. Results indicated that several times along the season some of the paths were harvested at lower intervals (i.e., see graph below - several paths were harvested day after day – for example the "blue" path A was harvested 8 times day after day; the "red" path B was harvested 5 times day after day). This could be due to either mistaken re-entrance to a row that was harvested in the previous day and/or incompletion of a path in a previous day that was re-entered in the following day. A total of 88%, 48%, 0% were harvested more than three times along the season every 1, 2, and 3 days respectively.

It is possible in the future to change the model input so it will incorporate for individual paths- each path with a different number or even use changed number of days along the season instead of constant of five days.

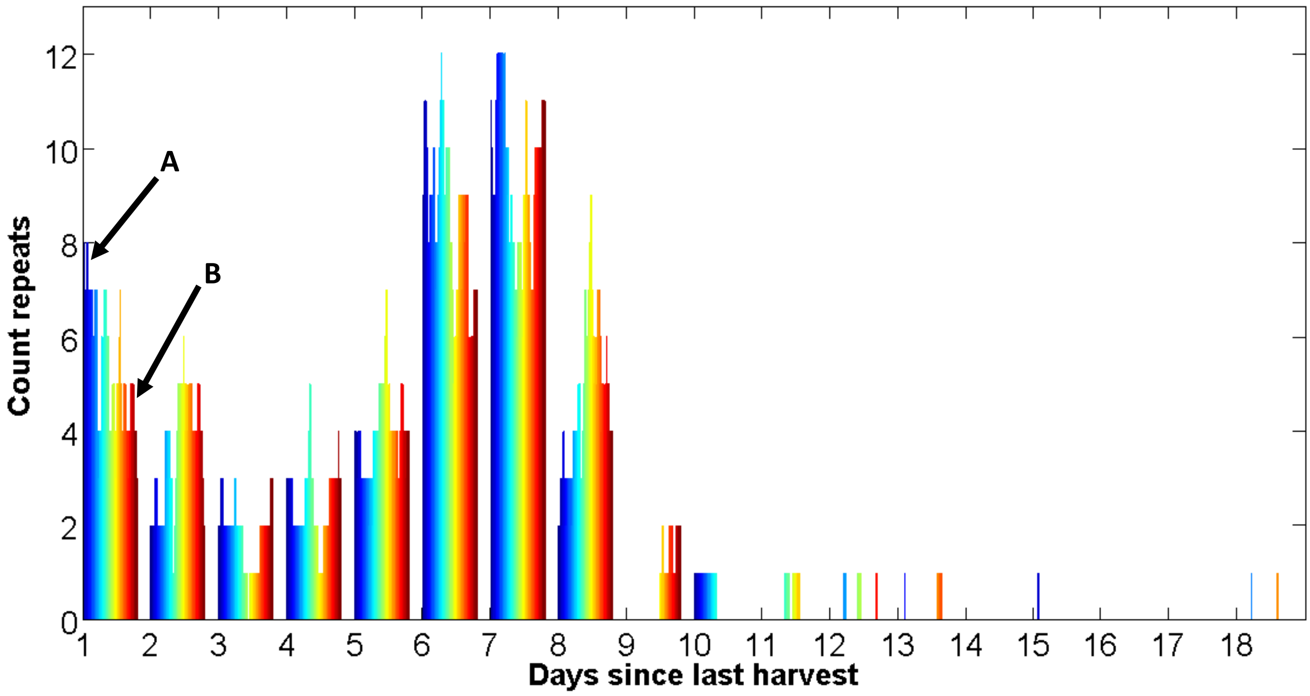


Figure 20: Histogram of individual "days since last harvest" parameter per 80 paths 101-180 (each color bar in the graph represents different path, for example a blue color path A and a red color path B)

4.4.3 Sweet pepper yield data

4.4.3.1 NL greenhouse

The parameters for the growth curve (eqaution (1)) were found using the data of the harvested peppers in all paths of the NL greenhouse in the season of 2012 applying the following steps:

1- The cumulative yield of each path in the greenhouse in kg per m^2, was displayed in a graph in order to visually inspect if it's indeed behaves in the form of the curve presented in equation (1). Each point in Figure 21 with a specific color represents the accumulated amount harvested in a specific path [kg per m^2].

2- The data was entered to a nonlinear regression model (fitnlm function) in Matlab with the general shape of the curve presented in equation (1) and the best fitted parameters b_1, b_2, b_3 for the data was found (Figure 21). The fitted model is (details in Appendix E):

$$(3) \qquad Y\left(\frac{kg}{m^2}\right) = \frac{33.709}{1 + e^{-0.020819*(x-236.06))}} \qquad R^2 = 0.978$$

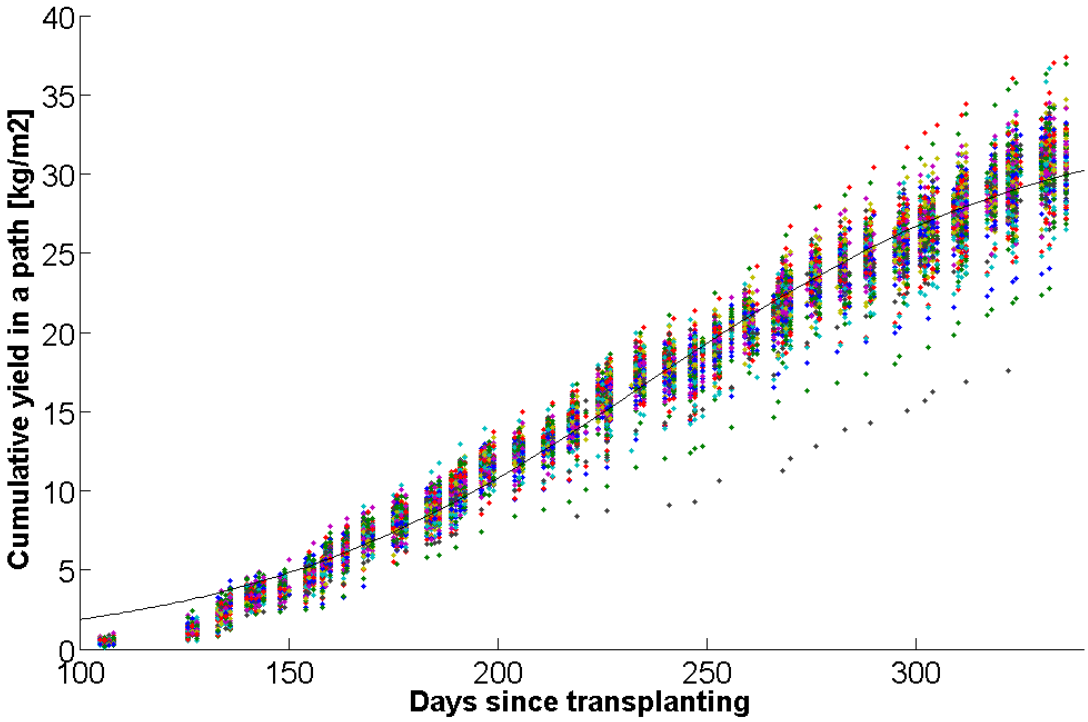


Figure 21: Cumulative yield in a path [kg/m^2] as a function of days since transplanting with the selected parameters' curve)

3- After equation (3) was achieved, the mean squared error (MSE) was calculated for each path to compare the growth of the path versus the growth equation. The average MSE of paths was: 2.111 with a std. of: 4.309 (detailed results in Appendix F). It was seen, that 90% of the paths have MSE value lower than 4. Therefore, paths with exceptions (paths with MSE greater than 4) were removed. The largest exception is path #266 in the greenhouse that has a MSE of 60.13. This path was further examined in section 4.4.3.3 and was mached with different parameters.

4- The new data after removal of 29 paths (paths with MSE greater than 4), was entered to the nonlinear regression model in Matlab as explained in step 3 above. The fitted model is (Appendix G):

$$(4) \qquad Y\left(\frac{kg}{m^2}\right) = \frac{33.825}{1 + e^{-0.020852*(x-235.76))}} \qquad R^2 = 0.986$$

The MSE of all the remaining paths versus the growth model (equation (4)) was calculated and it was found that the average MSE is 1.275, the std. is 0.737, the maximum MSE value is 4.321 and the minimum is 0.473 (Appendix H).

Therefore, this yield model (equation (4)) will be used as an average to model the yield in the entire greenhouse with the standard deviation of yield between paths of 0.381 kg per m^2.

When using the yield model in the simulation (as explained in section 4.3), the simulation uses the difference between two days to derive the compatible yield. To overcome the early yield the model produces, runs starts with the third HC (day 133) assuming the previous harvest took place "days since last harvest" (input parameter 4.4.2) ago, so the early yield of the model is not used.

4.4.3.2 Growth curve of IL net house

Different parameters for the same yield curve shape were matched based on the IL net house data with the purpose to check whether the curve shape can also fit and represent the IL net house yield and to determine the difference between the curves of both countries.

The IL database is different and less detailed than the NL database (section 4.2.2.2). It only contains yield data for the entire greenhouse and not for each path separately. In order for the data resolution to be compatible with both greenhouses for visual data comparison; the kg per m^2 for each date in the NL greenhouse is now calculated from the entire greenhouse rather than for each path individually.

The IL total yield recorded was distinctly lower than the yield in the NL greenhouse (Figure 22). Hence, different parameters for the yield model should be used for the IL net house. Using the same nonlinear regression model (fitnlm function) in Matlab, the equation for yield in the IL net house is (detailed results are in Appendix I):

$$(5) \qquad Y\left(\frac{kg}{m^2}\right) = \frac{16.632}{1 + e^{-0.031339*(x-160.63))}} \qquad R^2 = 0.985$$

Due to the high coefficient of determination (R squared), it seems that this curve shape can be used for the IL net house as well (in comparison to the NL greenhouse fitted parameters R squared - 0.986).

As mentioned in the previous section, the first days where the yield model produces more yield than the actual data, are not used in the simulation runs.

4.4.3.3 Sensitivity analysis of the growth curve

The growth model presented in equation (4) was based on the average between the yield amounts of all paths, and therefore it was examined also for the paths with extreme yields. For that purpose, the top four paths with the highest MSE from stage #4 from section 4.4.3.1 was tested separately against the growth curve (Figure 23). Among these four paths with the most extreme yield values, the edges are path 304 with the highest yield and path 266 with the lowest yield. Hence, two growth curves will be created separately for these two paths

(Figure 24). In Table 9 and Table 10, the parameters selected by Matlab's nonlinear regression function to the highest and lowest yield paths.

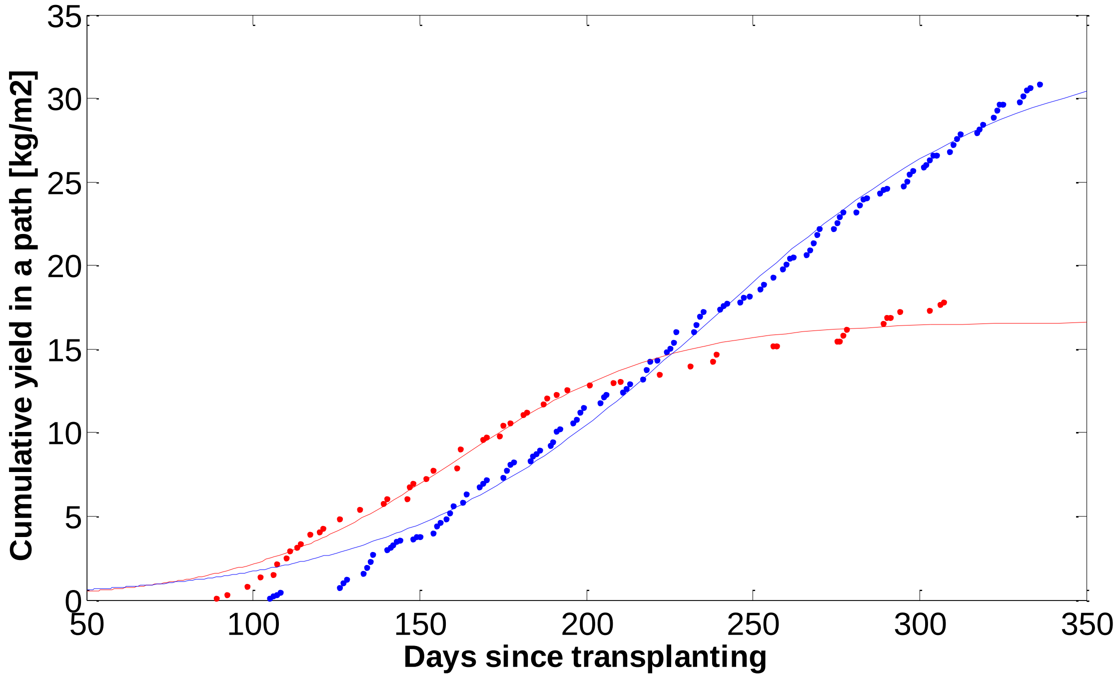


Figure 22: IL and NL cumulative yield
(Red dots and continuous line- IL yield + fitted yield curve. Blue dots and continuous line - NL yield + fitted yield curve)

Table 9: Parameters of both lowest and highest yield growth curves

	Lowest yield				Highest yield			
	Estimate	SE	tStat	pValue	Estimate	SE	tStat	pValue
b1	27.1	5.4434	4.9784	4.39e-05	41.073	1.1157	36.814	1.41e-29
b2	0.014501	0.001879	7.7162	5.94e-08	0.022129	0.000917	24.121	2.14e-23
b3	281.27	28.946	9.7171	8.58e-10	240.69	3.304	72.847	8.22e-40

Table 10: Details on the lowest and highest yield growth parameters

Criteria	Lowest yield	Highest yield
Number of observations	27	38
Error degrees of freedom	24	35
Root Mean Squared Error	0.89	0.96
R-Squared	0.973	0.994
Adjusted R-Squared	0.971	0.993

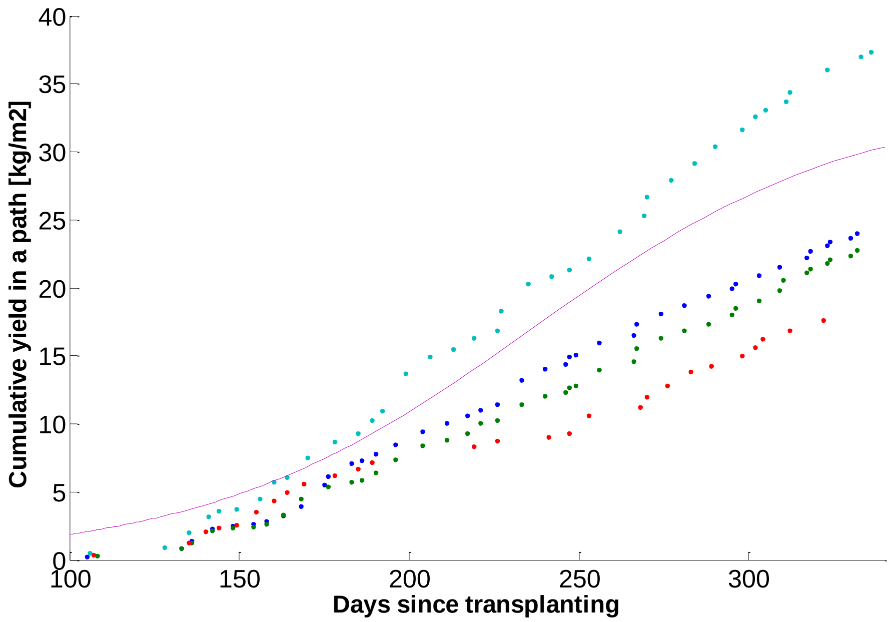


Figure 23: Four highest MSE of paths vs. the growth curve
(Dots: path 1: Blue, path 2: Green, path 266: Red, path 304: Light Blue)

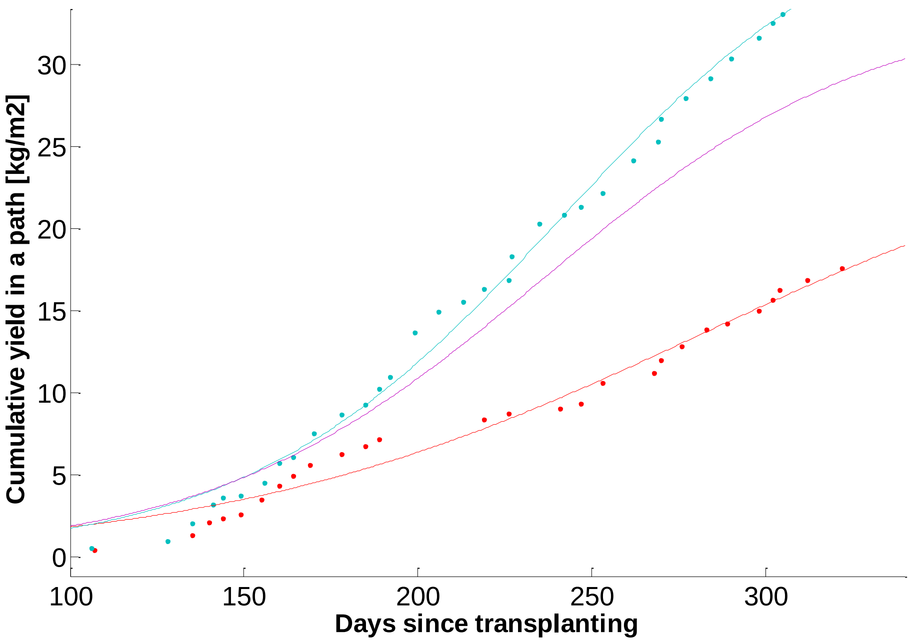


Figure 24: The fitted yield models for the paths with the highest and lowest yields
(At the center: the average growth curve from section 4.4.3)

5. Simulation model

5.1 Simulation model description

A simulation model was developed in the Matlab environment using Simulink and SimEvents for simulating different work scenarios in a sweet pepper greenhouse. In the following sections, the model is described based on the ODD protocol (section 2.4.1).

5.1.1 Entities, State variables, and scales

The model includes several types of entities (Table 11). The main entity of the model represents a path in the greenhouse that needs to be harvested. This path entity is created whenever there are peppers to harvest within it according to the inputs. The path entity includes all the locations of the peppers to be harvested.

Other important entities are the two main resources of the greenhouse- workers and robots.

The path entity can enter the harvesting process only when a resource entity (worker/ robot) is available. This is implemented by using the resource-entity as a Kanban-entity based on the Kanban concept used in 'Lean management' (van 't Ooster et al., 2012). The use of this concept ensures that there will not be more than one resource active in a path harvesting. In the simulation model, it was realized by using the "entity combiner"- combination of path-entity and resource-entity.

The resources entities (robot and worker) can be in different states during the simulation run. The essence of the states indicates whether the resource is active or not. When a resource is inactive, the harvesting jobs (path entities) will wait in a queue until the resource is active again. These possible states are implemented in the simulation model with Matlab's Stateflow chart (Appendix L).

In the model, once a run begins the Stateflow immediately enters the suitable group of states according to the input's definition of resources type for this run. There are three possibilities for the state: only worker, only robot or human-robot combination (Table 12).

In case the model is defined for human and robot collaboration, the system states are: *BothActive*, *OnlyWorkerActive*, *OnlyRobotActive* and *NotActive* (Figure 25). Switching between the states happens when one of the following signals is received:

RobotStart or **WorkerStart**- indicates the beginning of the resource's work and is defined as the moment where path-entities arrive in the queue for the resource. These signals are referred to as: 'Start' signal.

RobotBreak or **WorkerBreak**- indicates the part of the day in which the resource is inactive. The signal is received when the resource has reached its maximum time per day, so it enters the inactive (break) time or when a new day has started- meaning it is now ready to be active again (the break or inactive time of the previous day is over). These signals are referred as: 'Break' signal.

RobotFinish or **WorkerFinish**- indicates that the work of the resource for the entire harvesting window is finished. Finished work is defined as the moment where the queue of waiting path-entities is equal to zero and the amount of unoccupied resources is equal to the total amount of this resource type in the greenhouse. These signals are referred as: 'Finish' signal.

Table 11: The simulation model entities description

Entity	Classification	Description of use	Main attributes
Path	Real-world element, place of action	The main entity. Represents a path in the greenhouse that needs to be harvested.	Path counter, pepper locations, pepper amount, path coordinates, priority.
Worker	Real-world element, resource	Represents a human worker in the greenhouse. Whenever a worker is available, a harvesting action can be performed.	Worker index, speed (XYZ), timing of actions compose the harvesting action, location.
Robot		Represents a robotic harvester. Whenever a robot is available, a harvesting action can be performed by it. The robotic harvester has a given success rate, so it cannot complete harvesting of entire path at once.	Robot index, speed (XYZ), timing of actions compose the harvesting action, location, robot success rate.
Resource + Path (job entity)	Real-world element, assigning of a resource to a place of action	Represents a resource entering a path and start harvesting. Each time this entity gets to a server, one harvesting action within the path is made (on pepper is being harvested).	In addition to each entity separately: Harvest counter within the path, timing of four actions composing the harvest.
Break	Administrative, modelling purpose	Represents disabling of a resource. There are two types of break entities- one for each resource. A break is initiated each day after a resource has reached it's time limit. The purpose of this entity is to initiate transition to break state- meaning the resource is not available.	Serial num., resources time limit, breaks duration.
Time limit		Represents the simulation end time. Only one entity is created at the end of simulation and by its creation- all data from un-harvested paths can be collected.	Simulation length

Table 12: Resources states (at group level- all workers/ all robots) during simulation

Resource type defined in input	States of resources	Meaning	When
Only worker	WorkerHarvest	Workers are active (available/ during work)	During worker's work hours according to input
	WorkerBreak	Workers are inactive	Not during work hours
Only robot	RobotHarvest	Robots are active (available/ during work)	During robot's work hours of according to input
	RobotBreak	Robots are inactive	Not during work hours
Worker and robot	BothActive	Both resources are active (available/ during work)	During work hours of both resources.
	OnlyWorkerActive	Workers are active and robots are inactive	During worker's work hours and the robots are either on a break nor finished their harvesting tasks for the day
	OnlyRobotActive	Robots are active and workers are inactive	During robot's work hours and the workers are either on a break nor finished their harvesting tasks for the day
	NotActive	Both resources are inactive	Both resources are out of their work hours or finished their harvesting tasks for the day

In Figure 25, the flow of "worker and robot" group of states (Table 12) is described:

The initial state in, depends on which 'Start' signal arrives first: *OnlyRobotActive* or *OnlyWorkerActive*. The exit from this state can happen if one of the following signals is received: a 'Start' signal from the other resource- and the switch will be to *BothActive* state, or a 'Break' signal from the active resource- and the switch will be to *NotActive* state. In case the current state is *BothActive*, the system can only switch to either *OnlyRobotActive* or *OnlyWorkerActive*. This switch can happen only if a 'Break' or 'Finish' signal was received from a resource and the new state will be only the other resource active. In case the current state is *NotActive*, the only signal that can cause a switch to a different state is a 'Break' signal, signify that one of the resources has finished its break and starts working again.

The model uses parameters expressing time and space on resources and yield features for a realistic simulation. The steps of the simulation are VariableStepDiscrete and the simulation time is represented as seconds. The duration of all simulations is full 24h days. The model runs for a greenhouse area of GreenhouseLength x GreenhouseWidth m^2. The locations of the resources and yield represents coordinates in meters relative to the origin (0,0,0) which relates to the greenhouse entrance.

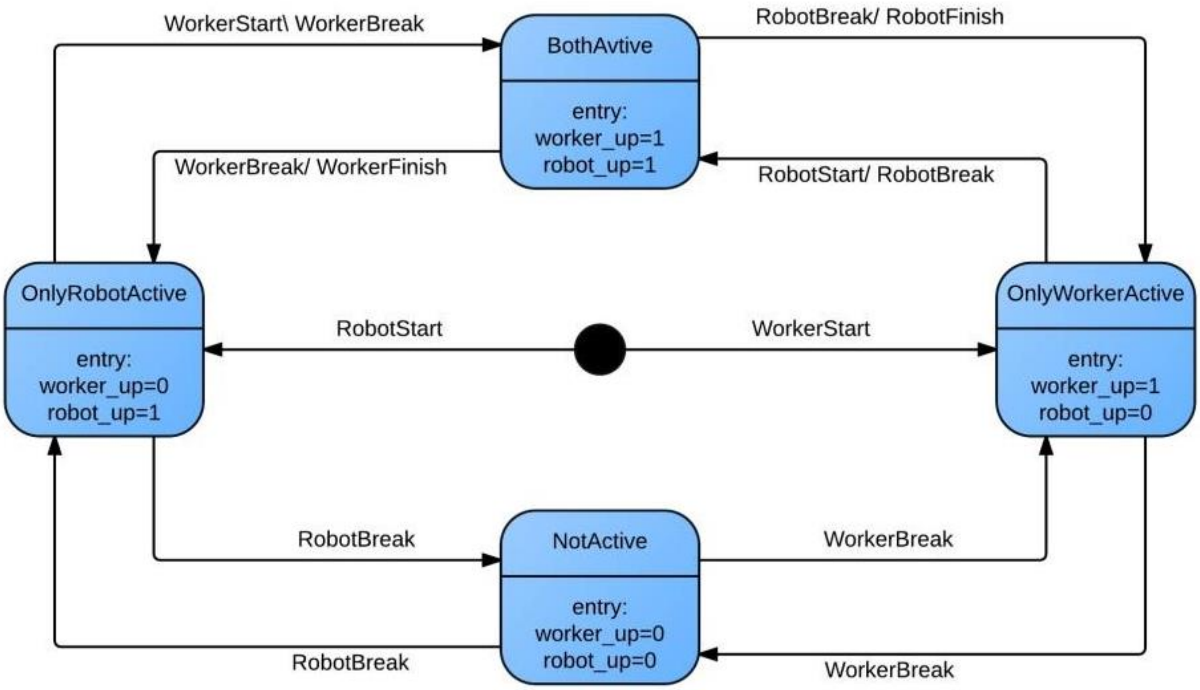


Figure 25: UML state diagram of workers and robots collaboration (the starting point is at the center) the states and signals are in a group level- all workers/ all robots in the greenhouse

5.1.2 Worker and robot modelling concepts

The worker resource in the simulation model is based on the analysis of the human workers harvesting action (section 4.2.1.2). The robot resource was built using the structure of the worker's harvesting operations with adapted timing, speed, success rate and other features. These features were estimated based on preliminary results of a parallel development (Pekkeriet, Hemming, & Bontsema, 2014). Since these values are not certain additional values were simulated in sensitivity analyses (detailed in section 6.3.3). Table 14 summarizes the differences between the harvesting robot and the human worker modelling.

5.1.3 Description of human workers harvest modelling

The human workers harvest is divided into three sub-actions:

1. Grab and Cut sweet pepper
2. Store sweet pepper to container
3. Change path side (at every side completion)

Each is simulated with a random variable from a distribution with calculated expectancy and standard deviation as derived from the data analysis phase (4.2.1.2).

5.1.4 Description of robots harvest modelling

5.1.4.1 Timing of harvesting action

The harvest time of the robot is a calculated value of the time to reach the pepper based on the following assumptions and parameters:

1. The Z height of the gripper is defined at the beginning of each path as the average pepper height above ground. The XY location is the location within the path: X is positioned 0.1m before the closest pepper perpendicular to Y, and Y is changing along the movement within the path (Figure 26).

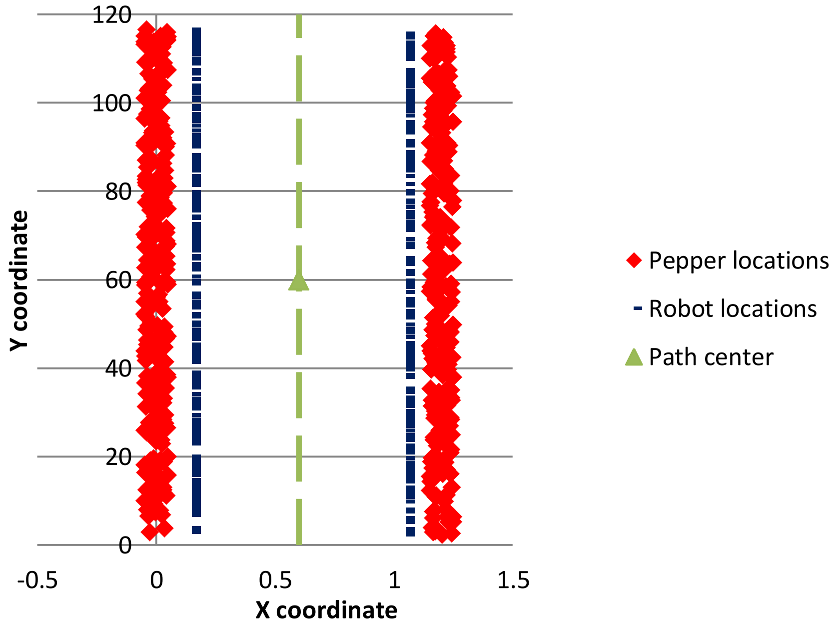


Figure 26: XY chart of a path with robotic (gripper) location

2. The robot's maximum Y distance from a pepper is 0.35 m ("Y tolerance" in Table 14). If the distance is larger, the robot will move to the pepper position (the Y distance will then be 0). The movement of the robot's carrier in the Y axis (within the path) is calculated similar to the human movement within a path, with a constant speed. The speed is assumed to be 0.4 m/s (almost twice than the trolley with a human worker on it which is 0.22 m/s).
3. The XYZ distance from the fruit will determine the time of the robot movement to reach and cut the pepper. The robot’s movement towards the pepper always starts from the same initial XZ location (as explained in #1) and is at maximum distance of 0.35 m from

the pepper on the Y axis (as explained in #2). The robot's gripper motion time is calculated as a trajectory with constant acceleration according to equation (6):

$$S = S_0 + V_0 t + \frac{1}{2} a t^2 \quad (6)$$

Where: $S = \sqrt{dx^2 + dy^2 + dz^2}$ (the shortest distance to the pepper) and $S_0, V_0 = 0$. Due to the short distances the robot passes from its initial position to the pepper's position, the main limitation is the acceleration and not the maximum speed.

4. The harvest time of each pepper is calculated as:

$$t_{harvest} = t_a + t_b + t_c$$

   a) Time of movement from initial robot position to the pepper: $t_a = \sqrt{\frac{2S}{a}}$

      (In the model inputs: t_a is Action 1).

   b) Open gripper and grab the pepper, cut the pepper and drop into a tube is assumed to be: $t_b = 1$ second.

   c) After every harvest, the robot must go back to the defined initial position to identify the next pepper. Time of robot movement back to initial position: $t_c = \sqrt{\frac{2S}{a}}$

      (In the model inputs: $t_b + t_c$ is Action 2)

   The harvest time in the simulation is set with optimistic values because the movements to the pepper and back are based on the shortest distance and the cut time itself including catch and release the pepper with the gripper is set to only one second (constant). It is important to mention that these values can be modified in the simulation when there will be more measures of these actions by the robot.

5. At the end of each path side, the robot's X location is changed to 0.1m before the closest pepper to the center of path from the other side.
6. The acceleration is defined according to the robotic arm capabilities (Cyton Gamma 1500): given the small size and workspace of the arm, the main limiting constraint is the deceleration of 0.2 m/s^2. Therefore 0.2 m/s^2 is incorporated in equation (6) in the "base" scenario.

5.1.4.2 Success rate

The robot harvest success rate, unlike the human workers is not 100%. The success rate is composed of detection rate and retries success:

- **Detection rate (R_{DET})** - the robot recognize only R_{DET}% of the peppers in the path. The rest of the peppers are missed. R_{DET} is defined as a model input.
- **Retries success (R_{RETRY})** - after detection, the base scenario assumes the harvest itself always succeeds. In the sensitivity analysis we introduced an assumption that the harvest operations does not always succeed. For every pepper identified (only R_{DET}% of the peppers are identified), the first try will have R_{RETRY} chance to succeed. If it does not succeed the next retry will have also R_{RETRY} chance to succeed and so on. Each retry takes the same time according to the described harvesting time in 5.1.4.1 (the robot starts each harvest from the same initial point and the acceleration is the same). The retries success R_{RETRY} and the number of retries (N_{RETRY}) are defined as model inputs.

The total success rate (equation (7)) is defined as the complementary probability to miss a pepper. The probability to miss a pepper is composed of: the probability to not detect a pepper (1- R_{DET}) plus the probability to detect a pepper but to fail the harvesting procedure (R_{DET} (1- R_{RETRY})^{NRETRY}). Example of calculation with: $R_{RETRY} = 70\%$, $N_{RETRY} = 2$ and different R_{DET} is presented in Table 13.

$$(7) \qquad 1 - ((1 - R_{DET}) + R_{DET} \cdot (1 - R_{RETRY})^{N_{RETRY}})$$

Table 13: Robots actual harvest success with two harvest retries with detachment success

R_{RETRY} \ R_{DET}	50%	70%	90%
70%	45.50%	63.70%	81.90%

5.1.5 Process overview and resources allocation

The high level model structure is guided by the flow of the main entity- greenhouse path between the different blocks (Figure 27). The model starts with paths creation and receiving all the needed attributes (subsystem Path creation) followed by dividing the work between the resources i.e. robot or worker as a sole resource or combination of both (subsystem assign paths to resources). Then, the harvesting action is performed for each of the path entities (subsystem robot harvest and worker harvest) till completion of the whole greenhouse (subsystem paths completed). If a harvest was performed by the robot resource (implying that not all peppers were harvested), the path entity will remain in the robot harvest and worker harvest subsystems until one of the resources completes it (preferably the worker).

Table 14: Summary of differences between the workers and the robots models

	Worker	Robot
Capability	When harvest in a path, all ripe peppers are harvested	Not all peppers are harvested. Depends on the detection accuracy and harvesting retries probability to succeed
XYZ Location	Represents the worker's feet. When in a path the worker is standing on a trolley. X- center of a path Y- location within the path Z- trolley base height	Represents the robot's gripper location. The gripper is aimed in every new path the robot enters. X- 0.1 m distant from the closest pepper to the path's center Y- location within the path (equivalent to the base of the robot location) Z- average peppers height
Movements within the paths	When in a path, the XYZ location can change: dX- leaning over towards the peppers dY- movement forward and backwards in the path dZ- trolley is lifted and lowered	When in a path, the only movement recorded is the movements forward and backwards in the path. This is the movement of the robot's base on the Y axis. During the harvest itself the gripper is moving towards the pepper and back to the origin, but this is not recorded, only the time it takes is recorded.
Timing of "grab and cut" sub-action of harvesting	This action starts at a reachable position to the pepper according to the "XYZ tolerance"*: The time from the hand moving towards a pepper to pepper is in hand detached from the plant. This timing is stochastic.	This action starts when the robot's base is maximum at "Y tolerance"* away from the pepper: The time from the gripper moving towards a pepper, grasping and cutting it and releasing through a tube for container to the gripper is back in the origin. This timing is calculated according to gripper possible acceleration and the shortest distance between the gripper and pepper.
Cost of resource	Cost per worker per hour	1. Initial purchase cost 2. Cost of one operator per hour. One operator to any number of robots in the greenhouse.

* These parameters are changeable in the simulation.

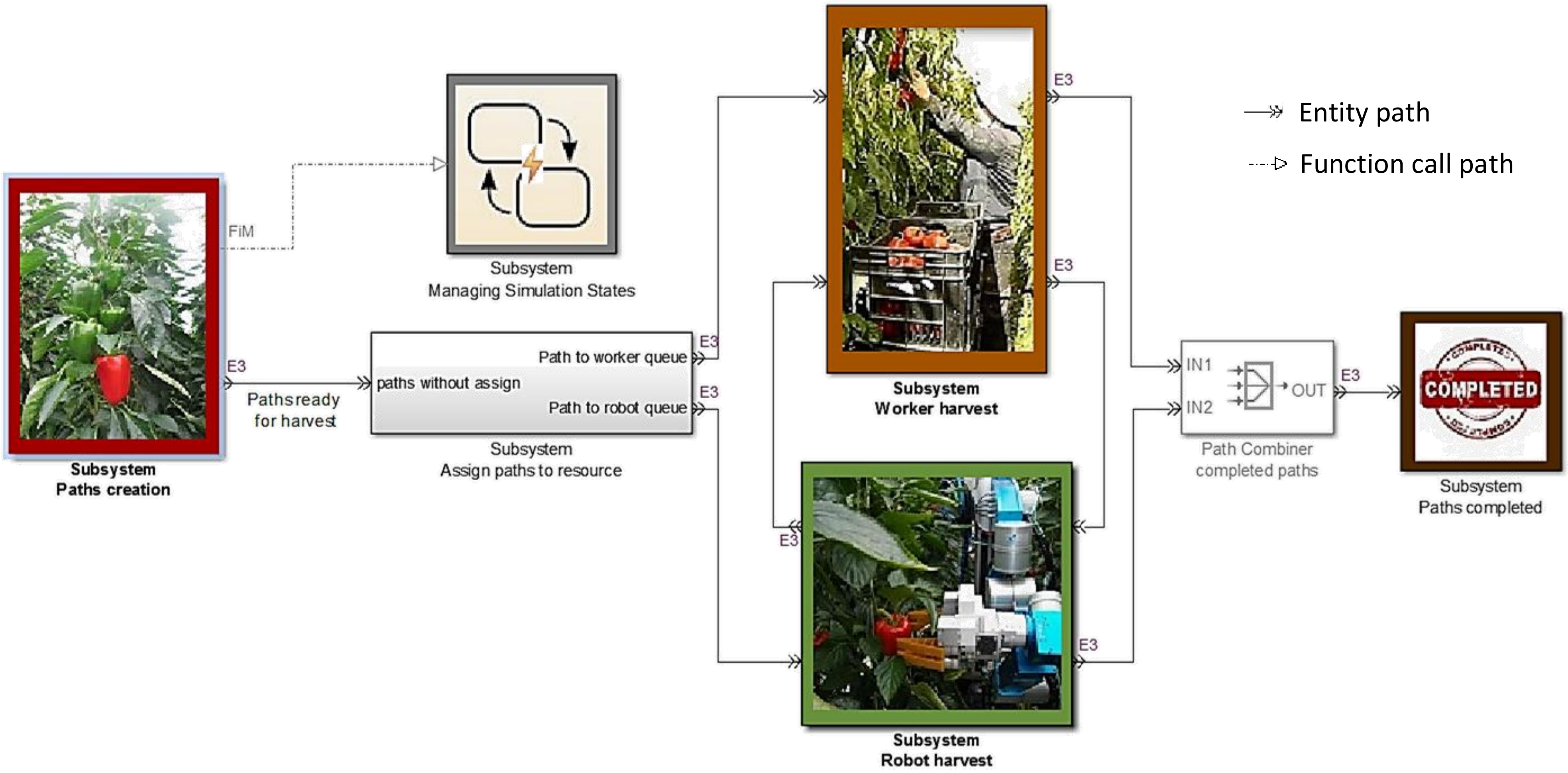


Figure 27: Simulation model structure in SimEvents

Only when the first path entity is created and starts to move forward in the system, a signal is sent from the "paths creation" subsystem to the "Managing simulation states" subsystem to activate and initiate the Stateflow chart and enter the correct state of the simulation (the states are defined in Table 12). After each entity is created, the first few blocks it passes are for receiving all the necessary attributes. Once the paths-entities arrive at a harvest subsystem, it waits for one of the resource-entities to be available so the harvest could start. The queue for the path-entities waiting for available workers in the worker harvest subsystem is a FIFO queue, so the allocation and assigning of paths to workers is done according to the path's arriving order. The queue for the path-entities in the robot harvest subsystem is different because it is possible that a robot will be simulated with less than 100% capability to succeed the harvest, so a path could return to the harvesting queue a few times until it is defined as complete (maximum 5% of peppers remaining). Therefore, the queue is a priority queue that gives higher priority to paths that were not harvested before in the simulation. With the number of harvest repetitions the priority of the path decreases, so first all the unharvested paths will be harvested. If all paths in the queue were not harvested before, the queue will behave like a FIFO queue. In worker-robot combined work, the paths can leave the queue from one resource type and move to the other. It can happen if a path is waiting in one resource queue but no entity from this resource is available to receive it as opposed to the other resource which is available. This is done to ensure maximum utilization of resources during their work hours.

Once a resource-entity is available, it is combined with the waiting path-entity to a new entity type: job-entity and the harvesting process can begin. This combined entity represents the allocation of a resource to harvest a path. The harvesting process of a path includes harvesting of each pepper individually, so the job-entity repeats the harvest block (Figure 28) the amount of peppers times. A pepper that was already harvested before (by the robot) still exists in the entity's attributes, but it will not be harvested again as it is marked as harvested and therefore skipped. The attributes of the job-entity representing the service times to harvest a pepper are changed stochastically according to the timing of actions from the input (section 5.1.8), each time before a harvesting action is performed. The harvesting action is modelled by two infinite servers for each resource: "select sweet pepper" server- simulating the time to reach to a position from which the pepper could be harvested and the second server is "grab, cut and store sweet pepper"- which is the time of the harvest itself.

The completion of a run is defined as the moment when the "time window" to harvest is over or when all paths are completed (the first achieved).

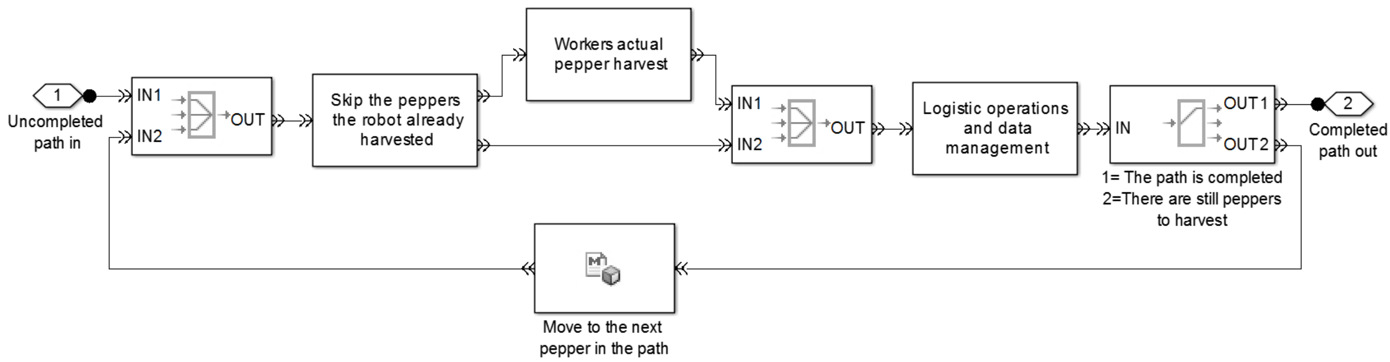


Figure 28: Workers harvesting submodel

5.1.5.1 Allocation of human-robot harvesting

As aforementioned in section 5.1.1, the harvesting operation has several possible states: harvesting by human alone, harvesting by robots alone or harvesting by both resources. In each state, the allocation of the harvesting action is different:

1. **Only human workers are active-** each path will wait in a queue (subsystem Worker harvest, Figure 27), the workers queue, until a worker is available. Once a worker is available, the harvest task is performed, afterwards the harvested path will continue to the "Paths completed" sub-model.
2. **Only robots are active-** each path will wait in a queue (subsystem Robot Harvest, Figure 27), the robots queue, until a robot is available. Once a robot is available, the harvest is made with a given success rate (section 5.1.4). If the success rate was defined as 100%, then the path will continue to the "Paths completed" sub-model. Otherwise, the path will return to the end of the queue until another harvest is made- in which the success rate is now calculated from the remaining peppers amount. The repeated harvest will continue until at least 95% of the original amount of peppers is harvested.
3. **Human-robot combined work (Figure 29)-** initially all the paths to harvest are transferred to the robots queue until a robot is available. If a path is waiting in the queue and there is an available worker, the path will be transferred to the workers queue to be harvested. If the harvest in a path was completed, the path will continue to the "Paths completed" sub-model. But, in case the harvest was made by a robot and the robot is defined with less than 100% success rate, the path will then be transferred to the workers queue, as it is preferred that the worker will complete the harvest in the path (without missing any more peppers). But, if a path is waiting in the workers queue and there is a robot available- the path will be transferred back to the robot for the second harvest.

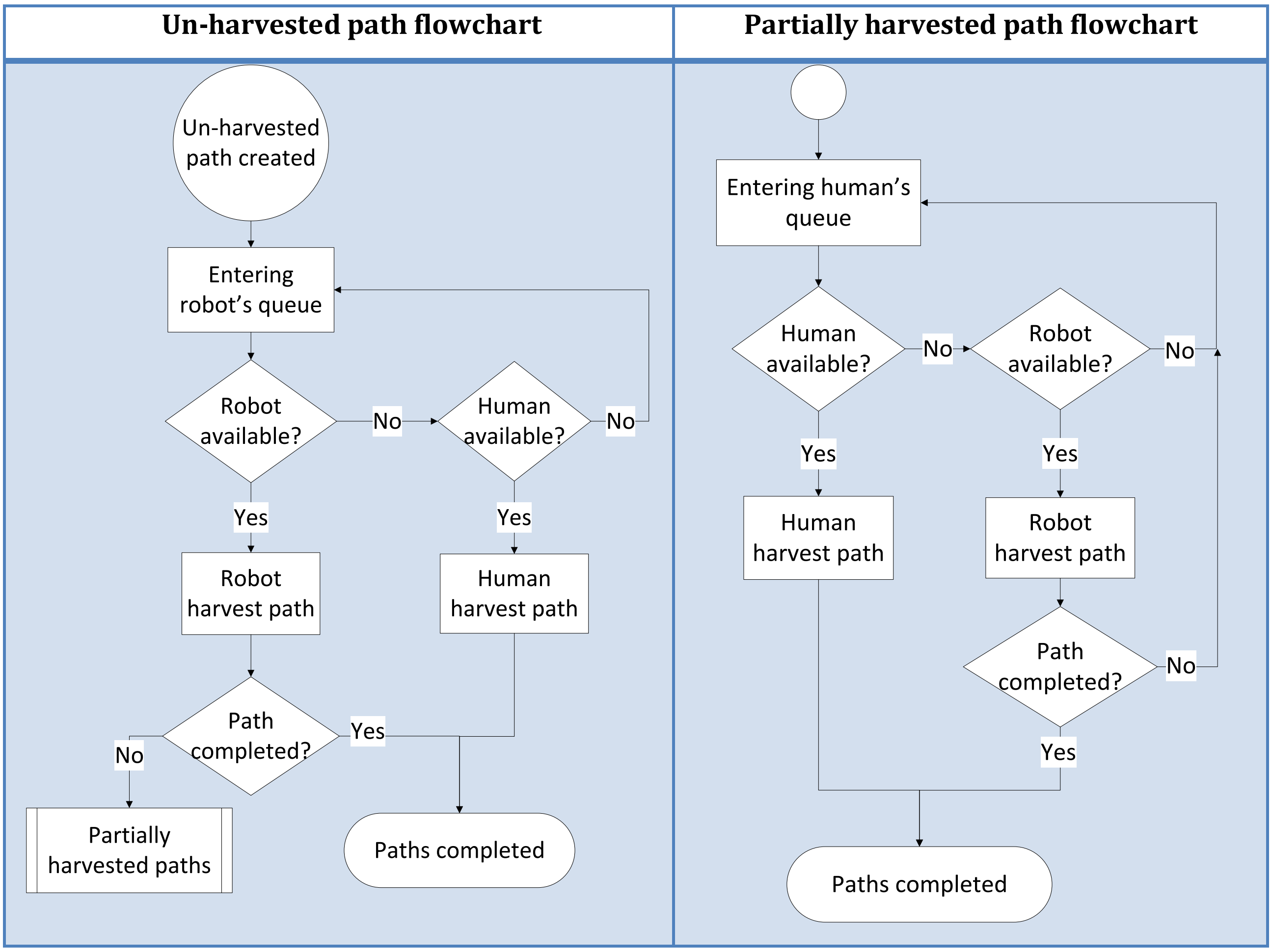


Figure 29: Human-robot combined work allocation flowcharts

5.1.6 Initialization

At initialization, all paths-entities (i.e. paths of the greenhouse that must be harvested) are created in the "*paths creation*" subsystem, all workers are created in the "*worker harvest*" subsystem and all robots are created in the "*robot harvest*" subsystem. In addition, the breaks ahead for each resource are created in the "*Managing simulation states*" subsystem (Figure 27).

The amount of entities from each type created initially are determined by the model inputs (section 5.1.8). The number of path-entities created depends on the run type of the simulation- if it is a calibration/ validation run type of a specific date, then the amount of path-entities to harvest is the amount of paths harvested that day in the NL greenhouse. If it is a run type of a full harvest cycle, then the amount will be as selected by the user in the inputs. The amount of resources- entities created in the simulation is the amount of workers and robots defined as a part of the inputs, specifically for each simulation.

The last type of entities is the breaks that are determined by the defined time window. Breaks are actually the time when resources have finished their working day and they are not active. Each day in the time window has one break.

The initial values of the entities are also received as an input which is prepared in a Matlab code and saved to workspace. At the beginning of the simulation, the entities "collect" this attributes from the workspace structure.

5.1.7 Subsystems

The model as described in "Process overview and resources allocation" (section 5.1.5), is composed of six subsystems: paths creation, managing simulation states, assign paths to resource, robot harvest, worker harvest and paths completed. This section will describe the subsystems and their functionality briefly.

5.1.7.1 Paths creation

In this subsystem the main entity of the simulation is created: a path. The attributes assigned to this entity are all pre-prepared in Matlab's function according to the received inputs (section 5.1.8) and are stored as a structure in Matlab workspace. After the entity is created, it passes a series of blocks to receive these attributes.

5.1.7.2 Managing simulation states

This subsystem's purpose is to manage the states of the resources during the simulation. A simulation can represent more than one day, and therefore it should have the ability to control the worktimes in the greenhouse. According to the inputs, this subsystem is responsible to activate and disable the resources every working day. The states of the simulation are described in detail in section 5.1.1.

This subsystem also creates the entity "*time limit*" in the subsystem Simulation completion call - which is an entity that sends signal to "*collect*" all the information of un-harvested paths from the workers and robots queues, a few minutes before the simulations ends.

5.1.7.3 Assign paths to resource

This subsystem divides the paths to the compatible resource according to the input's collaboration method- *only worker*, *only robot* or combination of both. If the collaboration method is *only worker*- it means that there are no robots available so the paths will be navigated straight to the worker harvest subsystem. If the collaboration method is *only robot*- it means that the robots will harvest the paths alone and therefore the paths will be sent directly to the robot harvest subsystem. The last is combination of *worker and robot*- both resources are available and the work will be divided between the two, but initially the path will be navigated to the robot where the allocation of work is performed (section 5.1.5.1).

5.1.7.4 Robot harvest

This subsystem is the harvesting process itself, performed by the robotic resources in the greenhouse. The subsystem includes: paths queueing and routing system, robots management, the actual harvesting in a path and routing system after harvest.

The queueing and routing system at the beginning of the subsystem is responsible for receiving all path entities to a queue and releasing them to one of the following options when available: to the robot harvest when there are robots available, to the worker harvest when the work defined is combination of resources and there are workers available or at the end of the simulation to documentation of un-harvested paths. The robots management system creates the available robots as entities according to the inputs and places them into a queue until a path- entity arrives. Once a robot and a path are combined to a job entity, the harvest of the peppers in the path is done- each time the job entity goes through the harvesting process, it executes the job of harvesting a single pepper. The robots harvesting process starts with sorting each pepper to be missed or detected according to the robot’s given detection rate, continues with the action "cut grab and store" for the spotted peppers and after each harvest, logistic actions are checked for their need. After each harvest, the timing of actions and robots location data are saved for documentation. When a path is completed, the job entity splits again to robot and path so the robot entity is available for another harvest and the path entity goes through a routing system: either the path is completed and continues to the paths completed subsystem (section 5.1.7.6) or it's not completed and it will go again to the robots harvest or switch to the worker harvest according to the collaboration type defined.

5.1.7.5 Worker harvest

This subsystem is the harvesting process itself, performed by the workers in the greenhouse. The subsystem includes: paths queueing and routing system, workers management and the actual harvesting in a path.

Just like in the robot harvest subsystem, the queueing and routing system at the beginning of the subsystem is responsible for receiving all path entities to a queue and releasing them to one of the following options when available: stay in the sub-model worker harvest when there are workers available, to migrate to the sub-model robot harvest when the work defined is workers and robots collaboration and there are robots available or at the end of the simulation to documentation of un-harvested paths. The workers management system creates the available workers as entities according to the inputs and places them into a queue until a path entity arrives. Once a worker and a path are combined to a job entity, the harvest of the peppers in the path is done. The harvesting process is done as in the robot harvest sub-model only that the workers are defined with 100% detection and harvest capability for ripe peppers.

When a path is completed, the job entity splits again to worker and path so the worker entity is available for another harvest and the path entity goes to the paths completed sub-model.

5.1.7.6 Paths completed

All the paths that were defined as "complete" arrive to this sub-model. A path is defined as complete when at least 95% of the peppers ready for harvest within it were harvested. When a completed path arrives, it is checked whether it's 100% harvested or not. If it was not 100% harvested, it means that only a robot performed the last harvest within it and the path entity will turn to documentation of the remaining peppers. After each path passes, the amount of harvested paths increases and checked whether the entire greenhouse was completed in order to stop the simulation. The paths entities stop at this sub-model in an entity sink.

5.1.8 Input data

The input data for the model is divided in two parts: inputs from an Excel file based on analyzed data and estimates and inputs read from an m file (Matlab function) related to specific decision inputs for running the simulation model (Table 15). At the beginning of each simulation, the inputs are read from both origins and processed into a Matlab structure (Table 16).

The inputs include the following information:

1. **Greenhouse-** the modeled greenhouse dimensions.

   The dimensions used for the research are the NL greenhouse dimensions (section 4.2.1.1).

2. **Yield-** yield information based on past harvesting in the NL greenhouse.

   The yield information includes amounts of pepper in kg per m^2 processed from existing database in two formats:

   - The past data after processing: for each date, in every path that was harvested are pepper amounts in kg per m^2 and the date's average and standard deviation.
   - The second format is a mathematical model that produces the total kg per m^2 for an average path in the greenhouse when given the necessary day since transplanting (section 4.3).

3. **Resources information and actions timing-** information about the main resources of the greenhouse- human workers and robots. The information of the human workers such as the probability density functions on processing times of basic actions is determined from measured data and includes timing of basic actions composed the harvesting action like: ‘grab and cut sweet pepper’ and ‘store pepper to container’. The information of robot performance, mainly success rate and action timings, are estimated and are changeable for sensitivity analysis. Transport times are defined deterministically based on the distance

to be traveled and the speed of the resource. Velocities of workers and robots, and coordinates of reference positions as the locations of entry and exit of paths in the greenhouse, are model inputs.

4. **Run decisions** including how many resources to assign to a run, the simulation period and the run type. The user can select which run type to use between four types depending on the run objectives:

   In run type 1, the simulation model will run one day at the time, based on past data. The user needs to define which dates to run and in each day run, the model will create paths to harvest (path entities) according to the paths harvested on the selected date. This run type is used to synchronize the simulation with the actual management and yield of the greenhouse for calibration and validation. Two probability density functions were used to assign amount of ripe peppers to the paths and to position peppers at unique path locations. A lognormal distribution was used to predict the number of ripe peppers per path. Parameters were the average kg of peppers per m^2 and standard deviation, for the selected date. The kg per m^2 selected for each path is than multiplied with the area of a path in m^2 and divided by the pepper weight in kg suitable for the harvest week. A uniform probability density function was used to randomize the position of ripe peppers in path, by assigning a unique coordinate value (x,y,z) for each pepper. This distribution method was inherited from van ‘t Ooster et al. (2012).

   In run type 2, the simulation model will run continuously for "time window" days and the paths to harvest in that period are all the paths of the greenhouse (a full harvest cycle). This "time window" is the amount of days to complete a harvest cycle so all peppers harvested will be first quality peppers (with no over ripe peppers). The yield of each path is estimated with the same two probability density functions mentioned in run type 1, only with the average taken from yield growth mathematical model (section 4.4.3) and standard deviation according to the average std. of kg per m^2 between the paths from all the past data.

   In run type 3, the yield is calculated as in run type 2 with the yield mathematical model. The difference from run type 2 is that in this run type it is possible to conduct a serial run that includes a few harvest cycles and therefore there is an additional parameter that determines how many days pass between one harvest cycle and the next. In addition, it is possible to determine which paths to simulate, in case we are not interested in the entire greenhouse. In this run type, each day is simulated separately and all the data is saved and processed to next harvesting day via Matlab.

Run type 4, is exactly as run type 3 only the yield data is not created and randomized, but received as an input. This run type is used for reviewing and comparing alternatives, in order to use the same environment between one alternative to the other.

Table 15: Input data for simulation model

Excel File- "Input details"	
Greenhouse	Greenhouse Length (m) Greenhouse Width (m) Main aisle width (m) Paths Length (m) Number of paths
Resources	Success (%) Work method Container capacity (kg) OverlapDistance (m) Speed X,Y,Z (m/sec)
Actions Timing	Grab and Cut sweet pepper (s) Store sweet pepper to container (s) Change path side (s)
Yield	PastData Forcasting PepperHightWeight
Finance	Worker hourly cost (euro) Robots hourly cost (euro) Income from 1st quality pepper (euro) Income from 2st quality pepper (euro)

Matlab function- "User decision"	
Run type	Selection between types 1-4
For run type 1	Date of first harvest Date to simulate Days to simulate since the chosen date
For run type 2/3/4	Days since transplanting Days since harvesting
For run type 3/4	Harvest cycle duration Days since last harvest Selection of paths to harvest
For all run types	Simulation time window Simulation repeats Human-robot collaboration method Working hours-worker Working hours-robot Number of workers for the run Number of robots for the run Run name

Table 16: Inputs structure in Matlab

GreenhouseLayout:	**ActionTiming:**	**ResoursesData:**	**YieldInformation:**
(Structure)	**(Structure)**	**(Structure)**	**(Structure)**
- GreenhouseLength - GreenhouseWidth - MainAisleWidth - PathsLength - PathsWidth - PathsAmount - Coordinates (first 3-XYZ beginning, last 3-XYZ end of path)	- Action1 - Action2 - Action3 (Each action with distribution type and 2 parameters of the distribution for the robot and worker)	Robot=1, Worker=2 - Success - WorkMethod - Speeds - ContainerCapacity - OverlapDist - WorkersCapabilities (only worker) - RobotRetries (only robot) - Acceleration (only robot)	- Yield_Pastdata - Yield_Dist - YieldForcast_Parameters - Yield_Avg_std - GrowthModel - PepperWeight - PepperHeight
PepperLocations:	**CostsInfo:**	**SimDesicions:**	
(Cell Array {paths,3})	**(Structure)**	**(Structure)**	
Each line is a path: <u>First column</u>= Locations (X,Y,Z,side,Priority) <u>Second column</u>= Total pepper amount in the path <u>Third column</u>= Path index	- CostWorkHour (Robot, Worker) - FstQuality - SndQuality (percentage and price for robot and workers)	- HarvestStart - SimDate - SimDays - HarvestCycleDuration - DaysSinceLastHarvest - SimTimeWindow - DaysSinceTransplanting - DayofFirstHarvest - DaysSinceHarvesting	- SimRepeat - CollabMethod - WorkersSecPerDay - RobotsSecPerDay - WorkersAmount - RobotsAmount - RunType - RunName

5.1.9 Model outputs

The output of the model includes- detailed process output of each run which is created in Matlab's workspace as a structure "Outputs" (Figure 30). The information saved in the structure is stored in four elements: workers data, robots data, missed pepper by robots and summary info (detailed structure of each element is on Appendix M). The main important information stored in the outputs structure is:

- Timing of each harvesting action in each path by the resources
- Utilization of each resource
- Missed paths and peppers by lack of time or by the robot performance
- Summary results of average and standard deviation of time per pepper\ per path, sum of the harvested peppers in the entire greenhouse and the standard deviation between the paths.

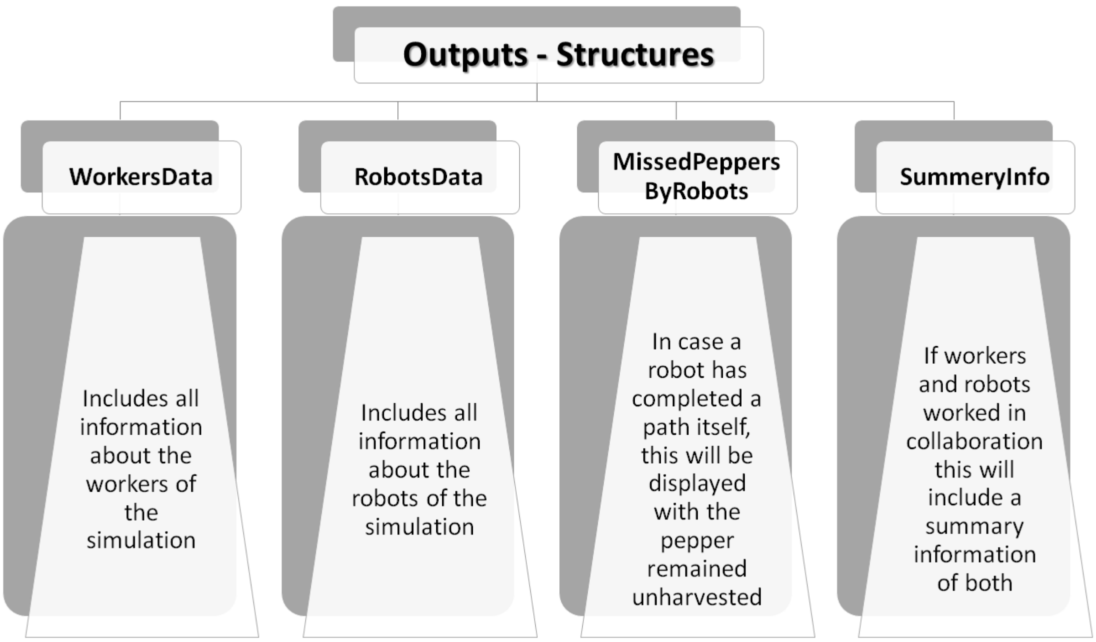


Figure 30: Outputs general structure in Matlab

5.2 Model verification, calibration and validation

5.2.1 Method

To evaluate the functionality of the simulation model, it was verified, calibrated and validated (according to definitions in section 2.4.3) with the harvesting process in a greenhouse by comparing the desired behavior to the actual simulation results.

The modelled harvesting performed by human workers describes the harvesting process as conducted in the greenhouse and therefore it is an "Observable System" whereas the robot harvester is not in commercial use yet and therefore it is a "Non-observable System" (section 2.4.3). Due to the differences between these systems the evaluation process was conducted differently for human workers on one hand and robots including human-robot combinations on the other hand.

Calibration and validation require actual data to compare to, with calculations of accuracy levels and therefore is applied only for the "Observable System"- the human workers and wasn't applied for the "Non-observable System"- the robots. The verification process on the other hand, does not require actual data to compare to but only performing examination that the model is functioning as intended and therefore was applied for both resources type.

In the following sections, the model verification will be described in details for the robots functionality and the calibration-validation will be described in details for the human workers functionality. Even though verification was also conducted for human workers, it was not described and documented in the thesis as the workers were the base for the simulation modelling and the verification was a general process that was performed constantly. The validation results presented in the thesis acknowledges that the verification was performed properly.

5.2.1.1 Human workers calibration and validation

The model was first calibrated to match the greenhouse's data and then validated for the performance evaluation throughout the harvesting season. The model's initial inputs are described in section 5.1.8.

Calibration of human workers functionality

The model was calibrated for the performance of the human workers in the simulation according to data collected and processed from the Dutch greenhouse. The calibration included adjustment of the model’s input and verifying the output against the data. The calibration runs were performed for one day (September 26th, 2012) on 110 paths harvested that day (approximately 1/3 of the entire greenhouse). The calibration included adjusting input parameters, which were not specifically measured at the Dutch greenhouse. The inputs tested were:

- **Move speed** (Speed Y in the model): the average velocity of the trolley with the worker on it within the paths. The initial value is 0.22 m s^{-1} (Aantjes, 2014).
- **Overlap distance**: a distance where the operator is still moving while the harvest action also already started. The initial value is 0.5 m as in GWorkS model for harvesting roses (van 't Ooster et al., 2012).
- **Time per sub action of harvesting**: the PDF parameters of harvesting time sub actions “grab and Cut Pepper” and “Store pepper in buffer”. The initial values are in Table 18.

After calibration was performed, the model was tested with non-calibrated data, to examine that the calibration is general enough and it is possible to use the model to obtain results and conclusions regarding the real greenhouse. The model calibration test was performed on the rest of the harvest cycle beginning on September 26th and lasted for three days.

The main outputs compared to the actual data acquired are:

1. **Yield[3]-** total yield harvested and standard deviation of yield between paths (peppers).
2. **Labor time-** average time per path and standard deviation of time per path (s).
3. **Cycle time per sweet pepper-** average time and standard deviation per unit (s).

The desired accuracy is 85-100% of the actual data.

Validation of human workers functionality

Validation was conducted using data from different dates in the greenhouse. For this phase, dates were selected from the entire harvesting season, to test the performance of the model using calibrated parameters. The harvesting season of 2012 which lasted 33 weeks was divided into four harvesting periods: first period between the dates- March 12th to May 12th, second period- May 13th to July 8th, third period- July 9th to September 2nd and the fourth period- September 3rd to October 29th. In order to validate the model for the entire harvesting season and include the harvesting of all paths in each period, a full harvest cycle was tested in each period. Each harvesting period selected includes a different number of days per harvest, different yield levels and heights and therefore they all must be validated to show the effects of these changes. The selected dates from each harvesting period are:

1. **April 30th to May 2nd-** three workdays, 302 paths harvested.
2. **June 11th to June 14th-** four workdays, 304 paths harvested.
3. **August 10th to August 16th-** five workdays (and two days off- weekend), 296 paths harvested.
4. **September 11th to September 13th-** three work days, 300 paths harvested.

The dates selected are presented in Figure 31. Each harvest cycle is presented in different color with the paths it covers in the greenhouse (paths 1-304) and the yield in kg per m^2 harvested in that path. These four datasets cover all the paths in the greenhouse and yield levels between 0.25- 2 kg per m^2 for most of the paths.

After running the model for these four validation datasets, the following output is computed and compared to the measured data:

---

[3] Peppers were translated from kg peppers to actual units and placed along a path by a random function. Therefore, the estimated total number of peppers harvested was compared to the simulated total.

- **Total number of peppers harvested**- compared to the total yield harvested in the harvest cycle. The yields per path in the database are kept as kg per path. In order to compare the database with the simulated data, the kg per path was translated to pepper units per path by dividing the amount of pepper in kg with the average weight of pepper compatible with the harvest period.
- **Labor time per path** - compared to average measured labor time per path.
- **Cycle time per pepper**- compared to average cycle time per pepper in all paths harvested in the harvest cycle.

Each harvest cycle run was simulated for 10 times, and the runs average and confidence interval (alpha= 0.05) was calculated for each of the parameters mentioned above.

The average result outputs were tested for accuracy as calculated in equation (8).

$$(8) \qquad accuracy = \left(1 - \frac{|average\ model\ output - measured\ data|}{measured\ data}\right) * 100\%$$

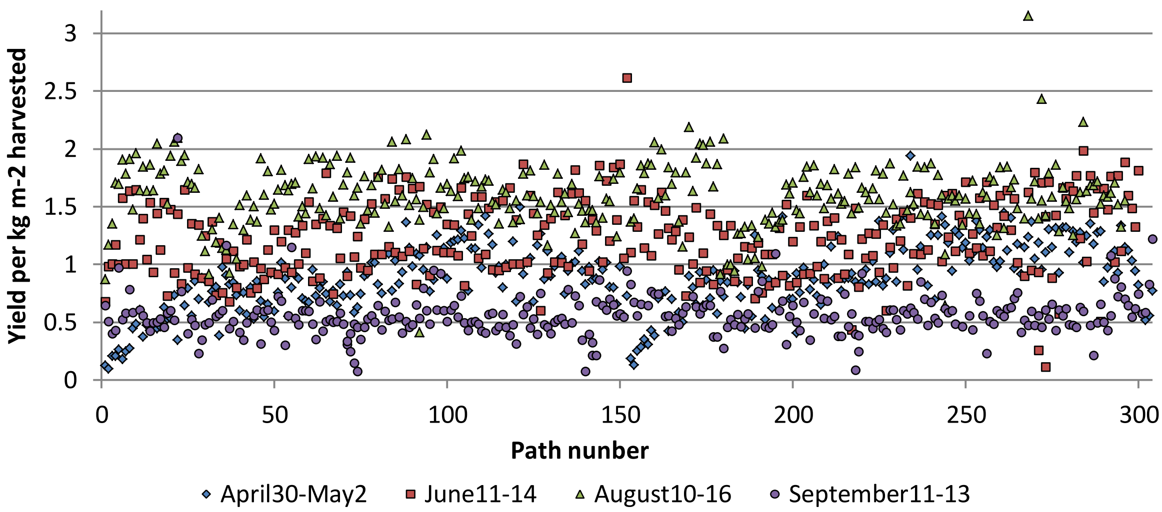


Figure 31: Paths harvested and yield levels of examined dates

5.2.1.2 Harvesting robots verification

The harvesting robot modelling in the simulation model is described in section 5.1.2. In order to examine if the functionality of the harvesting robot in the model is as planned, the model was verified by extreme scenario tests. The following tests were performed:

1. Definition of collaboration type to be- "human-robot collaboration" (type 4 in the model) and definition of the robot success rate in the model to be:
    a. **Zero:** when the robot success rate is defined as zero, all peppers are missed. The simulation is modelled so that only when a pepper is "identified" (modelled as receiving an attribute), the calculation of time to reach the pepper and the harvest

itself are performed. Therefore, if the robot will miss all peppers as in this case, no simulation time will pass.

Therefore, the expected behavior of the model is that it will be a regular harvest by human workers alone.

b. **One:** The input of the robot besides the robot success rate, were set to be identical to the worker's inputs including the parameters for timing of actions, work hours, speed etc.

   Therefore, the expected behavior of the model is that the robot will work as a regular worker- each path assigned to the robot will be harvested fully.

2. Definition of collaboration type to be- robot alone (type 2 in the model). The robot will have to harvest the paths without support of human harvesters. If, for example, the robot is defined with detection rate of R_{DET}, then the expected behavior is that the robot will harvest each time it enters a path R_{DET}% of the amount of peppers left to harvest. The completion of a path is defined when 95% of the initial amount of peppers were harvested.

5.2.2 Results

5.2.2.1 Calibration of human workers functionality

The calibration was performed on September 26th and then was tested on September 27th and September 28th. These initial dates were selected at the end of the season, to match the simulation with the data collected and used from Aantjes (2014) thesis which was measured at a different greenhouse in The Netherlands. The calibration was examined with the rest of the 26th harvest cycle in order to check whether the calibration works properly for other paths.

The first run results of September 26 were compared against the processed data received from the grower (Table 17). Results indicated that the input data entered to the model, does not match perfectly to the actual state, although it is very close. The main reason for that according to the results (in Table 17- before calibration) is that the harvesting in the simulation is faster than reality by 9%. In addition, the data analysis performed before the calibration (section 4.4.1) indicated that the harvest times on September 26th are relatively faster than the average for the same amount of peppers (Table 17- in the second column "real data" compared to "season averages" in brackets). The conclusion is that the parameters should be adjusted towards slower performance, and even slightly above the September 26th data, to calibrate closer to the actual season averages while achieving high accuracy rates.

Followed by that initial run, a series of additional runs were performed and in each, one of the input parameters was changed and the results were examined (Appendix N). After five runs with input changes, a fit of 90-100% for all aggregative parameters compared to the real data (sum and averages) and to the season averages was achieved (Table 17). The inputs changes are presented in Table 18. The parameter which did not reach the desired accuracy level is the standard deviations of labour time in a path. The standard deviation of the pepper amount per path is a less important parameter for validating the workers functionality and therefore is less relevant for the calibration. In addition, after the validation of the workers capability against the data, a different method for estimating the yield per day will be used. A possible explanation for the difference in labour time in a path standard deviation as discussed in van 't Ooster et al. (2012) for the GWorkS model, could be that the differences between the workers are significant in a way that treating all workers as an 'average worker' is not that accurate with respect to variability of output (in every run the std. was smaller for the simulation). For the purpose of this research, the workers difference will not be taken into account and therefore the standard deviation of the simulation versus real data will not be further examined and the focus will be on adapting the model correctly to the average values. After the inputs were adjusted and the parameters reached the desired accuracy level, a test was performed for other dates and paths. Ten runs were performed for each of the dates September 26^{th} to 28^{th} and the average result of the parameters: sum of peppers [u], average time to harvest a path [s] and average time per pepper [s] were compared to the data. Results indicated that the parameters fit at the level of 85-100% accuracy to this entire harvest cycle and the validation can be started with the same parameters (the results are presented in Appendix O).

Table 17: Calibration results for 26/09/2012 data

#	Parameters	Real data (season averages)	Simulation- Before calibration	Simulation- After calibration	Accuracy rate after calibration compared to real data (season averages)
1	SumPepper	60,469	64,030	60,756	99.50%
2	StdPepperPath	160.1	191.3	142.9	89.20%
3	AvgTimePath	1,810 (2,022)	1,727	1,969	91.2% (97.4%)
4	StdTimePath	496.9	313.7	291.7	58.70%
5	AvgTimePepper	3.292 (3.733)	2.995	3.597	90.7% (96.4%)
6	StdTimePepper	0.423	0.481	0.446	94.60%

Table 18: Input parameters before and after calibration

Input parameter	Before calibration	After calibration
Move speed [m/s]	0.22	0.22
Overlap distance [m]	0.5	0.3
Sub action “grab and Cut Pepper” [s]	Mu: 0.244, sigma 0.521	Mu: 0.465, sigma 0.443
Sub action “Store pepper in buffer” [s]	Mu: -0.576, sigma 0.532	Mu: -0.576, sigma 0.532
Sub action “Change path side” [s]	Mu: 10, sigma 1	Mu: 10, sigma 1

5.2.2.2 Validation of human workers functionality

The model was validated for the performance of the human workers as detailed in section 5.2.1.1. The result accuracy rates of the parameters tested for all harvest cycles reached the desired accuracy level and are between 86-99% (Table 19) except for one case: the harvesting time per path of the April 30 harvest cycle.

The accuracy of the total peppers amount parameter is the highest with an average of 94.7% and only 6.5% difference between the higher and lower accuracy rates. The other two parameters tested, average labor time in a path and the cycle time per pepper reached an average accuracy of 91.6% and 90.4% respectively. The highest difference between the maximum and minimum accuracy was in the parameter average labor time in a path with difference of 17.9%. This parameter- the harvesting time per path is presented in Figure 32 for all harvest cycles, with the vertical lines which separate the harvesting season into the four periods mentioned in section 5.2.1.1.

Table 19: Validation results- all parameters

Begin date	Total number of peppers harvested (u)			Average labor time in a path (s)			Cycle time per pepper (s)		
	Data	Sim	Accuracy	Data	Sim	Accuracy	Data	Sim	Accuracy
30-Apr	200642	185247	92.3%	2644.2	2103.3	79.5%	3.980	3.441	86.5%
11-Jun	288380	267143	92.6%	2595.6	2663.2	97.4%	2.736	3.031	89.2%
10-Aug	335396	331471	98.8%	3282.9	3106.1	94.6%	2.995	2.867	95.7%
11-Sep	117995	124010	94.9%	1799.8	1707.4	94.9%	4.576	4.131	90.3%

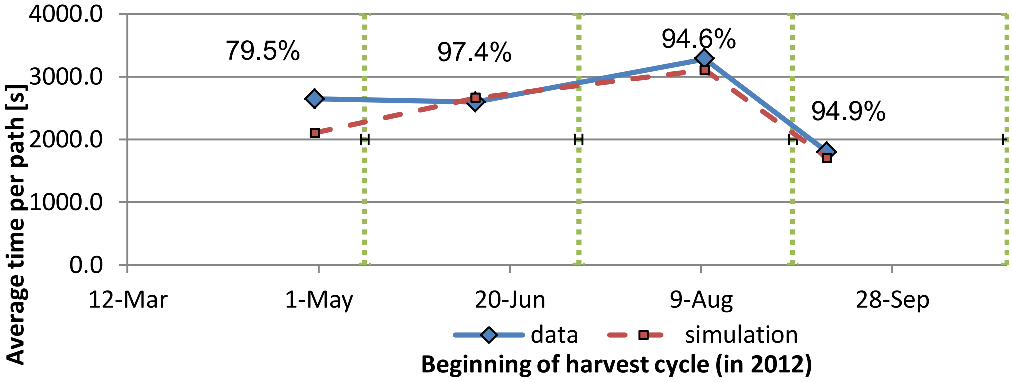


Figure 32: Validation results- average harvest time per path

As aforementioned, the harvest cycle between April 30th to May 2nd did not reach the desired accuracy level and therefore was further examined. In order to examine the cause for the low accuracy of the harvest time per path, first the yield amounts were tested. The data was divided into 15 groups according to the yield harvested in a path: 1-100, 101-200, 201-300 peppers etc. Then, the frequency of all groups was examined visually to make sure that the simulation modelled the yield amounts correctly. According to this comparison, it seems that the yield simulated is close enough to the actual data (Figure 33).

The next step was to analyze each date of the harvest cycle separately in order to examine if the problem is caused by a specific date. The harvesting time per path accuracy rates for each of the dates in the harvest cycle are: April 30th- 85.6%, May 1st- 79.6% and May 2nd- 72.7% and for each day, the simulation times were faster than the data. All accuracy rates are relatively low but it seems that May 1st and 2nd are significantly different than the simulation results. Next, the average harvesting time per path was examined for each date according to its yield group (that was mentioned above) against the simulation (Figure 34) and it seems that although the general trend of data is as expected- as higher the pepper amount in a path- the harvest time per path increases (conclusion from data analysis in section 4.4.1) there is an exception in May 2nd.

Table 20: Standard deviation of each factor tested in data analysis for all harvest cycles (the maximum std. of harvesting time per path and harvesting time per pepper for each harvest cycle is marked in red)

	Std. [s] between days		Std. [s] between paths		Std. [s] between workers		Maximum Std. in % (from the average result)	
Harvesting time per:	Pepper	Path	Pepper	Path	Pepper	Path	Pepper	Path
30/4-2/5	0.258	193.9	1.897	1100.6	**2.874**	**1241.4**	72%	47%
11-14/6	0.175	41.5	**0.553**	**694.6**	0.423	374.9	20%	27%
10-16/8	0.118	144.1	**0.588**	739.7	0.416	**751.5**	20%	23%
11-13/9	0.375	125.0	**5.266**	**545.6**	0.743	479.0	115%	30%

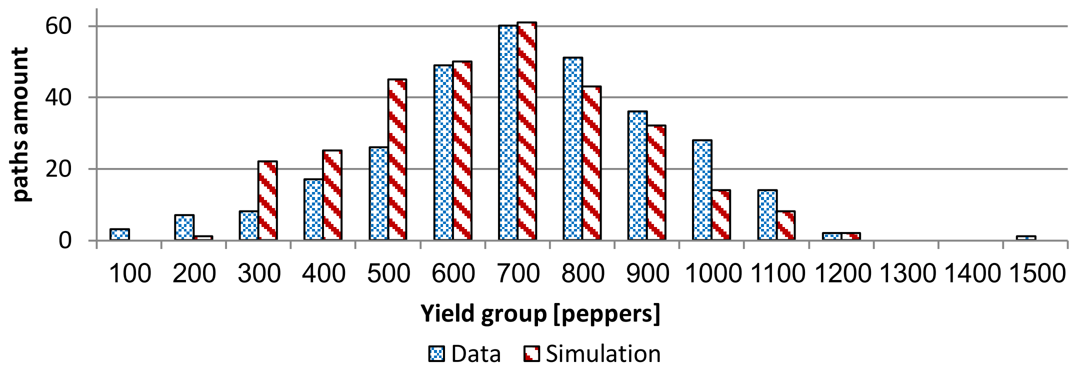


Figure 33: Data vs. simulation yield amounts 30/4-2/5/12

Due to the visual exception (Figure 34) on May 2nd, it was tested separately. According to the data analysis performed (section 4.4.1), the most likely factor to cause high variance in harvest times are the workers. In May 2nd there were 13 different workers harvesting the paths. When examining the incline of the average time per path versus the amount of peppers per path for each of the workers (Figure 35), it seems that most of the worker's harvest times behaves the same, but there are four workers that their average times of harvesting a path are significantly higher than the rest- workers 685, 686, 687 and 688. These workers were discovered in the data analysis phase (section 4.4.1) as workers that harvested only a small amount of peppers (which may reflect low experience) and in relatively high harvest times (5.3-10.7 second per pepper compared to the average of 3.6 seconds). In order to examine if those four workers were the cause of the model's deviation from data, their harvesting data was eliminated from the harvest cycle averages (13% of the whole harvest cycle database) and the accuracy rate was measured again. This yielded improvement, and the harvesting time per path accuracy rate reached 93.7% accuracy.

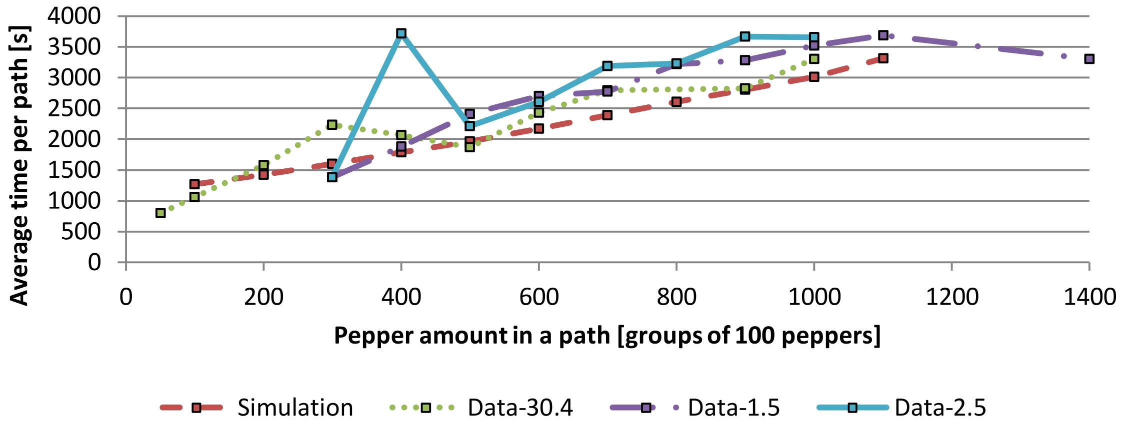


Figure 34: Average time per path for each yield group 30/4-2/5/12

The conclusion is that the model is fitted well to the average worker, but when there are major differences between the workers capabilities, the model does not predict the exact times of the workers. For the purpose of this research, the fitting to the "average worker" is sufficient and therefore the inputs selected and verified in the validation will be used in the next parts of the research.

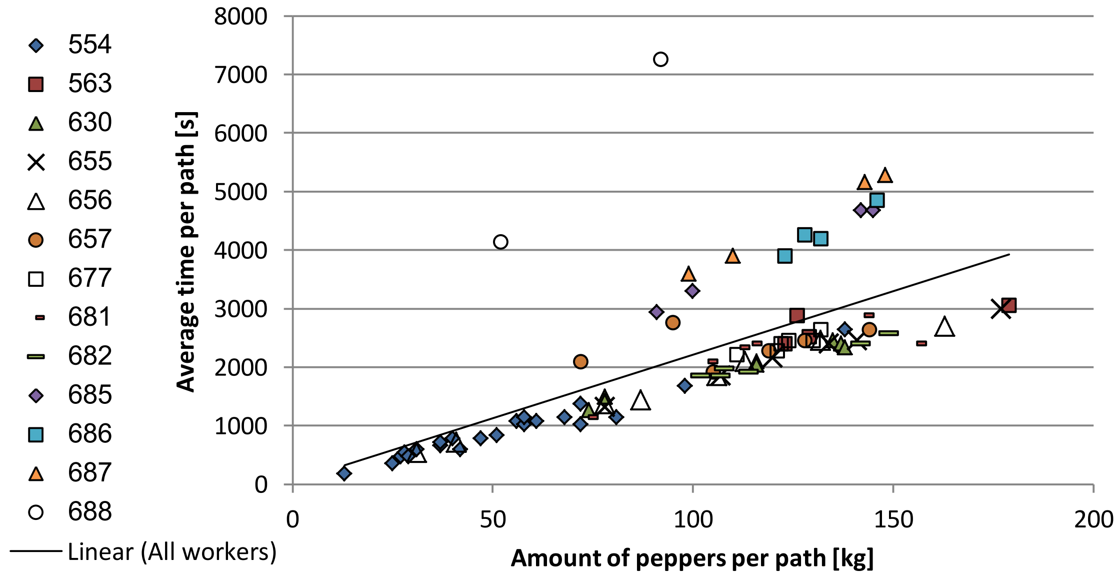


Figure 35: Average time per path for each worker on May 2nd 2012

5.2.2.3 Harvesting robots verification

The extreme scenario runs were performed on the date of 13/09/2012 of the NL greenhouse database. This date included harvest of 25 paths in total- paths 141-152 and paths 292-304. Initially, a visual verification was made on the simulated greenhouse graph that the correct paths were simulated and distributed with peppers (Figure 36).

In the second phase of verification, three simulations with five repeats each of the harvesting in September 13th by different resources combinations were compared:

1. 3 workers
2. 3 workers + one 0% robot (missing all the peppers in the paths assigned to it)
3. 2 workers + one 100% robot (harvest success of all peppers) defined with the same actions timing as the worker (meaning that the harvest time will be calculated as the human worker with stochastic timing of sub-actions and not with assigned accelerations).

These three resources combinations are expected to perform the same (as explained in section 5.2.1.2). The average harvest times per pepper were 3.770, 3.769 and 3.774 seconds for resource options 1-3 respectively. Hence, the accuracy of the extreme scenarios tested (resources options 2 and 3) against the normal functionality of workers (resources option 1) is 99.97% and 99.88% respectively. The slight differences are probably due to the random numbers generator. When there are changes in the composition of resources, there is different job order, and the random number generator assigns the generated numbers in different order for different harvesting tasks.

Additional verification was performed on the third resource option of two workers with one 100% robot. The robot was verified visually to examine the similarity to the other two workers (Figure 37). The average time per pepper of the workers in the scenario was matched with a power trend line to emphasize the expected behavior of the time per pepper versus the amount of peppers in a path as was found in the data analysis phase (section 4.4.1). It is clear from Figure 37 that the 100% robot harvest time per pepper behaves as expected.

The third phase verification was performed on a scenario with the robot as a sole resource (with timing as stated in section 5.1.4.1). The robot was derived with 80% detection capability, so that each time the robot enters into a path it is expected to identify and harvest only 80% of the remaining pepper amount. The completion is defined when more than 95% of the initial amount of pepper were harvested.

The results showed that average of 79.9% of the peppers are harvested each time and that maximum 4.9% of the initial pepper amount remain after the robot has completed the harvest in a path with an average of 3.5%. The harvest completion took 2-3 rounds of harvesting, depending on the initial amounts and the recognized amount at each harvest. The average time per pepper for this case was 7.812 seconds.

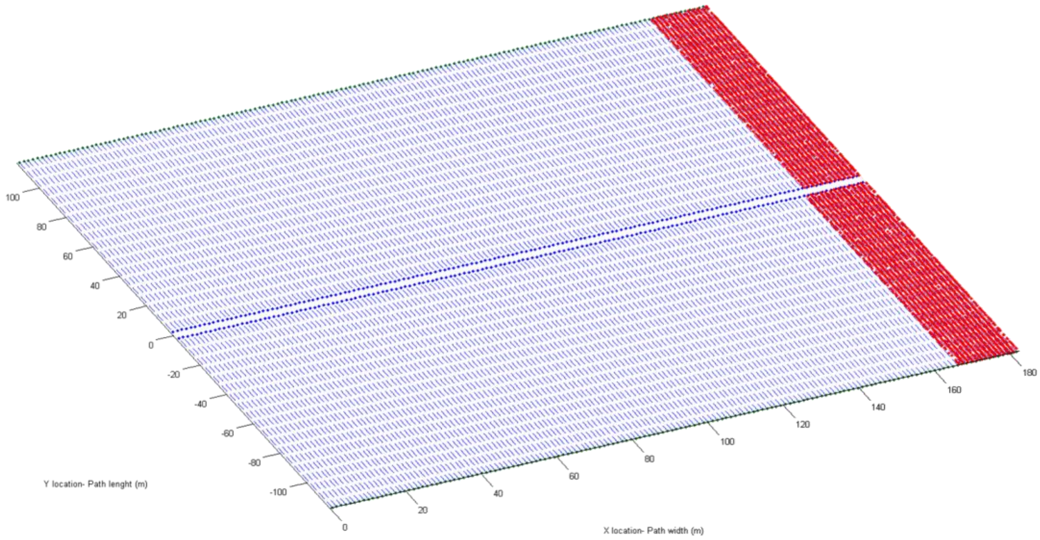


Figure 36: Simulated paths on September 13th (the red areas on the right side of the figure are the simulated peppers)

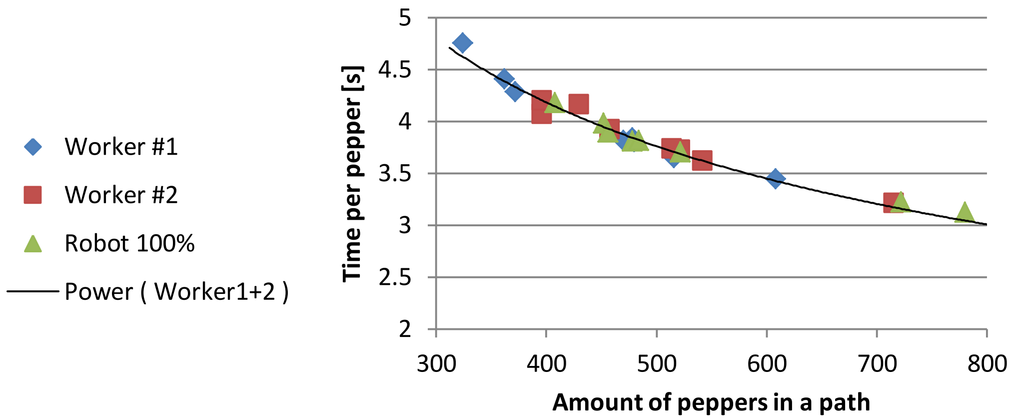


Figure 37: The average harvesting time per pepper with two workers and one 100% robot (with the same actions timing as the worker)

6. Human-robot combined solutions

6.1 Overview

Simulation runs were performed to find human-robot combinations to complete the harvest. A human-robot combined solution is a suggested number of resources in which the harvesting task in the greenhouse is divided between the two resource types.

The combinations differ in number of workers and robots, in robot capabilities and the resulting harvest division between the robots and workers.

6.2 Inputs for simulation runs

In order to find the needed resources for a harvesting season, the season and resources must be defined explicitly for the simulation model inputs.

The definitions regarding the season were derived from the greenhouse data of the 2012 season (sections 4.4.2, 4.4.3). The robots definitions parameters for all simulations were based on estimations and assumptions as detailed in section 5.1.4. However, to evaluate performance for a wide range of conditions, sensitivity analyses were performed for several values of the influencing parameters (section 6.3.3).

The inputs for the simulation runs can be divided into four types: harvest cycle features, yield data, parameters for harvesting timing and robot's capabilities.

Harvest cycle features

Based on data analysis (section 4.4.2), the inputs for the model regarding the harvest season are:

- 37 harvest cycles (although there were 41 harvest cycles in 2012 season, the first and last two harvests were excluded from the simulations).
- Time window to harvest: three days.
- Days since last harvest: five days.
- Workday: for human workers 9 hours and for robots 20 hours.

Yield data

The yield input for the model is a mathematical equation with parameters built based on the NL data (section 4.4.3). The baseline was derived using the parameters calculated for the entire greenhouse. In the sensitivity analysis phase parameters calculated for the low yield path and the high yield path were used as well as model inputs for the entire greenhouse as explained in section 4.3.1.

The mathematical model was used rather than the processed NL data itself, in order to detach from management decisions, weekends and holidays and other factors that limited the ability to generalize the model results.

The use of this model in the simulation is explained in section 5.1.8, run type 3 and 4.

Parameters for harvesting timing

Description of the harvesting process by both resources is described in sections 5.1.3 and 5.1.4. Table 21 summarizes the actions of each resource and the input parameters for the model. The human worker inputs are as derived in the calibration process (section 5.2.2.1) and the robots parameters are described in the following "Robot's capabilities" input type.

Table 21: Harvesting timing parameters for simulation runs

	Human workers		Robots	
	Description	**Timing**	**Description**	**Timing**
Action 1	Grab and cut pepper	LogNormal (0.465, 0.443)	Reach to pepper	Calculated value (depend on distance and acceleration)
Action 2	Store pepper to container	LogNormal (-0.576, 0.532)	Harvest pepper and move back to initial position	1s + Calculated value (same time as in Action 1)
Action 3	Change path side	Normal (10, 1)	Update gripper initial location to the other path side	Calculated value

Robot's capabilities

As a baseline, the robot detection capabilities (R_{DET}) were assumed to be 70% with a retry success (R_{RETRY}) of 100% resulting in a total harvest success of 70%. This baseline success rate is similar to current 66% average robot capabilities as reported in a recent literature review (Bac et al., 2014). The R_{DET} and R_{RETRY} parameters were later on evaluated for different levels in the sensitivity analysis 6.3.3.

The acceleration baseline was defined based on a small sized robotic arm (Cyton Gamma 1500) capabilities (section 5.1.4.1) - 0.2 m/s^2 and was tested in the sensitivity analysis phase with 1 m/s^2 and 0.1 m/s^2.

6.3 Results

6.3.1 Fixed workers

When the only resource in the 4.3 ha NL greenhouse is the human workers, results indicated that seven workers are needed to complete the harvest of all paths for the entire season (Figure 38). The smallest number of fixed workers tested was defined as three since this is the minimum estimated for other logistic operations needed in the greenhouse. When the number of fixed workers is between three to five workers, the harvest of most/all the harvest cycles (HC) is not completed within the time window. But, the six fixed workers solution shows that most of the season, the workers manage to harvest all peppers and only around the peak of the season (198-283 days since transplanting), the work is not finished. The average and maximum utilization of the workers for all solutions was calculated (Table 22).

The analyses evaluated the number of robots necessary to complete the season's harvesting depending on the robots given capability for a range of 3-6 fixed workers.

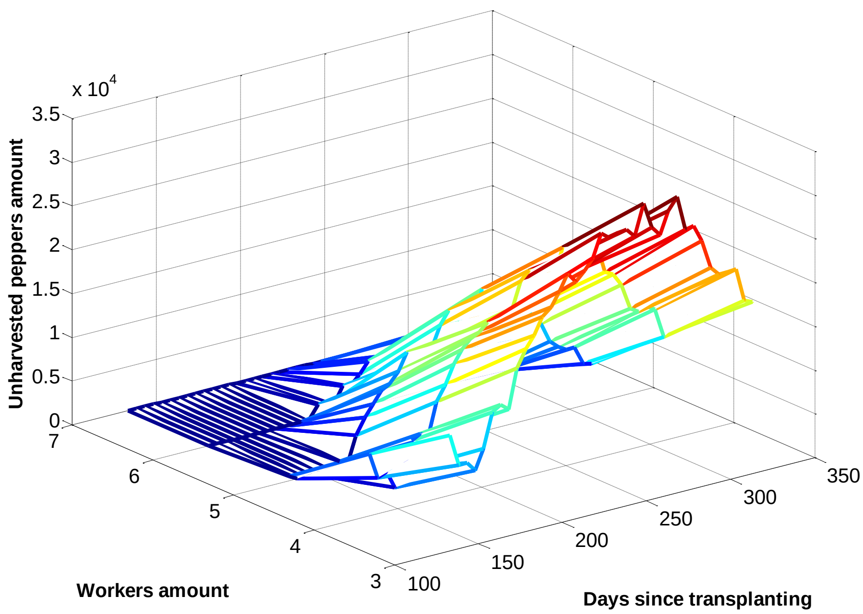


Figure 38: Unharvested peppers as a function of days since transplanting for different fixed number of workers

Table 22: Utilization of workers for only workers solutions

Utilization	3 workers	4 workers	5 workers	6 workers	7 workers
Average	0.98	0.98	0.97	0.94	0.85
Std.	0.01	0.01	0.02	0.06	0.09
Maximum	1.00	0.99	0.99	0.99	0.96

6.3.2 Introducing robots to the harvesting process

The results presented in Figure 39 shows that when using a robot with 70% harvest success with arm acceleration of 0.2 m/s^2 the number of robots needed to complete the harvest with 3, 4, 5 and 6 workers are 4, 3, 2 and 1 robots respectively. The test was performed gradually, where in each simulation run one robot was added to the harvesting process and the number of unharvested peppers in the peak of the season was evaluated. In Figure 39, the "0 robots" line represents the number of unharvested peppers in the entire season of initial state with only workers. Each additional line (with 1-4 robots) represents the number of unharvested peppers between 223 and 273 days since transplanting. Other days were not simulated.

Once all the human-robot combination solutions were selected, a full-season run was performed for each solution. The utilization of both resources, peppers amounts harvested and missed by the resources were calculated for each run (Table 23). The results showed that the human workers are fully utilized as expected due to the resource allocation mechanism of the simulation with an average of 96% utilization (std. 3.3%), and the robots are only partly utilized with an average of 63.9% utilization (std. 14%). The maximum robot utilization of the solutions (72-94%) indicates that there is need for the designated number of robots for at least part of the season in all solutions.

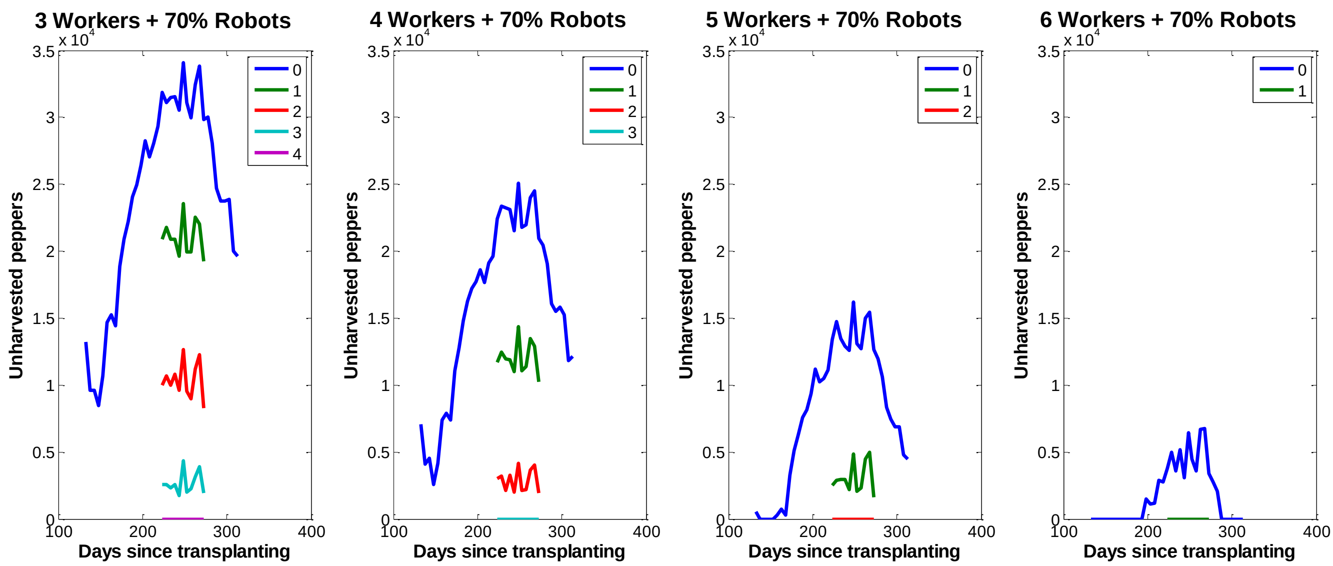


Figure 39: Unharvested peppers as a function of days since transplanting for different workers and 70% robots combinations

When examining the maximum utilization of the robots for each HC throughout the season, it can indicate whether the designated number of robots of a given solution is indeed the needed number to complete the harvest of the HC. For example in Figure 40, the solution of 3 workers and 4 robots was analyzed for the entire season with the maximum robots utilization (the individual utilization of each of the robots is approximately the same with average difference of 0.08 and std. of 0.002). It was discovered that because of the low utilization of the robots in the first 9 HCs, 3 robots are sufficient. Only after the first 9 HCs, the 4 robots are actually needed. The calculation of the actual number of robots required was performed using equation (9).

$$(9) \qquad Robots\ needed = \left\lceil \frac{MaxUtilization \cdot SimulatedRobots}{0.95} \right\rceil$$

Where: the number of "$SimulatedRobots$" in the described scenario was 4 and "0.95" is defined as the max utilization of a robot. When placing in "$MaxUtilization$" the maximum utilization of the robots- each time for a specific HC, the result will yield the number of robots needed for that HC. The critical utilization point for the presented solution of 3 workers and 4 robots is 0.712%. Below this utilization only 3 robots are needed, and above this utilization 4 robots are needed.

Table 23: Detailed results of human-robot combinations with 70% harvest success

	3 workers + 4 robots	4 workers + 3 robots	5 workers + 2 robots	6 workers + 1 robot
Average utilization robot	0.782	0.712	0.597	0.463
Max utilization robots	0.942	0.931	0.876	0.715
Average utilization worker	0.987	0.982	0.959	0.914
Total # [and %] peppers harvested by robots	1,280,832 [71.1%]	899,054 [49.9%]	520,938 [28.9%]	210,782 [11.7%]
Total # [and %] peppers harvested by workers	506,209 [28.1%]	893,702 [49.6%]	1,277,083 [70.9%]	1,590,316 [88.3%]
Total # [and %]missed peppers	14,775 [0.8%]	9,059 [0.5%]	3,794 [0.2%]	716 [~0%]

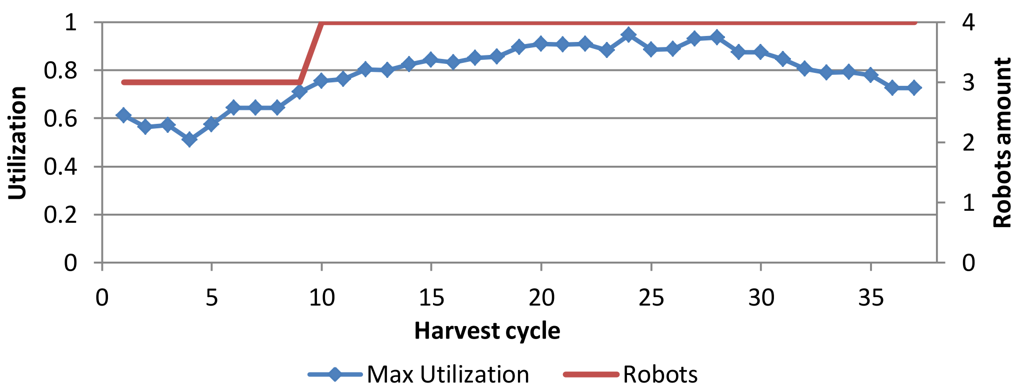


Figure 40: Maximum utilization of robots and number of robots needed with three workers for 70% success rate of robots solution

6.3.3 Sensitivity analysis

6.3.3.1 Robot detection rate

Less than 100% detection rate

The sensitivity analysis was performed for detection rates of 50%, 70% and 90% for a given number of workers between 3 and 6. The number of required robots was determined for each solution. It was found that in order to complete the harvest of the entire season, the same maximum number of robots is needed when the robots have 70% and 90% detection rates. With robots with 50% detection rate, all solutions require one more robot except for the case of 6 workers (Table 24). The process of finding the needed number of robots was performed gradually by adding one robot at the time, similar to the process explained in section 6.3.2. In Figure 42, the summary of the number of unharvested peppers of all the tested solutions is presented, where each column of graphs represents a fixed number of workers and each row of graphs represents specific robot detection rate. The solutions in which all peppers were harvested (i.e. simulations resulting with zero unharvested peppers in Figure 42) are presented in Table 24.

Each solution (1-12 from Table 24), was analyzed along the season according to the maximum utilization of the robots at each HC. The calculation of the number of robots needed for each HC for every solution was based on equation (9). The results are shown in Figure 41. Each line represents a solution from Table 24 and each column is a HC. For example, the first row (first solution) shows that the needed number of five 50% detection rate robots is actually needed only for 18 HCs (16-33).

Table 24: Maximum number of robots needed to complete the harvest with a fixed number of workers

Workers \ Robots	50%	70%	90%
3	Solution #1 5	Solution #2 4	Solution #3 4
4	Solution #4 4	Solution #5 3	Solution #6 3
5	Solution #7 3	Solution #8 2	Solution #9 2
6	Solution #10 1	Solution #11 1	Solution #12 1

#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41
1	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	4	4	4	4	4	4	4	4
2	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3	3	3
4	2	2	2	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3	3	3	3	3	3	3
5	2	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2
6	2	2	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	2	2
7	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3	3	3	3	3	2	2	2	2	2	2	2	2	2	2	2
8	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1
9	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0

Figure 41: Number of robots needed for each human-robot solution along the season (each line represents a solution from Table 24, each column is a harvest cycle. Within each cell is the needed number of robots)

This analysis opens the possibility to create new optional solutions with less than the maximum number of robots (Table 24) and perform changes in the workforce during the season to complete the harvest without additional simulations runs. If, for example, in the first solution we will decide to hire three fixed workers and purchase only three robots with 50% detection rate, then we could use Figure 41, solutions 1, 4, 7 and 10, to decide how many additional workers are needed to complete the work: one additional worker for HCs 8-19, two additional workers for HCs 20-32 and back to one additional worker for the rest of the season. In Table 25 all possible combinations for less than the maximal number of robots are presented with the number of workers needed to complete the harvest throughout the season.

Table 25: Fixed number of robots with workers changes throughout the season

Robots	Detection rate	Workers	HC	Workers	HC	Workers	HC	Workers	HC
2	50%	5	1-21	6	22-30	5	31-41		
3	50%	3	1-7	4	8-19	5	20-32	4	33-41
4	50%	3	1-15	4	16-33	3	34-41		
2	70%	4	1-11	5	12-38	4	39-41		
3	70%	3	1-11	4	12-41				
2	90%	4	1-12	5	13-36	4	37-41		
3	90%	3	1-13	4	14-36	3	37-41		

The solutions of Figure 41 were also translated to number of workers and robots per hectare, 8.6, 10, 15 and 20 hectares (Appendix J). The robots were translated based on the utilization of robots along the HCs of the season according to equations (10) and (11).

$$(10) \qquad RobotsPerHectare = \frac{SumofRobotsUtilization}{0.95 \cdot 4.3}$$

Where: $\mathrm{SumofRobotsUtilization}$ is the utilization sum of all simulated robots in the HC, 0.95 is defined as the max utilization of a robot (similar to equation (9)) and 4.3 is the size in hectares the simulation runs were performed.

$$(11) \qquad RobotsPerSizeX = \lceil RobotsPerHectare \cdot SizeX \rceil$$

Where: $\mathrm{RobotsPerHectare}$ is the calculated number of robots per hectare according to equation (10) and SizeX is the size in hectare the translation is for. The result is rounded upwards to represent a realistic number of resources.

The translation of number of workers to hectare was determined by dividing the number of workers (3-6) by 4.3 hectares. The reason for this difference from the robots calculation is the high utilization of the workers (average: 0.96, std.: 0.03) as opposed to the lower utilization of the robots (average: 0.61, std.: 0.11). When the utilization is relatively low, as in the robots case, the results must be normalized for the translation (hence the division in 0.95 in equation (10)).

Using the translated detailed results of number of resources for the entire season, Table 24 was also translated for per hectare information (Table 26). Each cell in the table is the maximum number of robots per hectare required for the solution (S1-S12 as in Table 24).

Table 26: Solutions S1-S12 from Table 24 translated to one hectare

Workers \ Detection rate	50%	70%	90%
0.70	1.06	0.92	0.85
0.93	0.82	0.67	0.63
1.16	0.52	0.42	0.40
1.40	0.20	0.19	0.17

The difference in the maximum number of robots between 50% and 70% and between 90% and 70% detection rate was summarized per 1, 4.3, 10 and 20 hectares (Table 27). The difference was calculated based on the translated number of robots as explained above (equation (10)), where each difference is calculated between the maximum number of robots of each solution (Appendix J, the second column). The difference for one hectare was based on the actual number of robots needed per hectare (not rounded) and therefore is a fraction, where the difference between the 4.3, 10 and 20 hectares which represents possible greenhouses sizes, was based on rounded number of robots and therefore is an integer.

The results indicate that although the simulations of half of the NL greenhouse (4.3 hectares) showed that there is no difference in the number of robots between 70% and 90% for every given number of workers (due to the rounded calculations), in larger greenhouse sizes differences are noted. Results indicate that as the greenhouse dimensions increase the significance of the detection rate increases (Table 27).

Table 27: Difference in number of robots between the examined detection rates per hectare (not rounded) and for 4.3, 10 and 20 hectares (rounded) for all fixed workers solutions

Difference between	50% - 70%				70% - 90%			
Greenhouse size / Workers per hectare	1	4.3	10	20	1	4.3	10	20
0.70	0.14	1	1	3	0.08	0	1	2
0.93	0.12	1	2	3	0.06	0	0	1
1.16	0.10	1	1	2	0.03	0	1	1
1.40	0.03	0	1	1	0.01	0	0	0

100% detection rate

In order to examine the equivalent solution to the current state where the work is completed by only one resource type, robots with 100% detection rate were analyzed. The robots were defined with an arm acceleration of 0.2 m/s^2. Additionally, it is assumed at this point that the detachment success is 100% as well, so as to result with a total success rate of 100%. Results indicate that five robots are needed to complete the harvesting season without human workers. According to simulation results, the average harvesting time per pepper of the robots is 4.96 seconds (Std. 0.03) as opposed to the human workers average harvesting time of 3.97 seconds (Std. 0.58). The difference in number of 100% robots needed (five) versus the number of human workers needed (seven) derives from the robots hours per day, which is defined as 20 hours compared to 9 hours per day for the human workers.

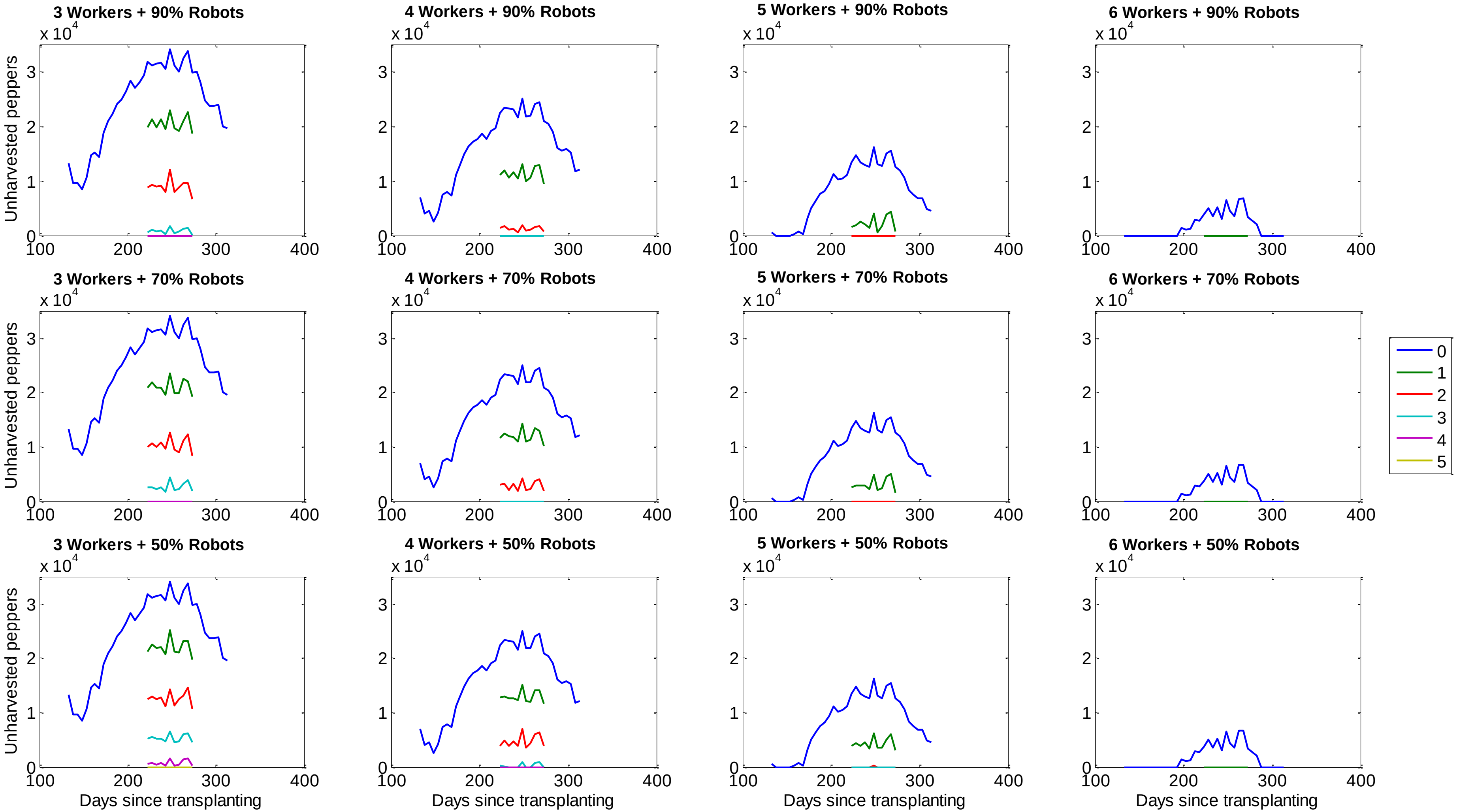


Figure 42: Unharvested peppers as a function of days since transplanting for different workers and different robots combinations

6.3.3.2 Robot's harvester arm acceleration

Changing the robot's arm acceleration influences directly the harvest time per pepper (section 5.1.4.1) as expected. The baseline acceleration was 0.2 m/s2 and in the sensitivity analysis 0.1 and 1 m/s2 were examined as well. The simulation runs showed that there is difference in the number of robots needed to complete the harvest for almost every solution tested (Figure 43). Specifically, in Figure 44 it is shown that for the solution of three workers with 90% detection accuracy robots, the increase in acceleration and hence decreased harvest time per pepper, reduce significantly the unharvested peppers for each additional robot and can result in one less robot for a 4.3 hectare sized greenhouse.

Table 28 presents the difference in number of robots per hectare for increasing the acceleration from 0.1 to 0.2 and from 0.2 to 1m/s2.

Results indicate that the higher the robot detection rate, the more significant the improvement in number of robots needed for the harvesting season. For example, when increasing the acceleration from 0.2 to 1 m/s2 for 90% detection rate robots, two less robots are needed for an 8.6 hectare sized greenhouse (based on the simulation results of half the greenhouse).

Table 28: Number of robots difference per hectare between different robot's arm acceleration

Detection rate	50%		70%		90%	
Acceleration / Workers Per hectare	(0.1,0.2)	(0.2,1)	(0.1,0.2)	(0.2,1)	(0.1,0.2)	(0.2,1)
0.70	0.17	0.23	0.19	0.24	0.19	0.25
0.93	0.10	0.20	0.15	0.15	0.14	0.20
1.16	0.07	0.12	0.12	0.09	0.07	0.09
1.40	0.07	0.03	0.01	0.04	0.02	0.04

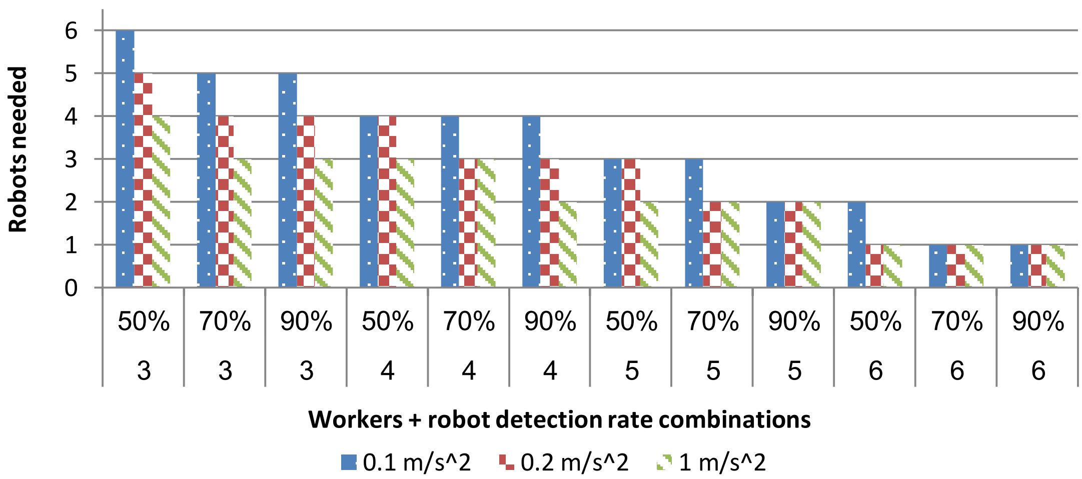


Figure 43: Maximum number of robots with accelerations of 0.1, 0.2 and 1 m/s^2 needed to complete the harvest with fixed workers in a 4.3 hectare greenhouse

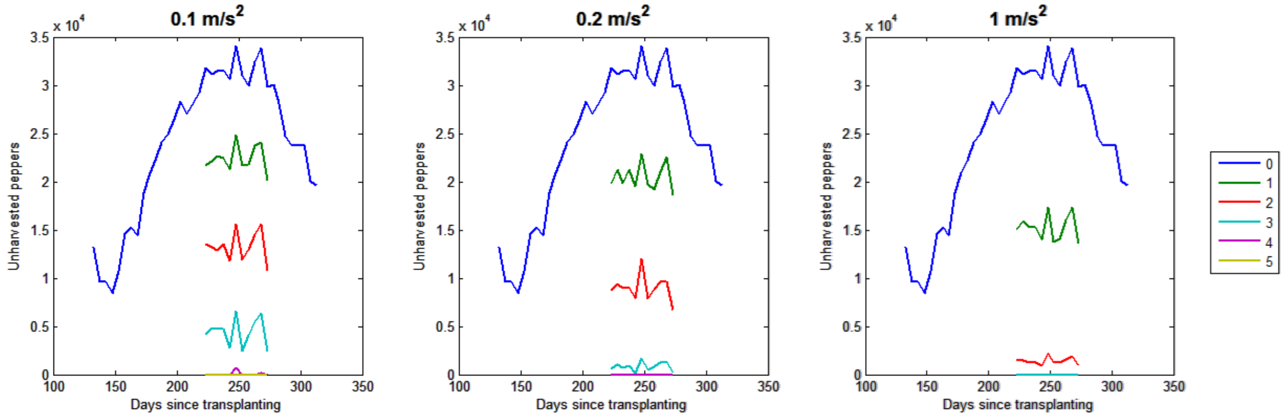


Figure 44: Unharvested peppers as a function of days since transplanting for 3 workers with 90% detection accuracy robots

6.3.3.3 Robot repetitive cycles

When defining that once the robot has recognized the pepper, it is not 100% certain the pepper will be harvested on the first trial (or at all), not only the harvest success decreases, but the overall average time per pepper increases. When running solutions of six fix workers with one 90% detection robot once without harvest repetitions, and one with two repetitions with 70% success each, results indicate that the average cycle time per pepper increases by 34% (5.29 seconds without repetitions versus 7.08 seconds with repetitions for robots with arm acceleration of 0.2 m/s^2). As a result, the robots needed to complete the harvesting season with a fixed number of workers increases. Table 29 shows the difference in robots needed per hectare to complete the work of combinations of 3-6 workers.

Table 29: Robots difference per hectare between robot performance without repetitive cycles and with repetitive cycles

Workers \ Robots	50%	70%	90%
3	0.26	0.28	0.23
4	0.20	0.23	0.16
5	0.12	0.16	0.12
6	0.08	0.02	0.04

6.3.3.4 Changes in yield

In order to test the effects of the yield on the required greenhouse resources, the yield parameters of the highest and lowest yield paths of the NL greenhouse were used (section 4.4.3.3). Two sets of simulation runs were performed and for each set, the yield was created using the highest\ lowest yield path as a representing path of the entire greenhouse peppers growth. Figure 45 shows the differences in the simulated yield level throughout the season for all yield levels tested. At every first day of a HC (on the X-axis), the simulated amount of peppers to harvest throughout the HC is presented (on the Y-axis).

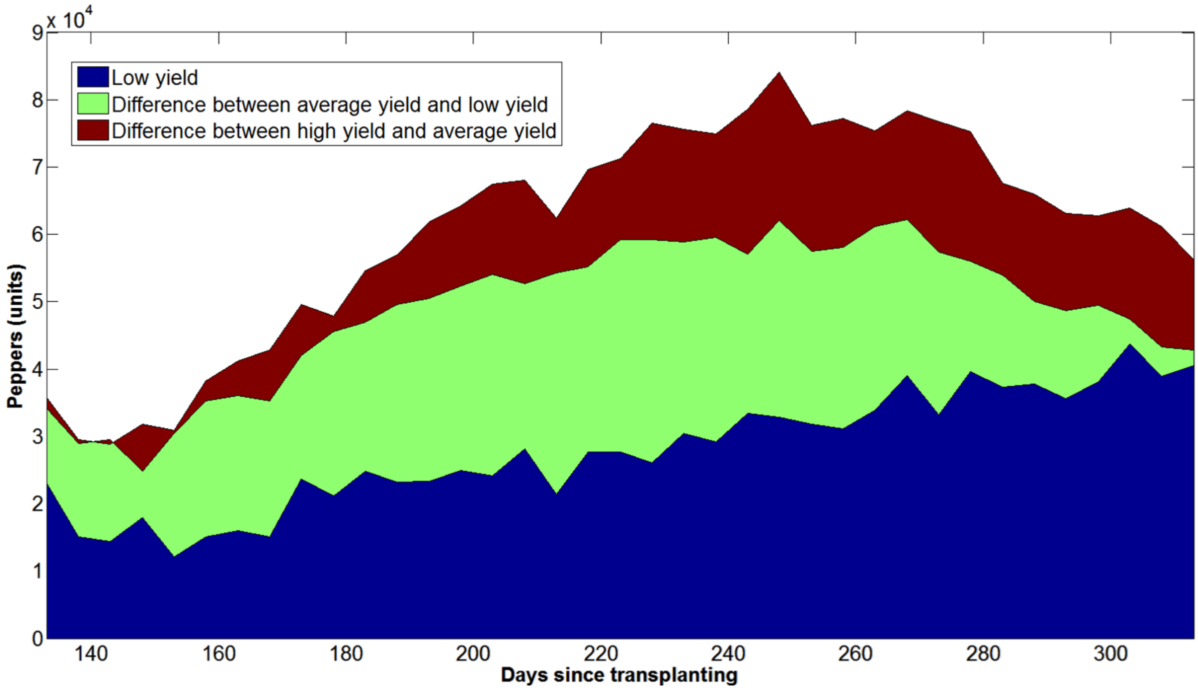


Figure 45: Yield amounts for the simulation model as created by low, average and high yield parameters

When simulating the 4.3 hectare greenhouse with high yields it was found that seven workers are not sufficient to complete the harvest of the season alone and therefore combined human-robot solutions were examined for 3-7 workers. In average, 0.3 robots per hectare are needed in addition to the number of robots per hectare in regular yield state. When this difference in extrapolated to a field size of 8.6 hectare, it can reach three additional robots.

When simulating a greenhouse with low yields, results indicate that some of the resources are not utilized (implying that we might have extra resources). It was found that six workers can complete the harvest without additional robots. For the other simulated solutions of 3-5 workers, it was found that the average robots savings is 0.23 robots per hectare which implies between 2-3 unnecessary robots.

Table 30 summarizes the differences of robot per hectare for the different yields tested for all examined solutions.

Table 30: Influence of changes in yield effect on number of robots per hectare

	High yield - Regular yield			Low yield - Regular yield		
	50%	**70%**	**90%**	**50%**	**70%**	**90%**
3	0.32	0.29	0.27	-0.24	-0.23	-0.24
4	0.29	0.30	0.29	-0.28	-0.24	-0.25
5	0.34	0.32	0.29	-0.27	-0.24	-0.25
6	0.36	0.30	0.29	-0.20	-0.19	-0.17
7	0.31	0.29	0.23	-	-	-

7. Economic analysis

7.1 Overview

The objective of the economic analysis is to find the maximum cost per robot it is worth paying for robots with given capabilities. The analysis was performed using an economic model presented in section 7.2 based on the methodology applied in CROPS (evaluation of economic viability of agricultural robotic systems, Ref: C0399), formulating the annual costs in the greenhouse resulting from the harvesting process. Modifications were made to account for human-robot combined work as opposed to the crops model which accounted work of only one resource type. The annual costs were formulated as the sum of fixed and operating costs, damaged pepper costs and unharvested peppers costs.

The economic analysis included calculating the costs of solutions with different numbers of workers and robots with different capabilities, as derived from the simulations (chapter 6). Each solution's annual cost was compared to the cost of harvesting by human workers alone in order to quantify the potential savings that could be invested in robots, denoted as investment space similar to the CROPS economic analysis. Each solution's annual investment space was translated to maximum robot initial cost as presented in section 7.3. The same process was performed first for a fixed greenhouse size and yield, and then for greenhouses with different parameters.

7.2 Model

The parameters that contribute to the calculation of the annual cost are divided into three categories (Table 31): basic (greenhouse and yield), workers (human labor including materials and investments) and robots costs (the robot/s including investment, operator and maintenance). The model's structure and parameters used are the same as the CROPS economic model (C0399_CROPS, (Pekkeriet et al., 2014)). The main differences between the economic model used in the thesis and CROPS model are:

1. The number of resources used in the model is received as an input (derived from the simulation results) and are not calculated as output as in the CROPS model.
2. The harvested peppers are divided between the human workers and the robots according to simulation results (work assignment) unlike the CROPS model that assigned all peppers to robots or workers.
3. The "basic parameters" (Table 31) inputs are adjusted to the tested greenhouse of the thesis.

Table 31: Structure of cost analysis tool for economic viability (based on C0399_CROPS)

Basic parameters	Workers parameters	Robots parameters
Production site size	Work hours	Work hours
Average product weight	Workers costs	Operator cost
Total product and kg per year	Investments and materials	Investments
	Quality losses	Quality losses
		Missed peppers losses

The annual cost of each resource (human/robot) is calculated by the general equation (12) including fixed and operating costs and costs related to damaged and unharvested peppers per year.

$$TC = C_{Investments} + C_{Labor} + C_{QualityLoss} + C_{MissedPeppers} \tag{12}$$

Where

$\boldsymbol{C_{Investments}}$ Is the annual fixed costs of the tangible assets (investments). Fixed costs included depreciation and interest. The straight line method was used to depreciate investments with assumed salvage value of zero. Interest was computed as percentage of the average annual value of each investment (investment cost/2). All investments costs used for human workers are taken from CROPS model. It was assumed that when calculating the costs of human-robots combined work, the same investments and equipment are needed. $C_{Investments}$ is calculated by:

$$C_{Investments} = \sum_{all\ investments}\left(\frac{C_{init} \cdot N}{n} + i \cdot \frac{C_{init} \cdot N}{2}\right) \tag{13}$$

C_{init} = initial cost of investment; N = number of items of one type needed; n = economic life cycle (years); i = interest rate

$\boldsymbol{C_{Labor}}$ Labor cost. For human resource- the workers cost, when assuming that each worker hired is working full days. This assumption is based on the simulation results. Table 23 indicates that all workers hired are fully utilized. For robot resource- the robot's operator cost (according to CROPS economic model). The operator is a qualified worker that should be in the greenhouse when the robots are operating, regardless of the number of robots active (i.e. one operator per any number of robots). C_{Labor} is calculated by:

$$C_{Labor} = L \cdot Hr \cdot Days \cdot C_{Hr} \tag{14}$$

L = labor needed (number of workers); Hr = hours per work day; $Days$ = number of workdays along the entire season; C_{Hr} = labor cost per hour

$\boldsymbol{C_{QualityLoss}}$ Is the loss in potential revenues due to damage inflicted upon the fruit by harvesting (poor-ripeness, over-ripeness or other physical damages to the pepper). The structure and parameters of this cost are taken from CROPS model. The following assumptions were made (CROPS): the quality loss is measured compared to a baseline were all peppers are first class quality peppers (even though it is only hypothetical as some peppers are faults not caused by timeliness, but growth defects etc.), a damaged pepper can be classified to only one type of the second class quality peppers and each type can theoretically have different price. In the thesis, all types of second quality peppers have the same price. $C_{QualityLoss}$ is calculated by:

$$(15) \qquad C_{QualityLoss} = P \cdot R_{Per} \cdot (S_{Fst} - (F_{Per} \cdot S_{Fst} + \sum_i (D_{Per_i} \cdot S_{Snd_i})))$$

P = peppers in kg of the entire season; R_{Per} = percentage of peppers harvested by the resource; S_{Fst} = the selling price per kg of first class quality peppers; F_{Per} = percentage of peppers per kg of first class quality peppers; D_{Per_i} = percentage of peppers for each damage i of second quality peppers; S_{Snd_i} = the selling price per kg for each damage i of second class quality peppers; $(F_{Per} + \sum_i D_{Per_i} = 1)$

$\boldsymbol{C_{MissedPeppers}}$ Is the cost of un-harvested peppers (relevant for robots harvest), which are considered lost. When a robot is defined with less than 100% harvest success, and it is the only resource harvesting in a path, there is possibility that some of the peppers will remain un-harvested. In reality, the peppers missed by the robots in one HC can be harvested in the next HC by the human workers (with larger probability for quality loss as over-ripeness) but in the simulation model, this option was not exercised and all peppers assigned to one HC had to be harvested within the limited time of that HC. For that reason, the workers can complete the robots work only within the designated HC time. However, in some cases none of the workers are available (or they have completed their work hours) and therefore the robots will harvest a path twice or even three times. After the robot completes the harvest in a path some peppers may remained un-harvested. They are considered lost. As compare to reality, considering these peppers as lost could overestimate the costs of missed revenues.

7.2.1 Basic parameters

The initial costs calculation is based on a greenhouse sized 43,000 m^2 on which the simulation was performed (equal to half of the NL greenhouse). The amount of peppers (units and kg) is the amount created in the simulation model by the yield model (section 4.4.3) for this greenhouse. To create identical conditions for comparison, the same yield was used for each suggested solution and its current state with only human workers.

The average product weight of 0.192 kg per pepper was calculated as the average weight of the 2012 harvesting season in the NL greenhouse.

7.2.2 Workers parameters

Labor cost: cost per working hour is 16.5€, total hours per worker is calculated as 9 hr/day, 34 weeks of harvesting with 0.6 (3/5) of the week devoted for harvesting (section 4.4.2). The number of workers is derived from the simulation results.

Investments and materials (Table 32): the long term (5 years) investments associated with the greenhouse are estimated to be- pipe rail trolleys (X12 units) and containers (X12 units). The long term investments associated with the workers is a workplace registration system. The short term (1 year) investments include knives purchased (X360) and maintenance costs of all equipment. The investments and material amounts from Table 32 are estimated for a greenhouse sized 4.3 hectares based on the CROPS economic analysis that was performed for a 4 hectare greenhouse. Amounts were proportionally adjusted for different sized greenhouses (the amount was divided by 4.3 and multiplied by the needed size, then rounded). The interest rate for the cost calculations is 5%.

Quality loss: the undamaged peppers are denoted as 1st class and the damaged peppers (all types of possible damages) are denoted as 2nd class. The prices are assumed as 1€ per kg of 1st class peppers and 0.6€ per kg of 2nd class peppers (as seen in the formulation of equation (15), each 2nd class pepper of type i can have theoretically different price but for current calculations we used $\forall i, S_{\mathrm{Snd}_i} = 0.6€$). Additionally, as in CROPS economic model, another loss factor was added for including natural losses that were evaluated as -0.05€ per kg.

For human labor, the assessment is that 90% of the peppers harvested are 1st quality, 9.5% of the peppers are 2nd quality and the loss factor is the remaining 0.5%. These percentages were multiplied by the amount of peppers the workers harvested (equation (15)).

Table 32: Investments and materials for the greenhouse and human workers (C0399_CROPS) same data was used in the economic analysis of the thesis

	Equipment and maintenance	Costs (€/piece)	Number needed (per 4.3 hectare)	Economic life cycle (year)
1	Pipe rail trolleys	€ 12,000	12	5
2	Containers	€ 500	12	5
3	Workplace registration system	€ 25,000	1	5
4	Knifes	€ 3	360	1
5	Maintenance	€ 2,000	1	1

7.2.3 Robots parameters

Operator cost: cost per operator's working hour is 20€ and it is assumed that an operator will be present for half the time the robots are active (based on CROPS economic model).

The total hours the robots are active in the greenhouse each day are 20 hr/day (the amount of operator hours per season is calculated similar to 7.2.2 only with 10 hr/day which is half the time and one worker).

Investments: the fixed costs when adding robots to the harvesting process is depreciation, interest and maintenance. The maintenance cost is assumed as 2.5% per year of the total robot investment and the interest rate is 5%. The number of required robots is derived from the simulation results.

When the robots are the only resources (for a tested scenario of robots with 100% harvest success), the pipe rail trolleys and containers cost are also added to the investment cost calculations as in Table 32, as it is assumed for now that the logistics in a path of a 100% harvesting robot is identical to the human workers operations. Otherwise, there is no need to add any additional investments to the robots costs because it is already calculated as part of the human workers investment, and it is assumed the robot will use the existing pipe rail system and the same containers.

Although the investments and equipment of human workers alone versus human-robot combined work is identical at the moment and therefore can be left out of calculations, the economic model is built to enable introduction of future changes when more information on the robot's harvesting capabilities and logistics in a path is available.

Quality loss: the definition and prices remain exactly as in the human worker's calculations (7.2.2), but the percentages of peppers in each category are different than for human labor costs. The assessment is that 92% of the peppers harvested are 1st quality, 7.5% of the peppers are 2nd quality and the loss factor due to natural causes is on the remaining 0.5% (based on CROPS economic model). These percentages are multiplied by the amount of peppers the robots harvest.

Missed peppers losses: the amount of missed peppers is determined per solution according to the simulation results of the specific solution.

7.3 Methods

The economic model aims to determine the maximum cost per robot that is economically viable (defined as equivalent to human workers harvesting which is taken as the baseline) for a given greenhouse depending on the robot capabilities. Therefore, the annual cost of robot investment is calculated by equation (16), which is based on equation (13) plus the robot's maintenance costs.

$$(16) \qquad Annual\ costs\ robots = \frac{C_{init} \cdot N}{n} + C_{init} \cdot N \cdot \frac{i}{2} + C_{init} \cdot N \cdot m = C_{init} \cdot N \cdot (\frac{1}{n} + \frac{i}{2} + m)$$

C_{init} = robot's initial investment (one robot) ; N = number of robots needed ; n = economic life cycle (years) ; i = interest rate ; m =maintenance % of the total price

In order to find the initial investment cost, the difference between the annual cost of the baseline (the non-robotic solution) and the allocated cost of scenario (the robotic solution) including all costs except the robot costs is calculated. This difference is the investment space of the solution (equation (17)). This investment space is the maximum annual cost that could be assigned to the robots costs for economic viability. The maximum initial investment presented in equation (18) is therefore calculated by rearranging equations (18), (17).

$$(17) \quad Investments\ space = TC_{Baseline} - TC_{RoboticSolution} = Max\ Annual\ costs\ robots$$

$$(18) \qquad Max\ C_{init} = \frac{Investments\ space}{N \cdot (\frac{1}{n} + \frac{i}{2} + m)}$$

The parameters and costs of human workers and robots used in the economic model are presented in Table 33 and Table 34.

Table 33: Workers parameters for economic model

Workers parameters		
Harvest weeks	34	weeks/year
% of week for harvesting	0.6	%
Working hours per day	9	hr/day
Total hour per worker	1285.2	hr
Costs per working hour	16.5	€/hr

Table 34: Robots parameters for economic model

Robots costs parameters			**Robots operator parameters**		
Robot initial cost	tested	€	**Harvest weeks**	34	weeks/year
Economic life cycle	5	Years	**% of week for harvesting**	0.6	%
Interest rate	5	%	**Working hours per day**	20	hr/day
Maintenance	2.5	%/year from robot investment	**Total hours of operator**	2856	hr
			Costs per working hour	20	€/hr

For the analysis of the robots investment cost, the solutions presented in chapter 6 were tested for economic viability. The analysis includes two parts (Table 35):

1. **Tested greenhouse**- different types of human-robot combined solutions for a greenhouse sized 4.3 hectares with average yield parameters. All solutions were compared to the same current state with only human workers.
2. **Greenhouse factors sensitivity analysis**- the most economical solution from the tested greenhouse phase was selected and analyzed for sensitivity to yield and greenhouse size. Each change in yield or greenhouse size caused a change in the current state the solutions are compared to of only human workers (i.e. the number of human workers needed to complete the harvest is changed).

Table 35: Economic analysis structure

<table>
<tr><th rowspan="2">Results in section</th><th colspan="5">Inputs</th><th rowspan="2">Fixed workers solutions</th><th rowspan="2">Changed workers solutions</th></tr>
<tr><th>Greenhouse size</th><th>Yield model</th><th>R_{DET}</th><th>Arm acceleration</th><th>R_{REPEAT}</th></tr>
<tr><td rowspan="6">Tested greenhouse: 7.4.1</td><td rowspan="6">4.3</td><td rowspan="6">Average</td><td>100%</td><td>0.2</td><td>100%</td><td rowspan="2">Description: 7.4.1.1</td><td>-</td></tr>
<tr><td rowspan="5">50%, 70%, 90%</td><td rowspan="2">0.2</td><td rowspan="2">100%</td><td>Description: 7.4.1.2</td></tr>
<tr><td colspan="2">Summary: 7.4.1.3</td></tr>
<tr><td>0.1</td><td>100%</td><td rowspan="3">Summary of all robot capability changes: 7.4.1.4</td><td rowspan="3">-</td></tr>
<tr><td>1</td><td>100%</td></tr>
<tr><td>0.2</td><td>70%</td></tr>
<tr><td rowspan="2">Greenhouse factors sensitivity analysis: 7.4.2</td><td>4.3</td><td>Low, High</td><td rowspan="2">50%, 70%, 90%</td><td rowspan="2">0.2</td><td rowspan="2">100%</td><td>Yield changes summary: 7.4.2.1</td><td rowspan="2">-</td></tr>
<tr><td>1.3, 8.6, 10, 15, 20</td><td>Average</td><td>Different greenhouses sizes: 7.4.2.2</td></tr>
</table>

7.3.1 Tested greenhouse

The solutions presented in chapter 6 were tested for economic viability. These solutions are compatible with the simulated greenhouse (half of the NL greenhouse).

The solutions differ in five parameters: number of workers, number of robots, % peppers harvested by workers, % peppers harvested by robots and % missed peppers. The greenhouse features including total yield and distributed yield in the paths for each harvest cycle, and harvesting season data remained constant for each analysis. The simulated number of peppers per year is 6,368,979 peppers per year (as derived from yield model with the NL average growth parameters). The rest of the parameters for the economic model "basic parameters" of the tested greenhouse are detailed in section 7.2.1.

7.3.2 Greenhouse factors sensitivity analysis

The economic analysis for other yield parameters and different greenhouse sizes was performed only for the solutions that showed the highest potential annual savings as result of inserting robots into the harvesting process. Each of the sensitivity changes were analyzed by comparing to different "current states" that included the number of human workers needed specifically for the tested scenario and the maximum cost per robot in each scenario was found.

Yield

For the same greenhouse size as the tested greenhouse (4.3 hectares), low and high yields were examined, based on the parameters found in the yield model (section 4.4.3, Table 9). The combined human-robot solutions for the changed yield economic analysis are based on the findings of section 6.3.3.4.

Greenhouse size

To analyze the effects of greenhouse size on the maximum robots cost, the translated number of workers and robots needed for the season to different greenhouse sizes were used (Appendix J) based on the calculations described in 6.3.3.1 equations (10),(11). The minimum greenhouse size that a robot will have potential of being profitable was found and was examined in addition to greenhouses sizes of 8.6, 10, 15 and 20 hectares.

7.4 Results

7.4.1 Tested greenhouse results

7.4.1.1 Fixed number of workers throughout the season

The simulation outputs of all solutions between 3-7 fixed workers were analyzed for the economic analysis. Table 36 summarizes the solutions with details on their cost affecting factors: number of resources, work division and missed peppers.

Table 36: Summary of fixed workers solutions for the economic analysis

Solution	Description	Workers	Robots	R_{DET}*	Harvested by worker	Harvested by robot	Not harvested
S0	Only human workers	7	0	-	1	0	0
S1	Human- robot combined solutions	3	5	50%	0.3405	0.6479	0.0116
S2			4	70%	0.2809	0.7109	0.0082
S3			4	90%	0.2592	0.7378	0.0030
S4		4	4	50%	0.4716	0.5233	0.0051
S5			3	70%	0.4960	0.4990	0.0050
S6			3	90%	0.4839	0.5144	0.0018
S7		5	3	50%	0.6644	0.3338	0.0018
S8			2	70%	0.7088	0.2891	0.0021
S9			2	90%	0.6969	0.3023	0.0008
S10		6	1	50%	0.8933	0.1062	0.0005
S11			1	70%	0.8826	0.1170	0.0004
S12			1	90%	0.8752	0.1246	0.0002
S13	Only robots	0	5	100%	0	1	0

(*R_{DET} = total success rate in these solutions since R_{RETRY}=100%)

Human workers base scenario (S0) – current state of tested greenhouse

The resulting costs of the seven workers (according to the costs detailed in Table 33) is 3.45 €/m^2 for the current base scenario in which seven workers are required. The annual investments costs resulting from solely human labor as detailed in Table 32, are summed into 0.989 €/m^2. The quality loss due to second quality peppers (section 7.2.2) for the amount of peppers of this scenario, when the human labor are the only harvesters the cost is 1.25 €/m^2 (includes not only quality loss due to the harvest process itself, but also due to the production period, misshaped peppers on the plant etc.).

In conclusion, the total cost of scenario with workers as a sole resource is 5.69 €/m^2/year and for the tested greenhouse of 4.3 hectares the cost is 244,858 €/year. This scenario is used as a baseline for all the other proposed solutions.

Robots with 100% success rate (S13)

The resulting cost of an operator required for operating five robots, is 0.66 €/m^2. The relevant greenhouse investments from Table 32 are the pipe rail trolleys and containers which is summed to 0.408 €/m^2. The quality loss costs due to second quality peppers (section 7.2.3) is 1.02 €/m^2. The sum of all these costs as compared to the base scenario creates an investment space of 3.6 €/m^2. The conclusion is that for that case (which is highly optimistic with the robots capabilities- 100% success rate and better quality output than human harvesters), the maximum investment cost of the robot can be up to 123,864 € per unit.

Human-Robot combined solutions (S1-S12)

Each solution from Table 36 was calculated in the economic model. Table 37 shows the maximum investment cost per robot to realize the same yearly costs as in the current state (S0).

The results show that the highest maximum cost for each robot type (different R_{DET}) is realized when hiring the lowest number of workers (three workers). Improvement of the robot detection rate from 50% to 70% increases this maximum investment cost per robot by 36%. Improvement of the robot detection rate from 70% to 90% increases the maximum cost by 12%. When hiring six workers, no additional robots can be afforded. This can be explained due to the robot's operator cost which is higher than adding the seventh worker to complete the harvest.

Between 3-5 workers, whenever a worker is added, the number of robots needed is decreased by one robot for all detection rates and the cost per robot decreases: from 3 to 4 workers by average of 15% (std. 1.4%) and from 4 to 5 workers by average of 39% (std. 2.2%).

Table 37: Maximum cost per robot for all S1- S12 solutions

Workers \ R_{DET}	50%	70%	90%
3	5 robots, each cost up to: € 39,504	4 robots, each cost up to: € 53,880	4 robots, each cost up to: € 60,191
4	4 robots, each cost up to: € 34,329	3 robots, each cost up to: € 45,634	3 robots, each cost up to: € 50,819
5	3 robots, each cost up to: € 20,174	2 robots, each cost up to: € 28,604	2 robots, each cost up to: € 31,832
6	1 robots, each cost up to: € 0	1 robots, each cost up to: € 0	1 robots, each cost up to: € 0

7.4.1.2 Fixed number of robots with workers changes throughout the season

The presented solutions in Table 25, describing a fixed number of robots and changes in the workforce accordingly, were simulated in order to derive from the outputs the cost affecting factors of each solution (same factors as in Table 36). Since the number of workers is changed during the season (unlike the previous section which suggested hiring a fixed number of workers that remained constant along the full season), the number of workers is not entered as an input to the calculation of the economic model (there is no constant number of workers throughout the season), but instead the economic model uses directly the total number of workers hours (for example: 3 workers worked 4 HC, 9 hours per day, than 4 workers works 5 HC… etc. total of 6,668 hours the entire season).

In comparison to the S1-S12 solutions, due to the changed number of workers throughout the season which lowers the labor costs, the investment space of these solutions increased on average by 11,060€ per year (std. 2,960€) causing the maximum allowed cost per robot to increase. In Figure 46, the maximum cost per robot for the solutions are presented as the colorful bars height and the previous section maximum prices are presented as the edge height of lower inner black bars. When the inner black bar reaches the bottom, it means either this number of robots solution was not examined in the previous section with fixed workers or the maximum price before was zero (the solution was more expensive than using only human workers).

Table 38: Summary of fixed robots solutions for the economic analysis

Robots	Detection rate	Peppers harvested		Missed peppers	Total Hours workers
		Workers	Robots		
2	50%	0.759	0.239	0.002	6,668
3		0.557	0.438	0.005	5,262
4		0.408	0.584	0.009	4,341
1	70%	0.870	0.130	0.001	7,127
2		0.672	0.325	0.003	5,869
3		0.464	0.530	0.006	4,803
1	90%	0.863	0.137	0.000	7,127
2		0.650	0.349	0.001	5,788
3		0.414	0.584	0.002	4,476

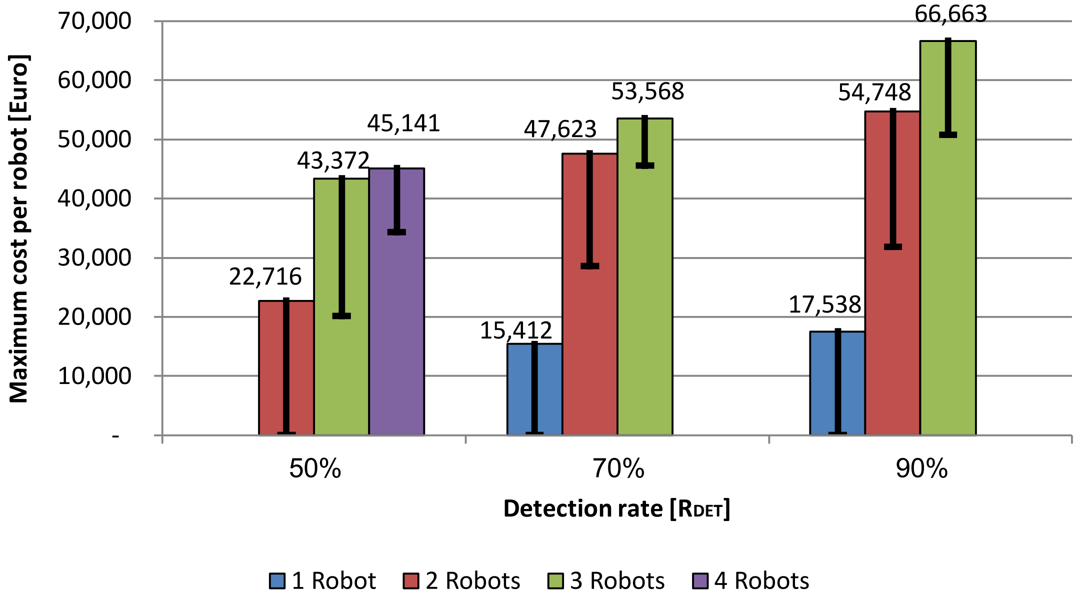


Figure 46: Maximum cost per robot for fixed number of robots solutions

7.4.1.3 Summary of all solutions

Each R_{DET} robot capability (50%, 70%, and 90%) was summarized for all possible number of robots solutions from sections 7.4.1.1 and 7.4.1.2. To determine the investment space for purchasing the robots the annual cost of each solution was compared to the S0 annual cost. The summary of the solutions is presented for each R_{DET} separately. Each summary includes the number of workers and robots needed, the resulting investment space and the maximum cost per robot for all solutions.

R_{DET} = 50% (Figure 47)

When a robot cost is between 0-16,956 € the preferred solution is to hire three workers and purchase five robots for the entire season, if the cost is between 16,956-45,141€ the preferred solution is to hire three to four workers according to the time of the year (Table 25) and purchase four robots. If the cost of one robot is more than 45,141€, it will not be economically feasible to purchase robots with these capabilities at all and the best solution will be to remain with the current state of seven workers throughout the season.

R_{DET} = 70% (Figure 48)

When the robot cost is between 0-53,880 € the preferred solution is to hire three workers and purchase four robots for the full season and if the cost of one robot is more than 53,880 €, it will not be economically feasible to purchase robots with these capabilities at all and the best solution will be to remain with the current state.

R_{DET} = 90% (Figure 49)

When the robot cost is between 0-40,776 € the preferred solution is to hire three workers and purchase four robots for the whole season, if the cost is between 40,776-66,663€ the preferred solution is to hire three to four workers according to the time of the year (Table 25) and purchase three robots. If the cost of one robot is more than 66,663€, it will not be economically feasible to purchase robots with these capabilities at all and the best solution will be to remain with the current state.

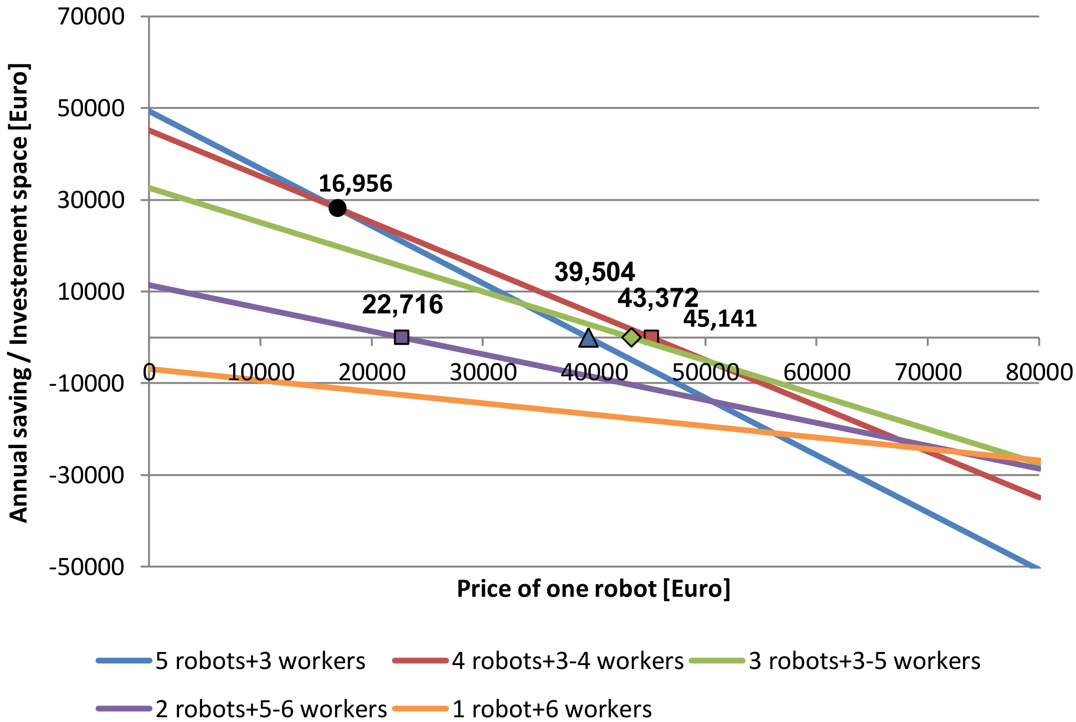


Figure 47: Investment space as a function of robot's price for R_{DET}=50%

The intercept is the annual saving of each solution if the robot price is 0€. As the robot price increases, the annual saving decreases where the slope is the annual robots cost

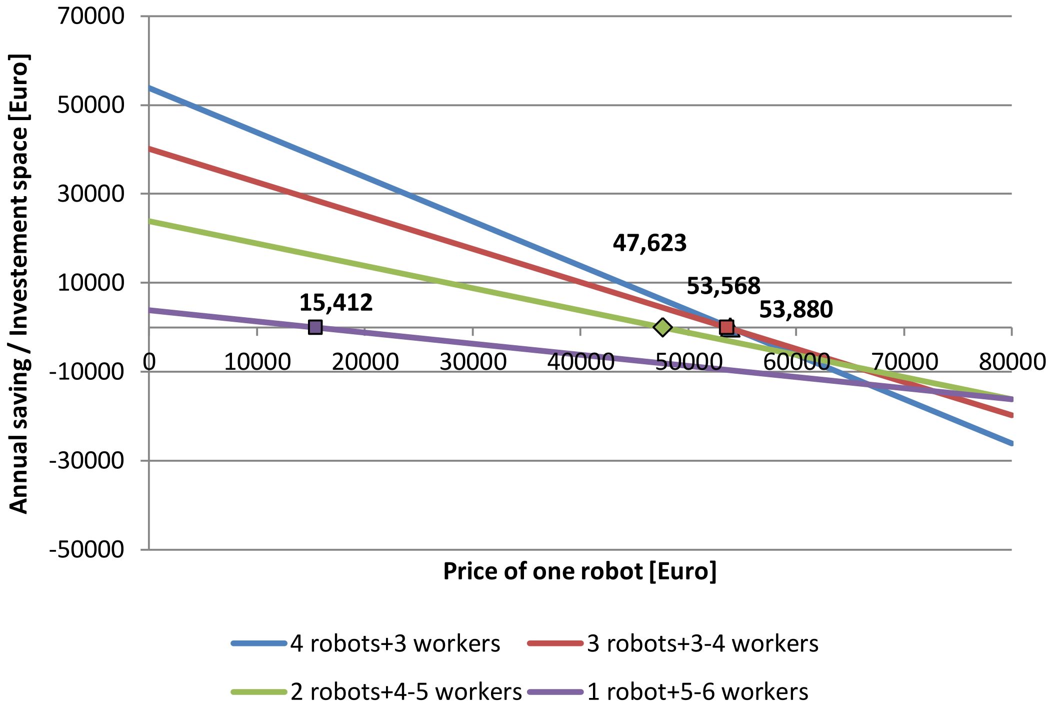


Figure 48: Investment space as a function of robot's price for R_{DET}=70%

The intercept is the annual saving of each solution if the robot price is 0€. As the robot price increases, the annual saving decreases where the slope is the annual robots cost

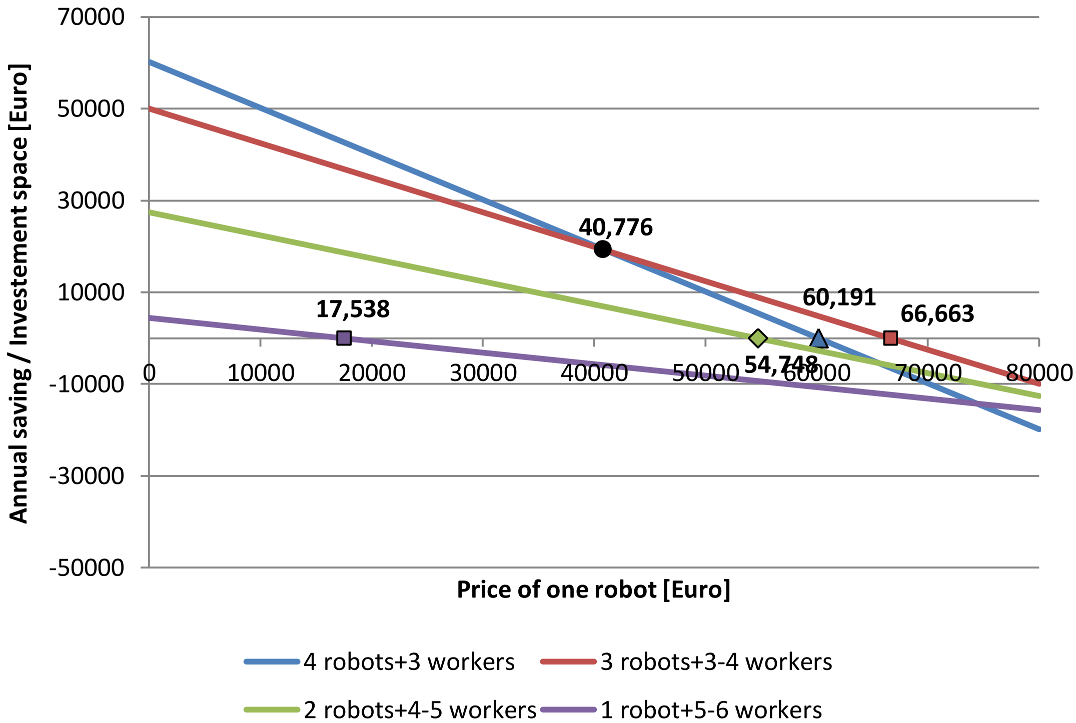


Figure 49: Investment space as a function of robot's price for R_{DET}=90%

The intercept is the annual saving of each solution if the robot price is 0€. As the robot price increases, the annual saving decreases where the slope is the annual robots cost

7.4.1.4 Sensitivity of robot capabilities

The maximum robot costs were tested for 12 different combinations of changes in robot capabilities: R_{DET}, Arm acceleration and R_{REPEAT}. Each combination was analyzed based on the number of robots and work division between resources derived from the simulation results of section 6.3.3. The maximum cost per robot for each solution was calculated (Table 39). Using the economic analysis results, the changes in the maximum robot cost for each change in the robot's capabilities was calculated and presented in Figure 50. The changes in the costs were calculated per robot due to changes in the number of robots between the solutions[4].

Each point in Figure 50 represents a combination of values (X=Arm acceleration, Y=R_{DET}, Z=R_{REPEAT}). Each arrow from one point to another demonstrates a possible direction of improvement in one robot capability (the changed capability differs in color). The thickness of an arrow demonstrates the magnification of the maximum robot cost. As the arrow is thicker, so is the increase in robot maximum cost.

For example, if the robot capabilities are (0.2, 70%, 70%) it pays more to work on improvement in the success of each harvest repeat towards (0.2, 70%, 100%) than it does to work on improvement in the detection success rate towards (0.2, 90%, 70%) because the improvement will be 14,362€ (thick arrow) rather than only 32€ (narrow arrow). The arrows weights were normalized according to a scale where the most significant improvement (and therefore the maximum thickness of an arrow) is of 25,000€.

Qualitative conclusions from the graph:

1. Improvement in R_{DET} is always more significant when increasing from 50% to 70% vs. increasing from 70% to 90%.
2. Improvement in arm acceleration and in R_{REPEAT} is more significant for robots with R_{DET}=90% than in any other detection rates.
3. When the arm acceleration is 0.1 or 0.2 m/s^2, there is approximately similar significance of changes in R_{DET} values (i.e. the improvement from R_{DET}=50% to R_{DET}=70% when R_{ACC}=0.1 and when R_{ACC}=0.2 is similar and the same for the improvement R_{DET}=70% to R_{DET}=90%, demonstrated by the blue upper left arrows in Figure 50).
4. The improvement of arm acceleration from 0.1 to 0.2 m/s^2 or from 0.2 or 1 m/s^2, has similar significance on the robot's cost, even though these changes are different in scale: one is 0.1 m/s^2 improvement and the other is 0.8 m/s^2 improvement.

[4] Due to the differences in the number of robots for each solution with different robot capabilities, if the graph was created for maximum price for all the robots or the investment space of each solution than it could have looked differently.

Table 39: Sensitivity of robots cost with changed capabilities (Compared to the base scenario: three fixed workers, tables for four and five fixed workers are in Appendix R)

	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12
R_{DET}	70%	50%	90%	70%	50%	90%	70%	50%	90%	70%	50%	90%
R_{REPEAT}	100%									70%		
Acceleration	0.2			0.1			1.0			0.2		
Number of Robots	4	5	4	5	6	5	3	4	3	5	6	5
Cost per robot [€]	53,880	39,504	60,191	41,985	31,952	47,521	70,637	48,346	79,866	39,518	30,221	39,487

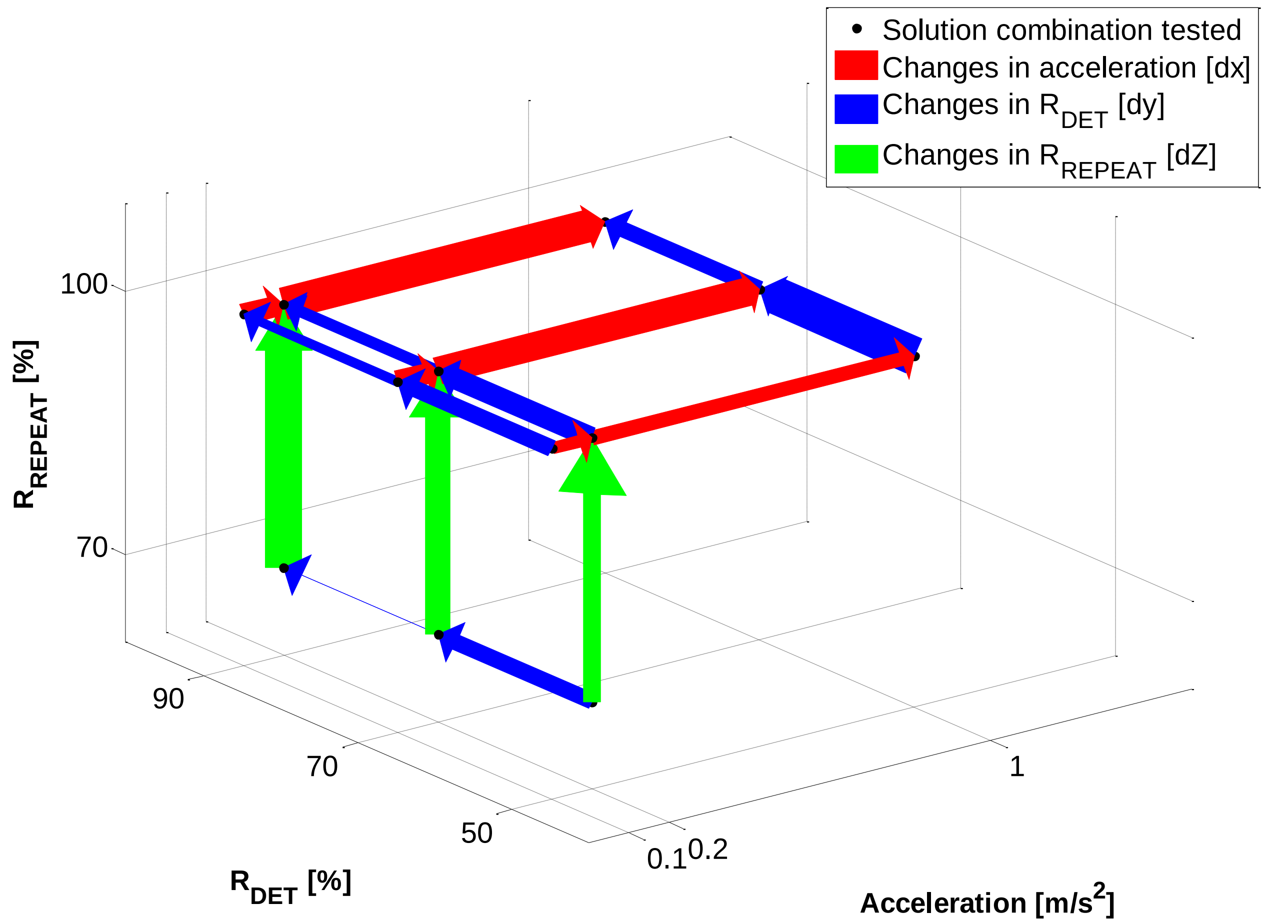


Figure 50: Sensitivity of robot maximum cost to changed robot capabilities (in acceleration, detection and harvest repeat).
The thickness of an arrow demonstrates the magnification of the maximum robot cost between two optional solutions tested (two points on graph)

7.4.2 Greenhouse factors sensitivity analysis

The highest maximum cost per robot for greenhouse size of 4.3 hectares, when the greenhouses yield was based on the yield model (with the basic parameters), was received in the scenarios with the fewest workers which was derived as three workers (Table 37). Therefore, the economic analysis of other yield parameters and different greenhouse sizes was focused on the same scenario with three workers.

7.4.2.1 Yield

Economic analysis was performed on the 4.3 hectares greenhouse human-robot solutions with high and low yields. The number of resources and work division for the economic model were based on results derived in section 6.3.3.4. The summary results of number of resources, investment space and maximum robot cost are presented in Appendix S. The highest maximum cost per robot for all solutions of three workers and 90%, 70%, 50% detection rate robots are in Figure 51. When the average yield is the baseline, the maximum cost per robot decreased by 18.5% (std. 2%) and 8.3% (std. 2%) for low and high yields respectively.

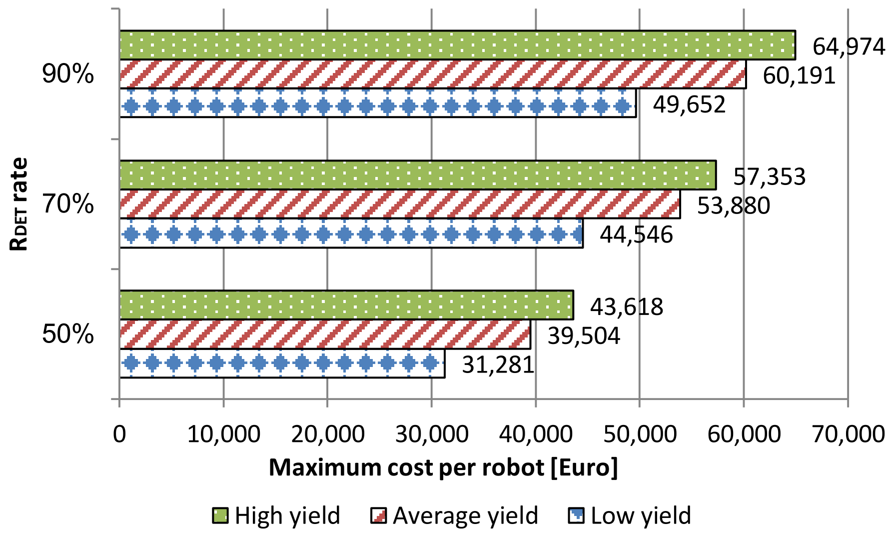


Figure 51: Sensitivity of robot initial investment to yield changes with 3 workers and 3-6 robots

7.4.2.2 Greenhouses sizes

All the solutions were analyzed in the economic model with an upgraded number of required resources, sweet pepper amounts and investment and materials needed for the greenhouse according to its size. The translation of the number of resources needed was performed by using the maximum utilization of the robots and the workers in the runs for 4.3 hectares (no additional simulation runs were performed) as described in section 6.3.3.1 with equations (10) and (11)

(Table 40). Upgrading the sweet pepper amounts and investment and materials was performed proportionally to the greenhouse size- for example if 12 containers were needed for the 4.3 hectare greenhouse, then for a 10 hectare greenhouse, 28 containers are needed (the calculated roundup of: 12*(10/4.3)).

According to the economic analysis of the tested greenhouse it was found that when robots replace only one worker, there will be no improvement in the annual cost (negative investment space) and therefore adding robots to the process will not pay off. As a result, for a grower to be willing to pay for robots (the maximum price per robot will be greater than zero) the current state must include a minimum of three workers- two workers that will be replaced by robots so it will pay off and one worker that will complete the robots work since the robots are not with 100% success rate. For this reason, the smallest tested greenhouse size is 1.3 hectares which is equal to the smallest greenhouse size that three workers can complete the harvest in time.

The results of the economic analysis for 1.3, 4.3, 8.6, 10, 15 and 20 hectares greenhouse sizes are presented in Figure 52 (full results with accurate prices are in Appendix T). As the size of the greenhouse increases, the larger the potential for costs reduction as a result of inserting robots to the harvesting process and therefore, the maximum cost per robot can increase and more robots can be bought. The only exception is the cost of 70% detection rate robots for greenhouses between 8.6 and 10 hectares (Figure 52, the red line). This exception can be explained by examining the needed number of robots of 70% versus 90% robots. For the first three greenhouse sizes (1.3, 4.3 and 8.6), the needed number of robots is identical between 70% and 90% and therefore their cost behavior is similar (same trend) but with a lower price for the 70% robots due to higher number of missed peppers (lower detection rate).

For greenhouses sized higher than 10 hectares, the needed number of robot for the 70% robots increases compared to the 90% and therefore the cost behavior changes. Another explanation is that for 10 hectares greenhouse, exactly 9.2 robots are needed, however this was rounded to 10 and therefore the utilization of each robot decreases as compared to the 8.6 hectares greenhouse where 7.9 robots are needed and rounded to 8 with almost maximum utilization of the robots.

In practice this roundup can be overcome by adjusting the greenhouse size to the actual number of robots (i.e. using a X hectare greenhouse where X=10/0.92 to ensure high utilization of 10 robots instead of 9.2).

Table 40: Translation of number of resources needed for different greenhouses sizes (4.3 is the basis)

<table>
<tr><th colspan="2" rowspan="2"></th><th colspan="2">4.3</th><th rowspan="2">1.3</th><th rowspan="2">8.6</th><th rowspan="2">10</th><th rowspan="2">15</th><th rowspan="2">20</th></tr>
<tr><th>Number</th><th>Max utilization</th></tr>
<tr><td>Only workers (current state)</td><td>Workers</td><td>7</td><td>0.964</td><td>3</td><td>14</td><td>16</td><td>24</td><td>32</td></tr>
<tr><td rowspan="4">Human-robot combined work</td><td>Workers</td><td>3</td><td>0.997</td><td>1</td><td>6</td><td>7</td><td>11</td><td>14</td></tr>
<tr><td>R_{DET}=50% robots</td><td>5</td><td>0.869</td><td>2</td><td>10</td><td>11</td><td>16</td><td>22</td></tr>
<tr><td>R_{DET}=70% robots</td><td>4</td><td>0.935</td><td>2</td><td>8</td><td>10</td><td>14</td><td>19</td></tr>
<tr><td>R_{DET}=90% robots</td><td>4</td><td>0.87</td><td>2</td><td>8</td><td>9</td><td>13</td><td>17</td></tr>
</table>

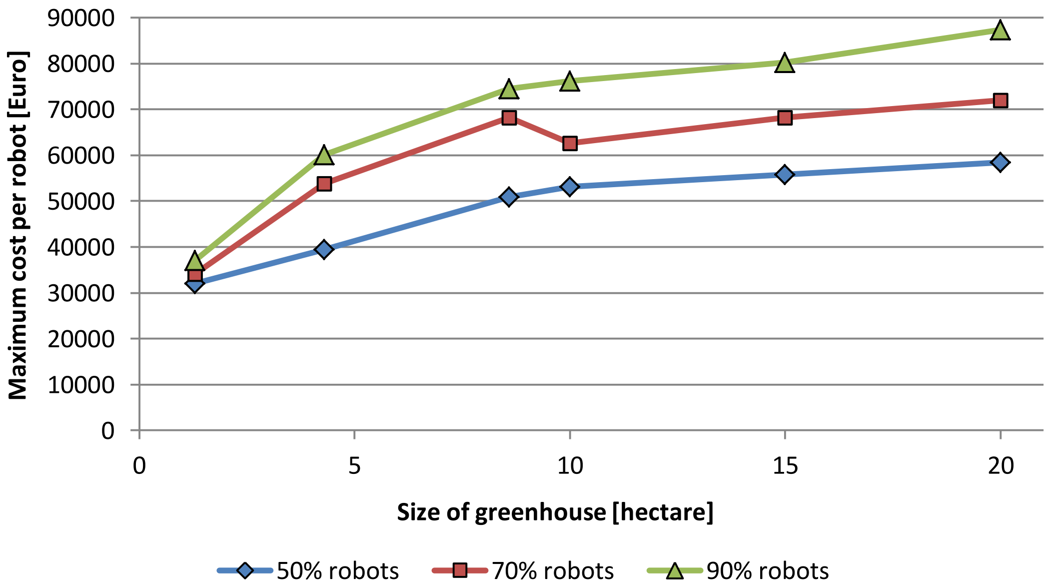


Figure 52: Maximum cost per robot for difference greenhouse sizes (1.3, 4.3, 8.6, 10, 15 and 20 hectares)

7.4.3 Summary

The following tables (Table 41, Table 42) summarize the economic analyses results for greenhouses sized 4.3 and 10 hectares. The number of robots to purchase and number of workers to hire is presented with the maximum cost per robot for different robot capabilities.

Table 41: Economic analysis summary for 4.3 hectare greenhouse

# Robots	Robot's capabilities			# Workers	Maximum cost per robot [€]
	R_{DET} [%]	R_{REPEAT} [%]	R_{ACC} [m/s^2]		
4	50	100	0.2	3-4	45,141
4	70	100	0.2	3	53,880
3	90	100	0.2	3-4	66,663
6	50	100	0.1	3	31,952
5	70	100	0.1	3	41,985
5	90	100	0.1	3	47,521
4	50	100	1.0	3	48,346
3	70	100	1.0	3	70,637
3	90	100	1.0	3	79,866
6	50	70	0.2	3	30,221
5	70	70	0.2	3	39,518
5	90	70	0.2	3	39,487

Table 42: Economic analysis summary for 10 hectare greenhouse

# Robots	Robot's capabilities			# Workers	Maximum cost per robot [€]
	R_{DET} [%]	R_{REPEAT} [%]	R_{ACC} [m/s^2]		
9	50	100	0.2	7	53,194
10	70	100	0.2	7	62,700
11	90	100	0.2	7	76,190

8. Discussion, conclusions and future work

This thesis yielded a model to evaluate the logistics of introducing robots into the harvesting process in parallel to human harvesting by modelling human-robot combined work and using an economic model to estimate related costs. The simulation model developed returns several options of human-robot combinations to complete the harvest in the greenhouse for specific greenhouse and robot features. Each combination derived by the simulation model is analyzed in an economic model for economic viability. In the following I discuss the results as related to the research questions and the main limitations of the research, followed by main conclusions and recommendations for future research.

8.1 Research questions

How many fixed workers are needed to harvest sweet peppers in a greenhouse when workers are the sole resource?

The basis for all the analysis in the thesis was the scenario including solely human workers. Results indicated that for a 4.3 hectare greenhouse, seven fixed workers are needed to complete the harvest of the entire season. This result was also translated to workers per hectare for greenhouses sized 8.6, 10, 15 and 20 hectares resulting with 1.46 (not rounded), 13, 15, 22 and 30 workers respectively.

How many robots are needed for a greenhouse with a known number of fixed workers?

Chapter 6 dealt with finding the number of robots for each number of workers (within a predefined range where the maximum is the number of fixed workers as a sole resource) and each robot capabilities- first for 4.3 hectare greenhouse and then translated to other sizes.

The simulation model built in this thesis is designed to provide answers exactly to this question for each desired greenhouse size, number of workers and robot capabilities.

The answer to this question for a 4.3 hectares greenhouse is provided in Table 24.

How many workers are needed to complete the harvest started by robots incapable of 100% harvest efficiency?

This question as well as the previous can be answered by using the simulation model. The difference between the questions is the starting point. The starting point and inputs for the simulation model of this question are the number of robots and the robots capabilities. Analyses in section 6.3.3 provided answers for robots with different capabilities in R_{DET} as presented in Table 25.

Answering this question more accurately will be relevant when more data on robot capabilities and costs will be available.

How do potential resources needed and financial savings depend on robot performance such as accuracy rate and harvest rate?

According to the results and as expected, the number of resources needed decreases as a result robot performance increases. Nevertheless, not in all cases the change is reflected in reduction of the number of resources since the number of resources is rounded upwards. In these cases, it's clear that the solutions reduce the utilization of the resources, but when rounding the number of resources needed the results do not improve. The actual change depends on the significance of the performance improvement and the resources utilization prior to the improvement. For example, in Table 24 it is shown that for three fixed workers- four robots with R_{DET}=70% are needed to complete the harvest. When improving R_{DET} to 90%, four workers are needed as well. The difference between the solutions is in the average robots utilization of 0.78 (R_{DET}=70%) compared to 0.71 (R_{DET}=90%) and in the maximum robot utilization of 0.94 (R_{DET}=70%) compared to 0.86 (R_{DET}=90%).

The financial savings always increased as robot performance increased. However, results indicated that some changes in robot performance cause increased savings more than other changes. For example, when the initial conditions are basic robot capabilities (R_{DET} = 70%, R_{REPEAT}=100% and R_{ACC}=0.2 m/s^2), improving the R_{ACC} from 0.2 m/s^2 to 1 m/s^2 increased the financial savings more than improving the R_{DET} rate from 70% to 100%.

All financial conclusions of robot performance improvement are detailed in Table 39 and Figure 50.

With given robot capabilities, what are the maximum costs of a harvesting robot a grower will be willing to pay without exceeding existing costs of the harvest operation by human labor alone?

The results of the economic chapter, chapter 7, address this question exactly. Twelve different combinations of robot capabilities were tested for a 4.3 hectare greenhouse using the economic model, and for each combination the maximum robot costs were calculated. For other greenhouses sizes, only three different combinations of robot capabilities were tested for sensitivity analysis and demonstration of translating the results (Table 41 and Table 42). The first part of the results is calculated with R_{REPEAT} = 100% which is rather optimistic at the moment. The results demonstrate that the maximum cost per robot fall steeply with this % drops to 70%, which is more realistic.

When robot capabilities and price are defined, what will be the selected logistic solution (i.e., what are the required number of workers and robots)?

The simulation model was built to provide answer to this question. First the simulation model should be run for the specific greenhouse size and robot capabilities with different options of number of workers. For each number of workers solution, the number of robots requires to complete the harvesting is derived.

Then, each solution can be entered to the economic model with the defined price, and the solution with the highest financial savings will be selected.

This question will be highly relevant once more data on robot capabilities will be available.

8.2 Research limitations

The lack of information on the robots performance required to incorporate several assumptions which may not necessarily reflect the current state of robotic development (Bac et al., 2014). Furthermore, there are several limitations in the assumptions:

1. The success rate of the robot which consists of detection rate and retry rate is calculated based on success probability. Possible cause of failure to harvest a pepper is the peppers position on the plant, occlusion or other complicating factors. As a result the success rate may decrease during a second pass through a path and again decrease during a third pass. This effect in success rate was neglected in this study as no data was available. In the model, in each harvest attempt the success rate remains with the same probability. The model could incorporate different success rates for each attempt.
2. The timing of the harvesting action was performed by calculating the shortest distance from a "zero position" to the pepper and back with an additional one second for the cutting time. No additional detection time was added, the detection is assumed to take place during the movements of the robot in the path. Without these assumptions, reaching to the pepper in a more complex route (due to obstacle avoidance if needed), the cutting time and detection time can increase significantly the total harvest time.
3. For a 50% detection rate, the average cycle time (including movement in the path, gripper movement towards the pepper and back and the harvest itself) for 0.1 m/s^2, 0.2 m/s^2 and 1 m/s^2 is 7.95 6.49,and 4.57 seconds per pepper respectively. According to Bac et al. (2014), current cycle time has a large range of 1 to 227 seconds with an average of 33 seconds among N=28 different research including different types of harvesting robots (and different crops).
4. It was assumed in the economic model formulation that there can be changes in the harvested pepper quality as a result of robotic harvesting versus human harvesting. In the

thesis, the robots were assumed to be better than human (7.5% of the peppers harvested by the robots are 2nd quality peppers compared to 9.5% of the peppers harvested by human workers).

5. The robot is modelled to harvest within the same time window of a harvest cycle as the human-workers with the only difference of working 20 hours straight. Two opposite limitations arise from that assumption:
    i. The robot can potentially work 7 days a week unlike the worker. In this simulation model this is not fulfilled (and therefore this capability is not utilized). Allowing a robot to work 7 days will lower the number of robots required. It would thus increase maximum investment cost or lower the performance requirements per robot.
    ii. Maintenance time has no reference within the 20 hours of work and it is possible that the actual daily harvest time is shorter. Taking the maintenance time into account can increase the number of required robots.

The current desired work plan for the human workers as described in the thesis is to complete the harvest in paths that was already partially harvested by a robot. One outcome to consider from this work plan is that the workers will harvest the paths with only small amounts of peppers. As a result and as demonstrated in Figure 18, the workers cycle time increases and therefore the workers are less effective in terms of time versus output (harvested peppers) and they are more expensive per pepper.

The economic model calculations were based on comparing robotic solutions to the existing state which includes only human workers. But, these worker-only solutions were also determined by simulation results and not based on real greenhouse costs and workforce. Real greenhouse costs can be higher due to much limited work capabilities because of unavailability on weekends and holidays and possibly less experienced workers that were not included in the simulation and can cause higher labor costs. As a result, the maximum cost to justify the robot can increase.

There are limitations in the translation of results from a 4.3 hectare greenhouse to other greenhouse sizes (without additional simulations). One limitation arises from the minimum number of workers tested. For a 4.3 hectare greenhouse, the minimum number of workers tested is three, as for this greenhouse size this is the minimum number of workers that can manage also other not automated actions. But when translating to other greenhouse sizes- for example to 10 hectare greenhouse, it creates a higher number of minimum workers (in that case: seven) and this number is not re-tested whether this is the actual minimum number of human workers for the additional operations needed. According to the results, for a greenhouse sized 10 hectares, the maximum cost found for robot with basic capabilities (R_{DET}=70%, R_{ACC}=0.2 m/s^2 and

R_{RETRY}=100%) is 62,700€. This cost changes to 53,200€ when R_{DET}=50% and to 76,200€ when R_{DET}=90%. Though it should be considered that if this minimum number of fixed workers can be lowered, then according to the findings of this thesis (the maximum cost was always found in the scenario with lowest number of workers) the maximum robot costs found has a potential to increase (which indicates higher potential savings).

The workforce has major impact on the maximum cost per robot and therefore should be estimated also with changes during the season as opposed to the current model which took into account only a fixed number of workers. For example, the maximum robot cost for purchasing three robots with the following capabilities: R_{DET}=50%, R_{RETRY}=100% and Acceleration=0.2 m/s^2 is 20,174€ when hiring five fixed workers. However, for the same robots' capabilities when hiring three fixed workers and adding an additional temporary worker or two workers depending on the yield and harvesting needs, the maximum cost per robot increases by 115% to 43,372€.

According to the results, the greenhouse yield has influence over the robot's price using the current cost calculating technique (i.e., comparing to simulated solutions of human workers only); high yield can increase the prices by maximum of 9% and low yield can decrease the price by maximum of 19%. The high and low yield amounts chosen for this analysis were based on a single extreme yield path, and reflected to the entire greenhouse causing the yield model to increase the greenhouse total yield by 25% and decrease by 43% from the average amounts. It should be considered that the extreme yield scenarios are not realistic as normally in a greenhouse, not all paths have extreme yield amounts but only a small portion of it.

8.3 Main conclusions

For a 4.3 hectare size greenhouse with basic robot capabilities (defined as R_{DET}=70%, R_{RETRY}=100% and Acceleration=0.2 m/s^2):

- Solutions of human-robot combined work includes between 3-6 workers and 1-4 robots.
- The maximum price for a robot according to these solutions is 53,880€.
- With increased robot capabilities (R_{DET}=90% and R_{ACC}=1 m/s^2) the price can rise to 79,866€.

For a 4.3 hectare size greenhouse with different robot capabilities tested (R_{DET}=50%, 70%, 90%; R_{REPEAT}=70%, 100%; R_{ACC}=0.1, 0.2, 1 m/s^2):

- The highest robot costs were received for each robot type with solutions containing the lowest number of workers.
- All scenarios where robot or robots are to replace only one worker from the greenhouse were found not economical.

- The most cost effective improvement when R_{RETRY}=100% is to shorten the harvest times (in the model this is expressed by increasing the acceleration parameter), rather than improving the detection rate- R_{DET} (average cost improvement of 12,898€ compare to 9,638€).

Different greenhouse sizes and yield levels:

- When translating the results to other greenhouse sizes, it was found that the smallest greenhouse in which a robot can be profitable is 1.3 hectares.
- The larger the greenhouse (with a certain limit as viewed in Figure 52) the more potential for costs reduction as a result of inserting robots to the harvesting process (the annual savings increase), and therefore the price per robot it is worth paying is higher.
- When the yield is relatively low (compare to the average), the robots will be less effective and therefore the maximum price can decrease in maximum 19% (when all paths has low yields causing decrease of 43% in total yield amounts).

8.4 Future work recommendations

Recommendations for future work relate to several issues including data analyses, simulation model and economic analysis.

Data analysis

- The HC duration was referred from the NL database by using an average number of days among all paths and all season. Two recommendations are suggested:
  - Using different number of days in a HC for each path.
  - Changing the number of days in a HC during the season, according to the growth of the peppers. At the beginning and end of a season the number of days will be higher than in the season's peak where the growth rate is higher.
- The sweet pepper yield growth is affected from many natural factors as mentioned in section 4.3. Since it was not in the scope of this research to evaluate these affects the focus was on the actual number of peppers as a function of time. Future work can further advance and incorporate specific growth parameters (such as temperature or humidity) and furthermore optimize the parameters for optimal logistics.
- The yield model used in the thesis was based on average yield of all paths. In order to be more accurate it is possible to incorporate separate yield model parameters for each path in the greenhouse.

- Further examination of high and low yields effects, should be tested using yield differences between companies. This will provide more realistic differences than the tested between the "best" and "worst" performing path in one greenhouse.

Simulation model

- The resources states during the current simulation are set for all the workers and all the robots together. At the moment there is one daily "break" which is the time out of a 24h day the resource is not working (i.e. 9h work and 15h "break"). Expanding the model can include more realistic breaks for workers or daily maintenance time for the robots during their workday (rather than only after their work day). The breaks can even be designed for each worker/robot alone and not necessarily all resources from the same type must take the break at the same time as in the current model.
- A worker in the model is defined as an average worker. A future direction can be adding performance differences between workers to test the effect of specialized workers versus low skilled workers. When neglecting these differences it may cause wrong cost-effectiveness results (van't Ooster et al., 2015). The analysis of different workers capabilities can be performed based on the research of Ooster (2015).
  In addition, the human workers success rate was always 100% but once individual workers will be modeled it is possible to also incorporate differences their success rates.
- At the moment, the simulation is built to simulate very organized work throughout the season of HCs in a sequence one after the other. The season is simulated each time with three harvesting days (for both resources types) and then two additional days for rest and/or other crop operations. In reality, workers are not available on weekends and holidays and therefore sometimes the time to harvest can be extended or shorten. On the other hand, robots do not have such a problem and can harvest constantly and continuously (except for maintenance times). Therefore, a suggested option to maximize the use of the robots is to simulate seven days with robots harvesting constantly, and the workers harvest just un-completed paths, and only part of the week.
- The division of tasks in the simulation model is performed by FIFO queues to both resources that create assignment of harvesting jobs by the ID number of a path to any resource available. A future research can include optimization of job scheduling and resource allocation to determine the shortest operation times and best performance from resources available for maximized labor efficiency and minimized cost.
- Human workers and robots according to current simulation definitions start the harvest day at the same time. According to the work allocation decision made in this thesis, there is

priority for un-harvested paths to the robots and priority of partly-harvested paths to the human workers. When both resources start the day at the same time, for increased utilization of workers, they harvest also un-harvested paths. This can be changed by starting the robots harvest sooner in the day or even the day before, so the workers are more likely to have only partly-harvested paths to harvest. This change has the potential of reducing the number of resources needed and should be examined.

- As aforementioned, the current desired work plan causes the workers to have larger cycle times and therefore they are less effective and more expensive per pepper. This current work plan that was one of the base assumptions should be examined- what is cheaper for completing the harvest in a path: using the robots which will cost in robot retries and losing some peppers or using the workers which increases price per pepper due to low effectiveness?
- The robot's R_{DET} (the probability to detect a pepper) is defined as identical at every entrance to a path. In reality it is more likely that the peppers that were not detected throughout the first visit in a path will be identified with lower probability in the next visit and so on. Therefore, it is recommended to consider changing R_{DET} at each visit.
- The robot's R_{RETRY} (the probability to succeed a harvest once it is detected) was used as a constant along the robots retries each attempt to harvest the same pepper with the same rate. In addition the maximum number of reties N_{RETRY} was tested with only two retries. In future research the R_{RETRY} can change to different percentage in each retry and the number of retries can be tested with more than two retries.

Economic analysis

- Many cost parameters in the economic model are taken from the economic analysis of CROPS. It is possible to further examine the parameters and adjust it to specific greenhouses, or further examine which cost might not be relevant for robotic solutions or the opposite, be more relevant. For example, equipment in the investment costs was adjusted for different greenhouse sizes, but was not verified against real greenhouses of the same sizes.
- When robot estimated prices for given capabilities will be available, the economic model can be used differently, as a tool to find the optimal solution for a greenhouse with given prices. When combining the economic analysis with the simulation model, further optimization can be performed to derive the optimal robots parameters with the number of resources to complete the harvest.

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9. Appendices

Appendix A: GWorkS model inputs description

In order to run the model properly for a specific greenhouse and crop, some input data must be received. The evaluated model input is defined as parameter vector P which consists of sub-vectors (Figure 8): *Pg*- physical greenhouse layout, *Pc*- crop system layout and crop status i.e. the demand for crop harvesting, *Po*- operator and facility-related parameters and *Pm*- greenhouse management parameters. On a daily basis, it is assumed that P is time-invariant (van't Ooster et al., 2013). The input data is entered into the model by m-files which translate and prepare the simulation as GWorkS is not yet equipped with a GUI:

1. **Simulation decisions-** entered into the script m-file 'GWorkS_main.m' and include the inputs that are related to the simulation itself, according to the user needs. It includes the simulation control decisions, like desired dates and repetitions, nodes (paths in the greenhouse), to read input from excel or mat-files, decisions about the graphs, animation etc. In addition, it includes output-decisions about what output should be saved or exported to excel and what output should be shown in plots.
2. **The greenhouse layout-** entered into the class m-file 'GreenhouseLayout.m' defines the greenhouse layout properties and methods in the object LO. As input, the class m-file includes the dimensions of the greenhouse, information about the paths within the greenhouse and which crop system is simulated. Example of such input is given in Table 43.
3. **Crop production system-** entered into the class m-file 'CropSystem_NoSA.m' defines the crop properties and methods in the object. It uses the physical layout of the crop production system according to the previous data (greenhouse layout) and harvested product in $kg.m^{-2}$ and harvest frequencies in 13 4-week periods, that is visit frequencies of paths (day^{-1}) for harvesting. The model distributes the peppers yield over the paths, assuming a lognormal distribution between the number of ripe peppers in paths with expectancy of μ and a standard deviation of μ / 4.
4. **Crop handling processes-** entered into the m-file 'WorkLoad_NoSA.m' defines and plans the harvesting process in the greenhouse on a daily basis. The planning assigns nodes or subnodes to workers based on targeted time span for a crop operation and expected worker performance. The inputs for this category for harvest are the workdays of the week, expected harvest capacity and targeted process duration, the skill of the workers.
5. **Resources-** entered into the class m-file 'Resources.m'. The model receives the amount of resources available for the tasks: amount of workers, trolleys and other equipment being used. Additional data such as the resource capacity, performance is also included. Using this

information, all resources exist will be created in the model and later on be used to perform an actual task.

After the input data is made available, the necessary objects with properties and methods are generated. The model reads all data from excel and saves it in Matlab format. Based on date and time the model will select appropriate input data. The method GWorkS.runSimulation opens and runs the Simulink model on daily basis.

Table 43: Greenhouse layout input description for simulation of both greenhouses

Field name	Description	Greenhouse data	
		Dutch	Israeli
GrhLength	The greenhouses outlines (m)	234	105
GrhWidth		182.4	96
GrhHeaves	Eaves height of the greenhouse, that is the height of sidewall, bottom to rain drains (m)	6.5	4
MainAisleWidth	Main Aisle feature (m)	4.5	4
EndAisleWidth	Width of path near side wall perpendicular to crop paths	0	2.5
nSpans	Number of ridge lines of greenhouse (roof tops)	38	24
nBays	Number of intra-distances between portals made of a trellis girder and poles	52	21
Crop	Indication of the crop grown	'Pepper'	'Pepper'
CropSystem	Parameters indicating the crop cultivation system and the associated main layout of the greenhouse interior	'StaticPepperNL'	'StaticPepperIL'
nSides	sides of main aisle with crop	2	2
nSpansTrellisGirder	Number of spans supported by one portal or trellis girder	2	12
CropRowDistance	distance between centerlines of crop rows (m)	1.205	1.140

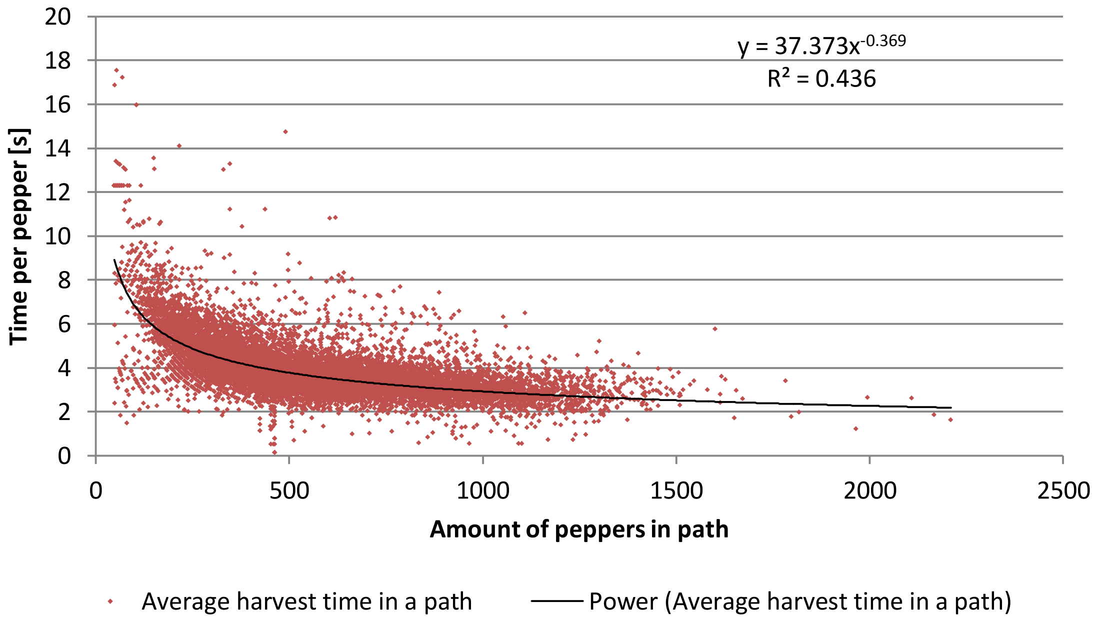
Appendix B: GWorkS model outputs description

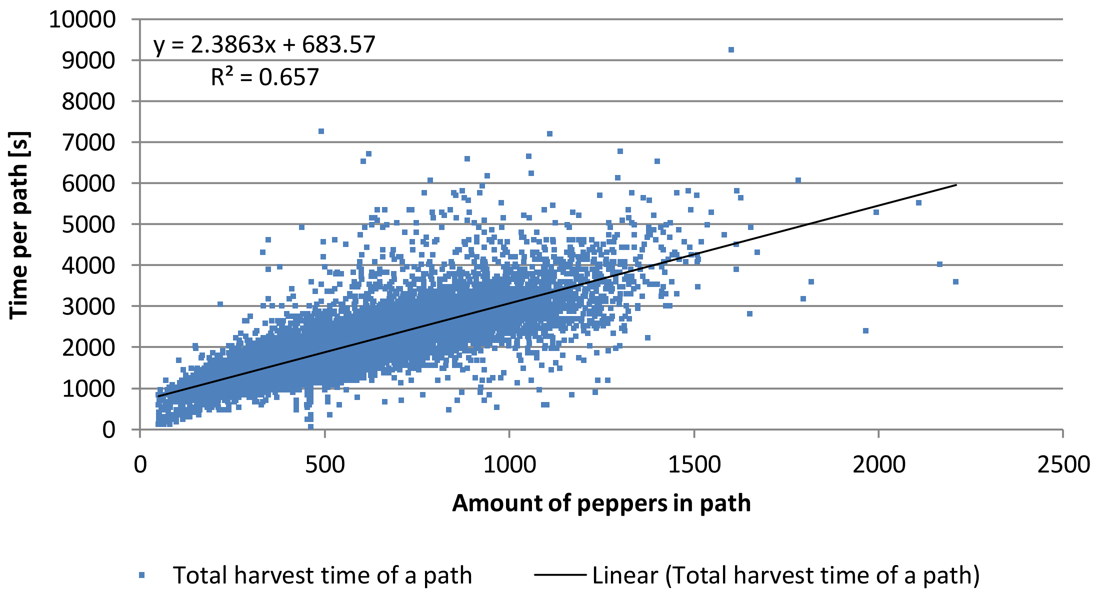
The model generates output as a graph using "scopes" of simEvents, and in the workspace of Matlab from which the result can be taken into Matlab code or out to excel for further analysis. From logged signals it is also possible to get output of work time, move time, wait time and walk distance in graphs.

The output includes- detailed process output within day and output cumulative performance indicators which is created in Matlab’s workspace as a structure y (Figure 8). The structure y consists of the elements:

1. **rServiceStation-** the main structure that includes all the information results; the plan versus what actually turned out, labor times, move times, walking distances, locations, yield etc. The information is brought from different point of views- the workers, the sweet pepper containers and paths.
2. **KeyIndicators-** the main important key performance indicators which are measures for analysis of the results taken from the previous structure. It includes mainly:
    - **“LabourTimeDay”:** the total labor time of the specific day simulated
    - **“HarvestRate”:** the average harvest rate in units of product per hour
    - **“WorkTimeDay”:** a detailed description of work time in nodes (paths) and subnodes (sides of the path) and the work time of each worker individually
    - **“CT_Node”:** the average cycle time per node
    - **“us”:** utilization of workers
3. **DayResult-** a matrix of summarized data including the date, run number, total harvested peppers, cycle time, move time and more detailed information for each node of interest. Each date’s information is written in one line and it is possible to export it as a row-record to an excel file.
4. **RoseNetDataMatrix-** information about the containers emptied at the end of each path, a more appropriate name would be ProductDataMatrix. The information includes details of each worker’s begin time and end time, duration- and how many peppers were harvested in that time.

Appendix C: Average harvest times (per path and per pepper) of 2012 season in the NL greenhouse





Appendix D: Welch test for testing hypothesis that two groups of different paths have equal harvest time means

Data for performing the tests:

Average time per path						
"Group calibration"			"Other group"			
1830.732	2305.5	2013.846	2131.5	2051.053	2023.5	1946.154
1555.5	2070.811	2079.512	2104.5	1840.976	2104.865	2041.622
1688.571	2083.902	2050.5	2130.732	2161.579	2105.714	1946.341
1685.854	1937.561	2102.927	2254.5	2020.5	2121.951	1751.111
2020.976	2170.5	2083.077	2007.805	2023.784	2047.692	1913.846
1878	2043.158	2102.791	1960.5	1908.947	2066.154	1818.947
2047.143	2047.5	2176.098	2020	2033.846	2034.286	1984.39
2019.512	1950	2191.5	2060.488	1959	2043	1938.947
1928.372	2008.5	2075.676	1933.5	2070.769	2138.462	2015.122
2010	2180.488	1902.632	2181.951	1951.5	1956.316	2007.692
1901.86	1924.5		2080.976	1999.459	2131.579	1981.538
2070	1958.571		2022.857	2008.5	2160	1998.462
1974.419	1975.5		1899	2154	2129.231	2116.098
2111.429	2158.5		2015.122	2149.756	2029.5	1978.421
2228.571	2028		2075.385	2067.692	2079	2063.333
2221.538	1960.976		1920	1916.923	2103.077	2002.105
2345.714	2224.39		2098.5	2038.462	2083.902	1999.5
2018.049	2115.349		2019	2146.5	1995	2050.769
1932.558	1976.757		2064	2093.846	2020.5	2053.5
1917.143	1978.605		2061	2049	2020	1961.053
1937.143	2120.488		1893.158	2078.462	2234.634	2093.684
2148	1998.571		1997.561	2008.5	1991.707	2027.692
2258.049	2115		1935	2021.053	1980	2021.053
1938	2317.143		2135.714	2276.923	2040	2112.632
2089.756	2303.415		1927.5	2125.263	2155.385	2250.811
2086.829	2155.385		2124.878	2262.632	1951.5	2088.649
2000.488	2155.5		2023.5	2163.243	2082.439	2191.579
2217.073	2121.429		2158.537	2349.474	2146.5	2190
1915.61	2094.146		2216.923	2135.294	1966.829	2172.353
2025.366	2160		1926.977	2148.333	1916.667	2173.333
1975.714	2195.385		1912.857	1992.973	1985.714	2161.667
1999.024	2238.571		2323.902	2226.486	1800	2070
2150.233	2001.951		2074.5	2230.909	1965.789	2261.053
2020.465	2237.561		2049	2035	2026.5	2148.333
2012.093	2361.081		2026.154	2070.909	2031.22	2215.135
2072.093	1924.186		2179.024	2138.462	1886.842	2106.486
1994.286	1953.333		1989.73	1950	1969.756	2226.486
1951.429	1844.286		2013.659	2143.784	1990.769	2111.351
2098.537	2060		2017.895	2077.059	1987.5	2185.946
2029.756	2131.429		2042.857	1839.474	2110.769	2231.667
2013	2029.5		2085	2575.263	2054.634	1992.632
2016	2149.231		2021.429	2015.122	2036.757	2614.737
2050.769	2174.286		2139.512	2174.118	2019.512	
1936.098	2032.857		2205.366	2170	1981.667	
2029.231	2129.231		1929.231	2003.415	2253.846	
2042.927	2126.154		2204.211	2070.732	1924.39	
2126.154	2131.5		1984.5	2148	1972.308	
2148	2092.683		1972.5	2015.385	1991.707	
2379.474	2112		1984.615	1984.286	2040	
2183.077	2091		1952.308	1992	2031	

Average time per pepper						
"Group calibration"			"Other group"			
4.357	3.460	3.762	3.638	3.703	3.600	3.403
3.909	3.609	3.583	3.666	3.464	3.563	3.489
3.870	3.641	3.613	3.831	3.442	3.546	3.430
3.796	3.624	3.575	3.723	3.506	3.726	3.699
3.825	3.553	3.598	3.544	3.474	3.675	3.387
3.574	3.654	3.558	3.523	3.473	3.643	3.333
3.721	3.555	3.756	3.586	3.632	3.451	3.434
3.836	3.527	3.770	3.530	3.563	3.511	3.449
3.820	3.504	3.840	3.338	3.613	3.539	3.785
3.623	4.293	3.305	3.670	3.598	3.428	3.421
3.505	4.037		3.598	3.625	3.726	3.473
3.866	3.759		3.592	3.638	3.757	3.749
3.626	3.733		3.521	3.906	3.606	3.618
3.826	3.853		3.543	3.637	3.530	3.717
4.031	3.729		3.721	3.647	3.566	3.480
3.831	3.717		3.565	3.561	3.677	3.565
4.234	3.984		3.706	3.532	3.705	3.379
3.822	3.899		3.656	3.853	3.570	3.655
3.834	3.585		3.781	3.837	3.638	3.744
3.660	3.620		3.665	3.547	3.850	3.859
3.564	3.837		3.384	3.833	3.887	3.607
3.650	3.748		3.505	3.653	3.626	3.696
3.880	3.807		3.608	3.628	3.606	3.446
3.392	4.170		3.820	3.783	3.779	3.629
3.792	4.123		3.496	3.658	3.708	3.810
3.876	4.006		3.686	3.928	3.498	3.509
3.621	3.845		3.568	3.590	3.576	3.863
3.793	3.908		3.716	3.564	3.729	3.713
3.526	3.798		3.763	3.675	3.546	3.631
3.768	3.825		3.565	3.499	3.521	3.541
3.710	3.741		3.417	3.622	3.588	3.536
3.603	3.988		3.555	3.677	3.525	3.536
3.873	3.616		3.679	3.717	3.624	3.588
3.812	3.682		3.600	3.541	3.861	3.549
3.735	3.933		3.595	3.688	3.608	3.453
3.816	3.676		3.609	3.835	3.621	3.741
3.669	3.616		3.585	3.699	3.617	3.581
3.591	3.485		3.565	4.103	3.512	3.713
3.984	3.873		3.886	3.667	3.649	3.795
3.702	3.656		3.586	3.663	4.017	3.793
3.702	3.563		3.670	3.973	3.748	3.645
3.645	3.664		3.604	3.383	3.616	3.694
3.764	4.146		3.829	3.526	3.551	
3.495	3.736		4.018	3.569	3.649	
3.559	3.785		3.626	3.519	3.899	
3.555	3.662		3.697	3.507	3.628	
3.657	3.738		3.754	3.685	3.647	
3.775	3.777		3.579	3.408	3.642	
3.831	3.802		3.647	3.548	3.755	
3.640	3.645		3.459	3.290	3.652	

Results of tests:

<u>Average time per path:</u>

mean	2060.6	2060.9
std	132.7	114.8
n	110	192

Welch test:

Alpah=0.05

f	201.37
t(0.975,201)	1.97
d	**29.82**

Interval: (-30.13 29.51)

<u>Average time per pepper:</u>

mean	3.746	3.627
std	0.181	0.137
n	110	192

Welch test:

Alpah=0.05

f	180.904
t(0.975,181)	1.973
d	**0.039**

Interval: (0.080 0.158)

According to the equations:

$$f = \frac{\left(\frac{{S_1}^2}{n_1}+\frac{{S_2}^2}{n_2}\right)^2}{\frac{\left(\frac{{S_1}^2}{n_1}\right)^2}{n_1-1}+\frac{\left(\frac{{S_2}^2}{n_2}\right)^2}{n_2-1}}$$

Where S_1, S_2 and n_1, n_2 are the standard deviation and the sizes of samples from groups 1 and 2 respectively

$$d = t_{1-\frac{\alpha}{2},f} \cdot \sqrt{\frac{{S_1}^2}{n_1}+\frac{{S_2}^2}{n_2}}$$

And the interval is calculated by:

$$((\overline{X_1}-\overline{X_2})-d\,,(\overline{X_1}-\overline{X_2})+d\,)$$

Appendix E: Detailed results of NL greenhouse growth model from Matlab

1. Matlab's Nonlinear regression model result:

   y ~ Growth(b,X)

   Growth: yhat = (b1)./(1+exp(-b2*(x-b3)))

   Estimated Coefficients:

	Estimate	SE	tStat	pValue
b1	33.709	0.091622	367.91	0
b2	0.020819	8.94E-05	232.97	0
b3	236.06	0.35158	671.41	0

   Number of observations: 12,105, Error degrees of freedom: 12,102

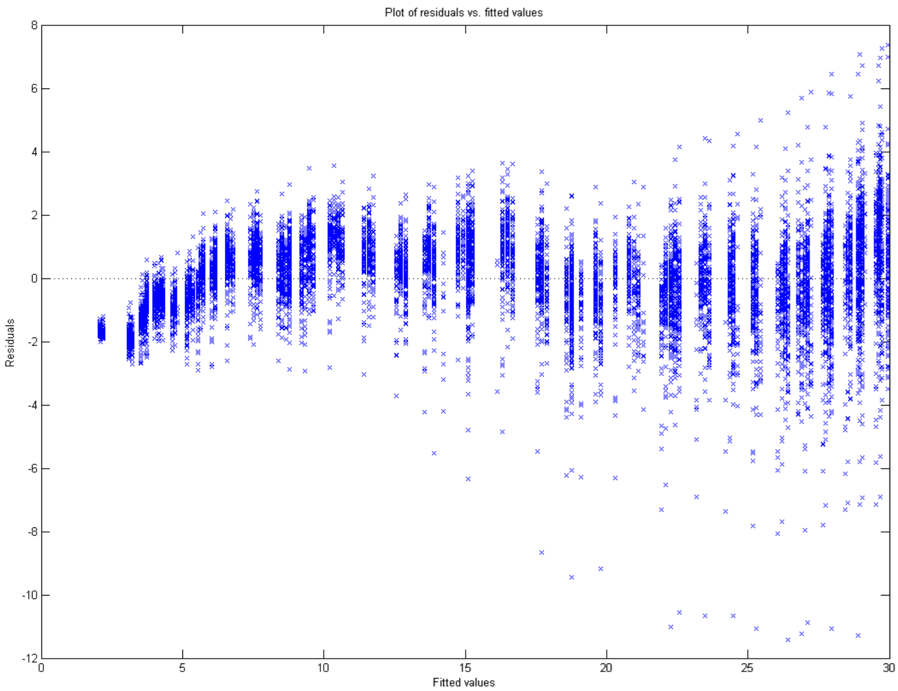
   Root Mean Squared Error: 1.41

   R-Squared: 0.978, Adjusted R-Squared 0.978

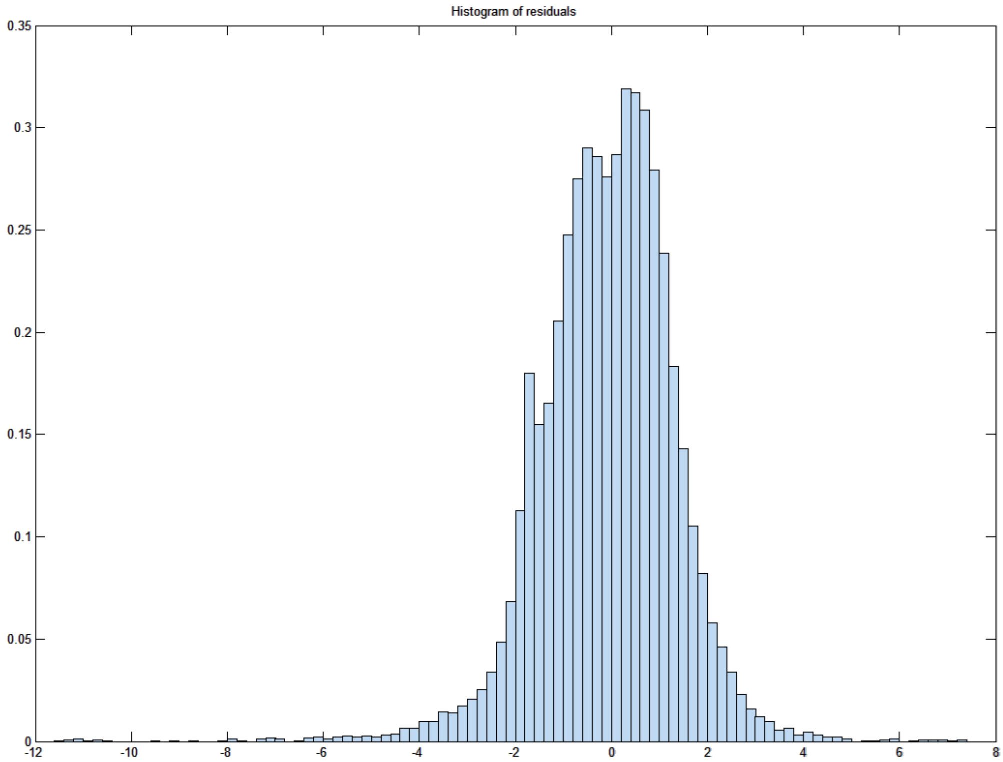
   F-statistic vs. zero model: 7e+05, p-value = 0

2. Graphs of fitted model:

   Plot of residuals vs. fitted values:



Histogram of residuals:

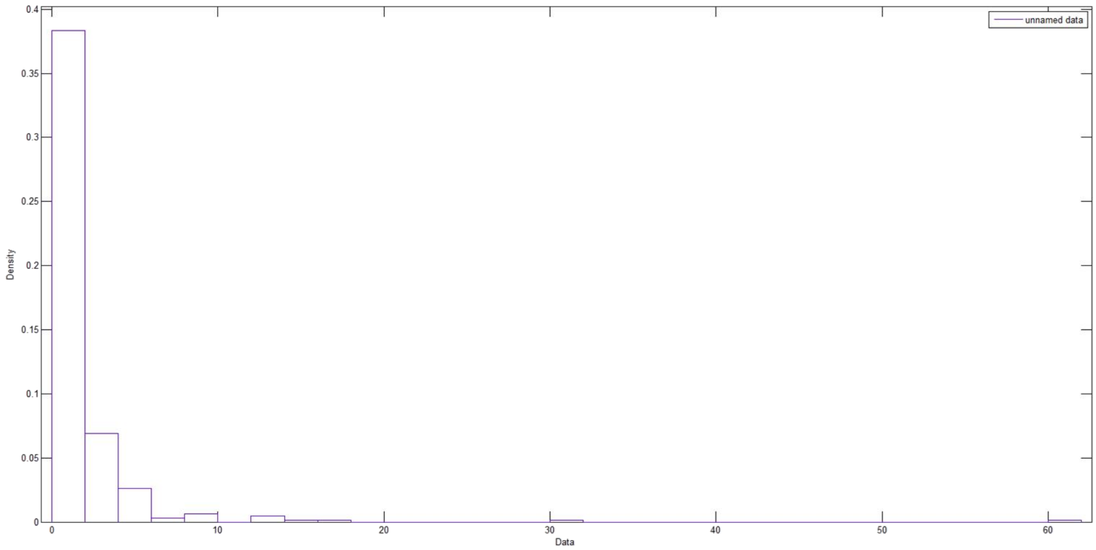


Appendix F: Yield model goodness of fit (MSE) to each path individually (304 paths)

Path	MSE	Path	MSE	Path	MSE	Path	MSE	Path	MSE	Path	MSE
1	17.180	53	9.204	105	1.290	157	0.657	209	1.846	261	0.714
2	31.022	54	0.705	106	0.969	158	0.903	210	1.139	262	0.492
3	13.060	55	1.272	107	1.606	159	1.181	211	1.324	263	0.513
4	13.204	56	0.981	108	2.509	160	1.005	212	2.439	264	1.145
5	0.890	57	2.521	109	0.619	161	1.320	213	1.157	265	1.014
6	3.062	58	0.983	110	2.092	162	3.522	214	0.550	266	60.135
7	0.972	59	1.318	111	0.506	163	1.518	215	5.428	267	0.657
8	1.037	60	2.223	112	2.057	164	0.915	216	0.881	268	0.687
9	0.873	61	0.985	113	0.840	165	0.647	217	0.683	269	1.944
10	0.687	62	1.272	114	2.306	166	0.574	218	0.928	270	1.173
11	1.425	63	0.924	115	1.020	167	1.079	219	3.048	271	0.629
12	0.598	64	0.789	116	2.393	168	0.802	220	0.841	272	1.734
13	0.939	65	3.391	117	1.694	169	1.072	221	1.890	273	1.273
14	0.917	66	1.346	118	0.626	170	0.731	222	0.544	274	1.139
15	1.325	67	0.947	119	1.146	171	1.052	223	0.770	275	2.255
16	1.040	68	0.877	120	0.788	172	0.789	224	0.748	276	4.276
17	1.659	69	3.460	121	0.769	173	0.621	225	1.109	277	1.310
18	1.416	70	1.002	122	5.889	174	0.834	226	0.848	278	0.678
19	1.113	71	4.159	123	0.701	175	0.957	227	1.447	279	1.999
20	0.905	72	1.260	124	0.951	176	0.729	228	0.631	280	0.864
21	1.089	73	2.488	125	2.123	177	2.739	229	1.436	281	0.583
22	1.167	74	0.860	126	0.765	178	0.973	230	0.611	282	4.456
23	1.796	75	0.942	127	2.567	179	0.632	231	1.032	283	0.688
24	1.248	76	0.840	128	0.681	180	3.222	232	1.791	284	1.529
25	0.847	77	0.606	129	1.196	181	0.733	233	2.616	285	0.777
26	0.539	78	0.731	130	1.908	182	0.817	234	1.374	286	0.643
27	0.800	79	0.959	131	0.796	183	3.442	235	1.355	287	0.531
28	1.371	80	1.124	132	1.891	184	0.788	236	1.129	288	0.596
29	1.008	81	1.161	133	0.845	185	0.833	237	0.564	289	0.962
30	0.915	82	1.933	134	1.359	186	0.667	238	0.631	290	1.166
31	1.027	83	1.568	135	1.308	187	0.743	239	1.707	291	2.241
32	0.709	84	0.705	136	0.565	188	0.441	240	1.107	292	1.222
33	2.951	85	1.997	137	0.826	189	1.048	241	1.455	293	0.454
34	0.767	86	0.632	138	0.630	190	0.763	242	5.333	294	0.964
35	1.147	87	1.872	139	6.115	191	1.901	243	0.961	295	2.163
36	1.062	88	0.668	140	4.605	192	0.702	244	2.276	296	1.155
37	0.850	89	2.295	141	0.691	193	1.307	245	1.483	297	2.353
38	0.783	90	1.189	142	3.933	194	3.484	246	2.478	298	2.185
39	0.884	91	1.352	143	0.817	195	1.432	247	1.820	299	1.011
40	0.603	92	1.063	144	3.145	196	1.096	248	4.801	300	2.029
41	0.638	93	13.004	145	1.675	197	2.558	249	0.896	301	1.022
42	0.936	94	0.482	146	4.528	198	0.631	250	0.663	302	1.358
43	0.799	95	1.093	147	1.360	199	5.892	251	0.887	303	2.384
44	0.975	96	0.504	148	4.546	200	1.481	252	1.856	304	14.130
45	0.555	97	4.977	149	4.244	201	2.913	253	0.609		
46	0.737	98	1.381	150	3.209	202	5.471	254	1.264		
47	1.794	99	1.592	151	8.975	203	4.857	255	1.388		
48	1.122	100	8.207	152	4.036	204	0.639	256	7.683		
49	0.648	101	3.271	153	1.554	205	0.569	257	0.840		
50	2.896	102	0.642	154	9.465	206	1.628	258	0.620		
51	0.897	103	1.285	155	1.567	207	1.451	259	2.881		
52	1.729	104	1.268	156	3.152	208	2.338	260	0.699		

Average MSE: 2.111, Std. MSE: 4.309

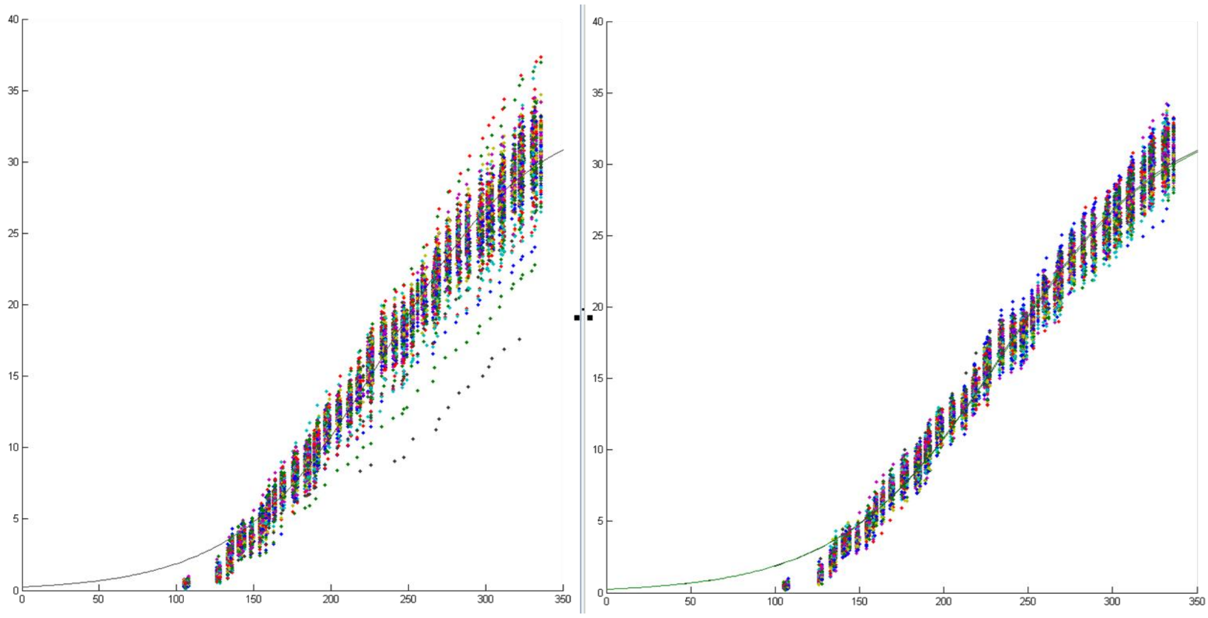
MSE Density (PDF)



Most paths have MSE between 0-2, and 2-4 (90% of paths). Therefore the rest of the paths with MSE greater than 4 were removed.

Appendix G: Growth model NL after removing exceptions

1. The fitted model (continuous line) vs. the greenhouses data (dots):
   Left graph is before exceptions removal (all 304 paths), right graph is after removal of 29 path (275 paths remained).



2. Matlab's Nonlinear regression model result:
   y ~ Growth(b,X)
   Growth: yhat = (b1)./(1+exp(-b2*(x-b3)))
   Estimated Coefficients:

	Estimate	SE	tStat	pValue
b1	33.825	0.075311	449.13	0
b2	0.020852	7.37E-05	283.06	0
b3	235.76	0.288	818.6	0

Number of observations: 10987, Error degrees of freedom: 10984

Root Mean Squared Error: 1.11

R-Squared: 0.986, Adjusted R-Squared 0.986

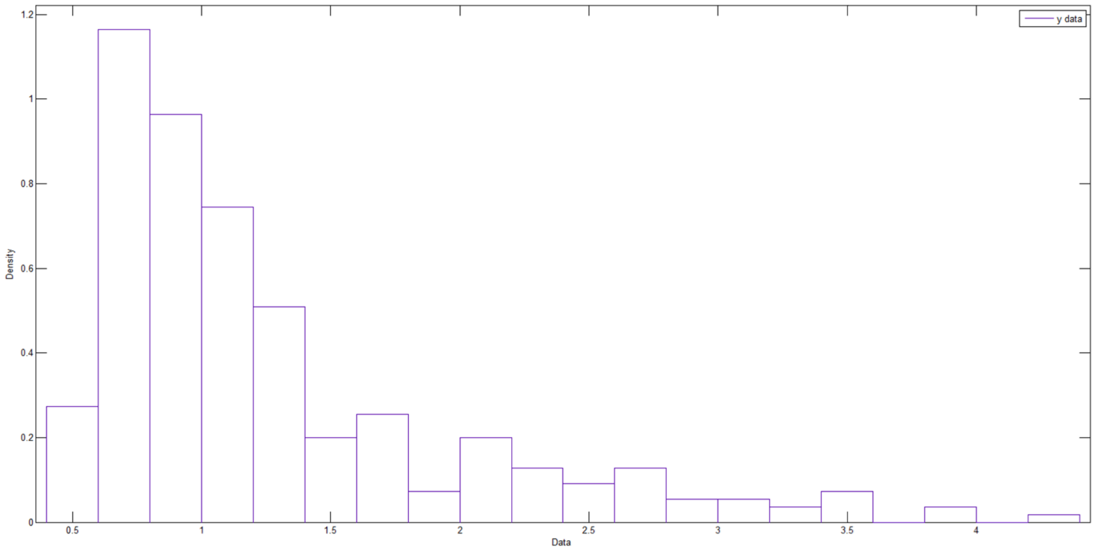
F-statistic vs. zero model: 1.03e+06, p-value = 0

Appendix H: Growth model goodness of fit (MSE) to each path individually (275 paths)

Path	MSE	Path	MSE	Path	MSE	Path	MSE	Path	MSE	Path	MSE
5	1.004	58	1.102	114	2.068	175	0.859	231	0.919	289	1.072
6	3.399	59	1.179	115	0.914	176	0.764	232	2.038	290	1.334
7	0.886	60	2.489	116	2.667	177	2.510	233	2.354	291	2.444
8	1.199	61	0.991	117	1.910	178	0.910	234	1.273	292	1.241
9	0.941	62	1.180	118	0.704	179	0.626	235	1.205	293	0.473
10	0.669	63	0.872	119	1.055	180	3.540	236	1.283	294	1.094
11	1.293	64	0.761	120	0.851	181	0.763	237	0.543	295	1.947
12	0.623	65	3.078	121	0.860	182	0.928	238	0.626	296	1.307
13	0.874	66	1.196	123	0.764	183	3.119	239	1.511	297	2.112
14	0.866	67	0.950	124	1.061	184	0.800	240	0.973	298	2.441
15	1.196	68	0.988	125	1.967	185	0.771	241	1.271	299	0.910
16	0.938	69	3.143	126	0.700	186	0.746	243	0.851	300	2.283
17	1.494	70	0.942	127	2.870	187	0.700	244	2.525	301	1.168
18	1.615	72	1.116	128	0.658	188	0.488	245	1.661	302	1.552
19	1.248	73	2.235	129	1.107	189	0.981	246	2.786	303	2.658
20	1.021	74	0.946	130	2.140	190	0.685	247	1.626		
21	0.978	75	0.910	131	0.737	191	1.708	249	0.806		
22	1.124	76	0.927	132	2.135	192	0.765	250	0.706		
23	1.590	77	0.619	133	0.853	193	1.136	251	1.017		
24	1.100	78	0.718	134	1.553	194	3.866	252	2.096		
25	0.790	79	0.858	135	1.175	195	1.274	253	0.616		
26	0.578	80	1.278	136	0.620	196	0.968	254	1.392		
27	0.695	81	1.027	137	0.815	197	2.288	255	1.210		
28	1.273	82	2.141	138	0.629	198	0.619	257	0.730		
29	0.919	83	1.391	141	0.713	200	1.298	258	0.694		
30	0.984	84	0.795	142	4.321	201	2.641	259	3.219		
31	1.148	85	1.771	143	0.835	204	0.722	260	0.767		
32	0.685	86	0.633	144	3.493	205	0.668	261	0.767		
33	2.651	87	1.659	145	1.880	206	1.449	262	0.535		
34	0.752	88	0.680	147	1.534	207	1.265	263	0.477		
35	1.023	89	2.044	150	3.545	208	2.081	264	1.286		
36	1.026	90	1.065	153	1.752	209	1.650	265	0.888		
37	0.746	91	1.200	155	1.742	210	1.003	267	0.745		
38	0.755	92	0.982	156	3.484	211	1.170	268	0.663		
39	0.848	94	0.497	157	0.664	212	2.166	269	1.733		
40	0.669	95	0.950	158	1.035	213	1.034	270	1.351		
41	0.594	96	0.540	159	1.353	214	0.507	271	0.690		
42	1.015	98	1.579	160	0.943	216	0.838	272	1.543		
43	0.822	99	1.396	161	1.173	217	0.707	273	1.113		
44	1.129	101	2.958	162	3.904	218	0.829	274	1.312		
45	0.566	102	0.667	163	1.356	219	2.757	275	2.026		
46	0.825	103	1.143	164	0.987	220	0.808	277	1.229		
47	1.590	104	1.129	165	0.644	221	1.681	278	0.781		
48	1.001	105	1.143	166	0.621	222	0.599	279	1.784		
49	0.618	106	1.130	167	0.956	223	0.747	280	1.006		
50	2.609	107	1.411	168	0.853	224	0.715	281	0.638		
51	0.865	108	2.814	169	1.227	225	0.971	283	0.722		
52	1.605	109	0.638	170	0.710	226	0.764	284	1.751		
54	0.808	110	2.337	171	0.928	227	1.270	285	0.719		
55	1.155	111	0.538	172	0.711	228	0.601	286	0.703		
56	1.093	112	2.286	173	0.642	229	1.267	287	0.542		
57	2.281	113	0.935	174	0.808	230	0.677	288	0.567		

Average MSE: 1.275, Std. MSE: 0.737228

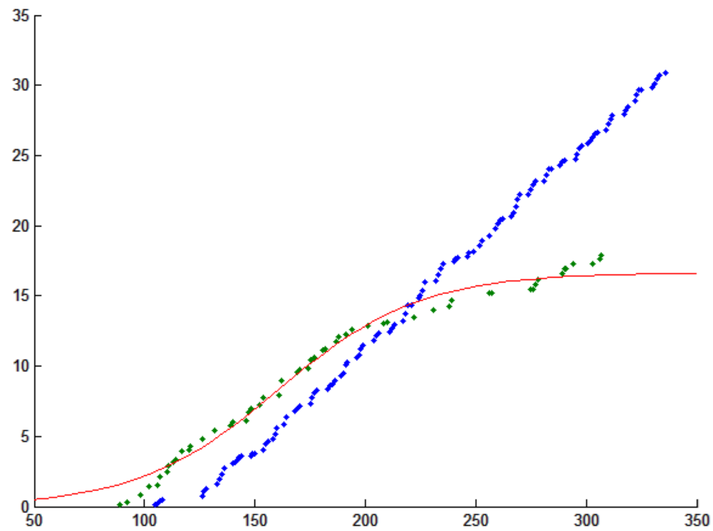
MSE Density (PDF)



All paths MSE is within the range of 4.5.

Appendix I: Detailed results of IL greenhouse growth model from Matlab

1. The fitted model (red continuous line) vs. the net house data (green dots):



*** Blue dots are the kg per m^2 of the NL greenhouse for reference

2. Matlab's Nonlinear regression model result:

   y ~ Growth(b,X)

   Growth: yhat = (b1)./(1+exp(-b2*(x-b3)))

   Estimated Coefficients:

	Estimate	SE	tStat	pValue
b1	16.632	0.21657	76.8	3.3266e-55
b2	0.031339	0.001321	23.724	1.4763e-29
b3	160.63	1.523	105.47	2.5321e-62

   Number of observations: 55, Error degrees of freedom: 52

   Root Mean Squared Error: 0.662

   R-Squared: 0.986, Adjusted R-Squared 0.985

   F-statistic vs. zero model: 5.14e+03, p-value = 2.85e-6

Appendix J: Number of robots needed for each human-robot solution along the season per hectare, 8.6 (Dutch greenhouse), 10, 15 and 20 hectares

Amounts per hectare:

workers	max robots	min robots		133	138	143	148	153	158	163	168	173	178	183	188	193	198	203	208	213	218	223	228	233	238	243	248	253	258	263	268	273	278	283	288	293	298	303	308	313
0.6977	0.92	0.50	70%	0.59	0.55	0.55	0.50	0.56	0.62	0.63	0.62	0.69	0.74	0.74	0.78	0.78	0.80	0.82	0.81	0.83	0.83	0.88	0.88	0.88	0.89	0.86	0.92	0.86	0.86	0.90	0.91	0.85	0.85	0.82	0.78	0.77	0.77	0.76	0.71	0.71
0.6977	0.84	0.48	90%	0.56	0.51	0.51	0.48	0.52	0.57	0.57	0.57	0.63	0.67	0.68	0.71	0.71	0.74	0.75	0.74	0.76	0.76	0.81	0.81	0.81	0.81	0.79	0.84	0.80	0.79	0.82	0.84	0.79	0.78	0.76	0.71	0.71	0.70	0.69	0.65	0.65
0.9302	0.80	0.41	50%	0.46	0.42	0.42	0.41	0.43	0.46	0.47	0.46	0.54	0.59	0.60	0.63	0.65	0.68	0.69	0.68	0.69	0.71	0.76	0.76	0.75	0.75	0.72	0.79	0.75	0.76	0.78	0.80	0.72	0.72	0.70	0.65	0.63	0.63	0.61	0.57	0.57
0.9302	0.68	0.31	70%	0.37	0.32	0.33	0.31	0.34	0.38	0.39	0.38	0.45	0.49	0.50	0.52	0.53	0.55	0.57	0.56	0.58	0.60	0.64	0.64	0.63	0.64	0.61	0.68	0.63	0.62	0.65	0.66	0.61	0.60	0.57	0.53	0.51	0.54	0.50	0.47	0.45
0.9302	0.62	0.30	90%	0.34	0.32	0.32	0.30	0.32	0.35	0.35	0.35	0.40	0.44	0.47	0.49	0.50	0.51	0.54	0.52	0.53	0.53	0.59	0.58	0.58	0.58	0.54	0.62	0.57	0.56	0.61	0.62	0.58	0.54	0.53	0.49	0.48	0.49	0.46	0.42	0.43
1.1628	0.52	0.26	50%	0.29	0.27	0.27	0.26	0.27	0.29	0.29	0.29	0.31	0.32	0.33	0.36	0.36	0.37	0.39	0.39	0.41	0.42	0.45	0.48	0.47	0.48	0.43	0.51	0.46	0.45	0.51	0.52	0.45	0.44	0.41	0.35	0.33	0.36	0.34	0.31	0.31
1.1628	0.43	0.18	70%	0.20	0.19	0.19	0.18	0.19	0.20	0.20	0.20	0.22	0.23	0.24	0.28	0.28	0.29	0.33	0.31	0.32	0.35	0.39	0.38	0.39	0.39	0.36	0.43	0.37	0.36	0.40	0.41	0.36	0.35	0.34	0.27	0.26	0.26	0.25	0.23	0.23
1.1628	0.40	0.18	90%	0.20	0.19	0.19	0.18	0.19	0.20	0.20	0.20	0.21	0.23	0.23	0.26	0.27	0.28	0.31	0.29	0.31	0.30	0.36	0.36	0.33	0.36	0.33	0.39	0.35	0.34	0.40	0.40	0.31	0.34	0.32	0.26	0.26	0.27	0.24	0.22	0.23
1.3953	0.21	0.08	50%	0.09	0.08	0.08	0.08	0.09	0.09	0.09	0.09	0.09	0.10	0.10	0.10	0.10	0.12	0.12	0.11	0.12	0.12	0.15	0.15	0.17	0.19	0.14	0.20	0.12	0.15	0.18	0.21	0.13	0.12	0.12	0.10	0.10	0.10	0.10	0.10	0.10
1.3953	0.18	0.08	70%	0.09	0.08	0.08	0.08	0.09	0.09	0.09	0.09	0.10	0.10	0.10	0.10	0.10	0.11	0.12	0.11	0.12	0.11	0.15	0.16	0.13	0.16	0.12	0.16	0.12	0.15	0.17	0.18	0.13	0.12	0.12	0.11	0.10	0.10	0.10	0.10	0.09
1.3953	0.17	0.08	90%	0.09	0.09	0.08	0.08	0.08	0.09	0.09	0.09	0.09	0.10	0.11	0.11	0.11	0.10	0.11	0.11	0.10	0.12	0.15	0.15	0.14	0.16	0.11	0.15	0.12	0.13	0.15	0.17	0.12	0.11	0.12	0.10	0.10	0.11	0.11	0.10	0.10

Amounts per 8.6 hectare:

workers	max robots	min robots		133	138	143	148	153	158	163	168	173	178	183	188	193	198	203	208	213	218	223	228	233	238	243	248	253	258	263	268	273	278	283	288	293	298	303	308	313
6	10	6	50%	7	6	6	6	6	7	7	7	7	8	8	8	8	9	9	8	9	9	9	9	9	9	9	10	9	9	9	10	9	9	9	8	8	8	8	7	8
6	8	5	70%	6	5	5	5	5	6	6	6	6	7	7	7	7	7	8	7	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	7	7	7	7	7	7
6	8	5	90%	5	5	5	5	5	5	5	5	6	6	6	7	7	7	7	7	7	7	7	7	7	7	7	8	7	7	8	8	7	7	7	7	7	7	6	6	6
8	7	4	50%	4	4	4	4	4	4	5	4	5	6	6	6	6	6	6	6	6	7	7	7	7	7	7	7	7	7	7	7	7	7	6	6	6	6	6	5	5
8	6	3	70%	4	3	3	3	3	4	4	4	4	5	5	5	5	5	5	5	5	6	6	6	6	6	6	6	6	6	6	6	6	6	5	5	5	5	5	5	4
8	6	3	90%	3	3	3	3	3	4	3	4	4	4	5	5	5	5	5	5	5	5	6	5	5	5	5	6	5	5	6	6	5	5	5	5	5	5	4	4	4
10	5	3	50%	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	5	5	5	4	5	4	4	5	5	4	4	4	3	3	4	3	3	3
10	4	2	70%	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3	3	3	2	2
10	4	2	90%	2	2	2	2	2	2	2	2	2	3	3	3	3	3	3	3	3	3	4	4	3	4	3	4	4	3	4	4	3	3	3	3	3	3	3	2	2
12	2	1	50%	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	1
12	2	1	70%	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1	2	1	2	2	2	2	2	2	1	2	2	2	2	2	2	1	1	1	1	1	1
12	2	1	90%	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	1	2	2	2	2	2	2	1	2	1	1	1	1	1	1

Amounts per 10 hectare:

workers	max robots	min robots		133	138	143	148	153	158	163	168	173	178	183	188	193	198	203	208
7	11	7	50%	8	7	7	7	7	8	8	8	8	9	9	9	10	10	10	10
7	10	5	70%	6	6	6	5	6	7	7	7	7	8	8	8	8	9	9	9
7	9	5	90%	6	6	6	5	6	6	6	6	7	7	7	8	8	8	8	8
10	9	5	50%	5	5	5	5	5	5	5	5	6	6	7	7	7	7	7	7
10	7	4	70%	4	4	4	4	4	4	4	4	5	5	5	6	6	6	6	6
10	7	4	90%	4	4	4	4	4	4	4	4	4	5	5	5	5	6	6	6
12	6	3	50%	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4
12	5	2	70%	2	2	2	2	2	3	3	2	3	3	3	3	3	3	4	4
12	4	2	90%	2	2	2	2	2	2	3	2	3	3	3	3	3	3	4	3
14	3	1	50%	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2
14	2	1	70%	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2
14	2	1	90%	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2

workers	max robots	min robots		213	218	223	228	233	238	243	248	253	258	263	268	273	278	283	288	293	298	303	308	313
7	11	7	50%	10	10	11	11	11	11	10	11	11	11	11	11	10	10	10	9	9	9	9	9	9
7	10	5	70%	9	9	9	9	9	9	9	10	9	9	10	10	9	9	9	8	8	8	8	8	8
7	9	5	90%	8	8	9	9	9	9	8	9	8	8	9	9	8	8	8	8	8	7	7	7	7
10	9	5	50%	7	8	8	8	8	8	8	8	8	8	8	9	8	8	7	7	7	7	7	6	6
10	7	4	70%	6	6	7	7	7	7	7	7	7	7	7	7	7	6	6	6	6	6	6	5	5
10	7	4	90%	6	6	6	6	6	6	6	7	6	6	7	7	6	6	6	5	5	5	5	5	5
12	6	3	50%	5	5	5	5	5	5	5	6	5	5	6	6	5	5	5	4	4	4	4	4	4
12	5	2	70%	4	4	4	4	4	4	4	5	4	4	5	5	4	4	4	3	3	3	3	3	3
12	4	2	90%	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3	3	3	3
14	3	1	50%	2	2	2	2	2	2	2	2	2	2	2	3	2	2	2	2	2	2	2	1	1
14	2	1	70%	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1
14	2	1	90%	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1

Amounts per 15 hectare:

workers	max robots	min robots		133	138	143	148	153	158	163	168	173	178	183	188	193	198	203	208
11	16	10	50%	11	10	10	10	10	11	11	11	12	13	13	14	14	15	15	14
11	14	8	70%	9	9	9	8	9	10	10	10	11	12	12	12	12	13	13	13
11	13	8	90%	9	8	8	8	8	9	9	9	10	11	11	11	11	12	12	12
14	13	7	50%	7	7	7	7	7	7	8	7	9	9	10	10	10	11	11	11
14	11	5	70%	6	5	5	5	6	6	6	6	7	8	8	8	8	9	9	9
14	10	5	90%	6	5	5	5	5	6	6	6	6	7	8	8	8	8	9	8
18	8	4	50%	5	5	5	4	5	5	5	5	5	5	5	6	6	6	6	6
18	7	3	70%	3	3	3	3	3	4	4	3	4	4	4	5	5	5	5	5
18	6	3	90%	3	3	3	3	3	3	4	3	4	4	4	4	5	5	5	5
21	4	2	50%	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
21	3	2	70%	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
21	3	2	90%	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2

workers	max robots	min robots		213	218	223	228	233	238	243	248	253	258	263	268	273	278	283	288	293	298	303	308	313
11	16	10	50%	15	15	16	16	16	16	15	16	16	16	16	16	15	15	15	14	14	14	13	13	13
11	14	8	70%	13	13	14	14	14	14	13	14	13	13	14	14	13	13	13	12	12	12	12	11	11
11	13	8	90%	12	12	13	13	13	13	12	13	12	12	13	13	12	12	12	11	11	11	11	10	10
14	13	7	50%	11	11	12	12	12	12	11	12	12	12	12	13	11	11	11	10	10	10	10	9	9
14	11	5	70%	9	9	10	10	10	10	10	11	10	10	10	10	10	9	9	8	8	9	8	7	7
14	10	5	90%	8	8	9	9	9	9	9	10	9	9	10	10	9	9	8	8	8	8	7	7	7
18	8	4	50%	7	7	7	8	7	8	7	8	7	7	8	8	7	7	7	6	5	6	6	5	5
18	7	3	70%	5	6	6	6	6	6	6	7	6	6	7	7	6	6	6	5	4	4	4	4	4
18	6	3	90%	5	5	6	6	5	6	5	6	6	6	6	6	5	6	5	4	4	5	4	4	4
21	4	2	50%	2	2	3	3	3	3	3	3	2	3	3	4	3	2	2	2	2	2	2	2	2
21	3	2	70%	2	2	3	3	2	3	2	3	2	3	3	3	2	2	2	2	2	2	2	2	2
21	3	2	90%	2	2	3	3	3	3	2	3	2	2	3	3	2	2	2	2	2	2	2	2	2

Amounts per 20 hectare:

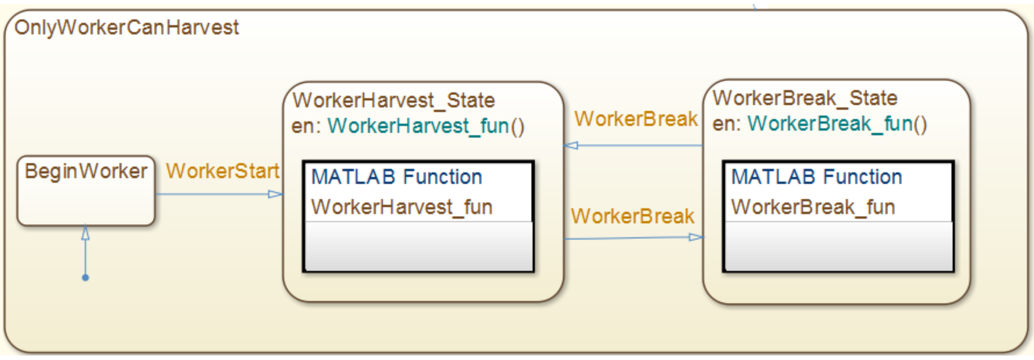
workers	max robots	min robots		133	138	143	148	153	158	163	168	173	178	183	188	193	198	203	208	213
14	22	13	50%	15	13	13	13	14	15	15	15	16	17	18	18	19	19	19	19	19
14	19	10	70%	12	11	12	10	12	13	13	13	14	15	15	16	16	17	17	17	17
14	17	10	90%	12	11	11	10	11	12	12	12	13	14	14	15	15	15	15	15	16
19	17	9	50%	10	9	9	9	9	10	10	10	11	12	13	13	13	14	14	14	14
19	14	7	70%	8	7	7	7	7	8	8	8	9	10	10	11	11	11	12	12	12
19	13	7	90%	7	7	7	7	7	8	7	8	8	9	10	10	10	11	11	11	11
24	11	6	50%	6	6	6	6	6	6	6	6	7	7	7	8	8	8	8	8	9
24	9	4	70%	4	4	4	4	4	5	5	4	5	5	5	6	6	6	7	7	7
24	8	4	90%	4	4	4	4	4	4	5	4	5	5	5	6	6	6	7	6	7
28	5	2	50%	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3	3	3
28	4	2	70%	2	2	2	2	2	2	2	2	2	3	3	3	3	3	3	3	3
28	4	2	90%	2	2	2	2	2	2	2	2	2	3	3	3	3	3	3	3	3

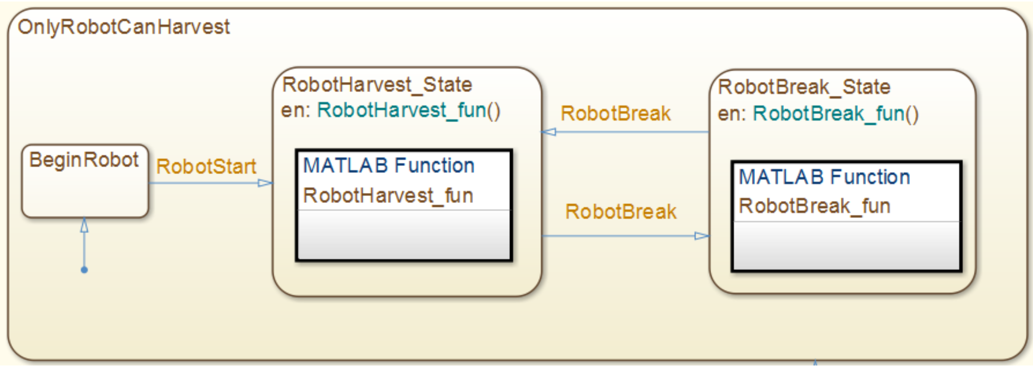
workers	max robots	min robots		218	223	228	233	238	243	248	253	258	263	268	273	278	283	288	293	298	303	308	313
14	22	13	50%	20	21	21	21	21	20	22	21	21	21	22	20	20	20	18	18	18	18	17	17
14	19	10	70%	17	18	18	18	18	18	19	18	18	19	19	18	18	17	16	16	16	16	15	15
14	17	10	90%	16	17	17	17	17	16	17	16	16	17	17	16	16	16	15	15	14	14	14	13
19	17	9	50%	15	16	16	15	16	15	16	15	16	16	17	15	15	14	14	13	13	13	12	12
19	14	7	70%	12	13	13	13	13	13	14	13	13	13	14	13	12	12	11	11	11	11	10	10
19	13	7	90%	11	12	12	12	12	11	13	12	12	13	13	12	11	11	10	10	10	10	9	9
24	11	6	50%	9	10	10	10	10	9	11	10	9	11	11	9	9	9	7	7	8	7	7	7
24	9	4	70%	7	8	8	8	8	8	9	8	8	9	9	8	8	7	6	6	6	6	5	5
24	8	4	90%	7	8	8	7	8	7	8	8	7	8	8	7	7	7	6	6	6	5	5	5
28	5	2	50%	3	4	4	4	4	3	4	3	4	4	5	3	3	3	3	3	3	3	2	2
28	4	2	70%	3	4	4	3	4	3	4	3	4	4	4	3	3	3	3	3	3	3	2	2
28	4	2	90%	3	3	3	3	4	3	4	3	3	4	4	3	3	3	3	3	3	3	2	2

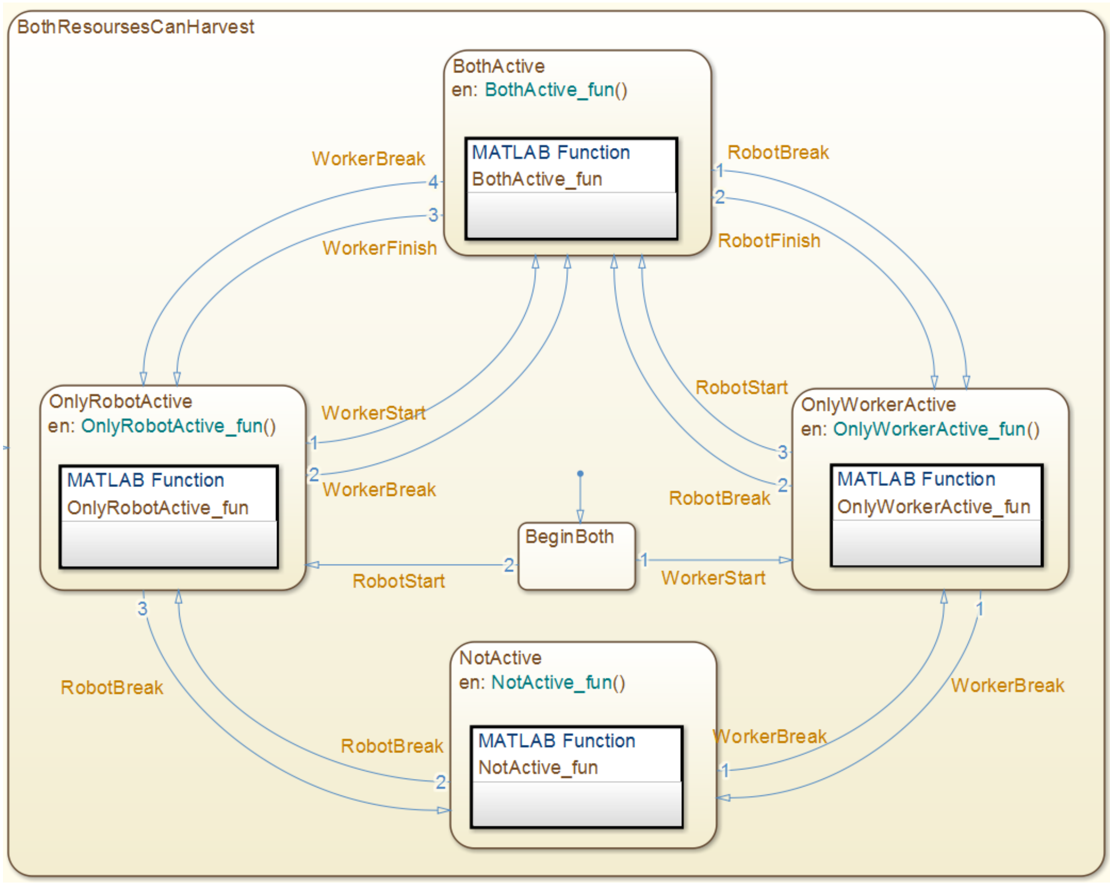
Appendix K: Harvest cycles analysis of 2012 harvesting season

HC #	Start day (days since transplanting)	from	to	Time window: workdays	Average days since last harvest
1	105	12/3/12	15/3/12	4	-
2	126	2/4/12	4/4/12	3	21
3	133	9/4/12	11/4/12	3	7
4	136	12/4/12	17/4/12	3	5
5	142	18/4/12	20/4/12	3	4
6	148	24/4/12	26/4/12	3	6
7	154	30/4/12	2/5/12	3	6
8	158	4/5/12	7/5/12	3	4.333
9	163	9/5/12	10/5/12	2	4
10	168	14/5/12	16/5/12	3	5
11	175	21/5/12	22/5/12	2	7
12	177	23/5/12	24/5/12	2	2
13	183	29/5/12	31/5/12	3	6
14	186	1/6/12	4/6/12	2	3.5
15	190	5/6/12	7/6/12	3	3
16	196	11/6/12	14/6/12	4	6
17	204	19/6/12	21/6/12	3	8
18	211	26/6/12	28/6/12	3	7
19	217	2/7/12	4/7/12	3	6
20	221	6/7/12	10/7/12	3	5.333
21	226	11/7/12	12/7/12	2	3.75
22	233	18/7/12	20/7/12	3	7
23	240	25/7/12	27/7/12	3	3
24	246	31/7/12	1/8/12	2	4.5
25	249	3/8/12	7/8/12	3	3.5
26	256	10/8/12	15/8/12	4	6.75
27-28	266	20/8/12	24/8/12	2.5	4.75
29	274	28/8/12	31/8/12	4	7
30	282	5/9/12	7/9/12	3	7
31	288	11/9/12	13/9/12	3	6
32-33	295	18/9/12	25/9/12	3	5.25
34	303	26/9/12	28/9/12	3	5
35-36	309	2/10/12	5/10/12	2	3.875
37-41	317	10/10/12	29/10/12	2.609	3.4
		Average (rounded):		**3**	**5**

Appendix L: Stateflow chart of the model in Matlab







Appendix M: Simulation model output structure

Output Structure- WorkersData

PathsMissed	Measures	HarvestingOperations	PathsSummeryInfo	TimeInfo
(Structure)	**(Structure)**	**(Cell array)**	**(Array)**	**(Structure)**
- **Amount** - amount of paths that were not completed (paths waiting for the worker at the end of simulation) - **PathsList**- indexes of paths missed	- **SumPepper** - **StdPepperPath** - **AvgTimePath** - **StdTimePath** - **AvgTimePepper** - **StdTimePepper**	For each path: **1. Detailed timing** (pepper num, select pepper time, cut time, empty container, move between paths, total time, total time without move between paths) **2. PathID** **3. WorkerNum** **4. Total peppers** harvested by worker **5. TotalTime** (without moving to and from the path) **6. Harvest time** (Time [5] /Peppers [4]) **7. TotalTime** (including move between paths)	For each path: 1. pathID 2. TotalPeppers 3. BeginTime 4. EndTime 5. TotalTime 6. ResourceType (1-worker) 7. WorkerNum 8. Simulation day of harvest	- TotalTime: in which simulation time the workers work was finished (in hours) - Details: (array) Each line is: harvesting day, WorkerNum, total time the worker worked in hours and utilization (once with move between paths and once without). - DayLength: for each date, the length of the work day- according to time defined or the maximum workers work.
TotalPepperMissed	**Summery Results- separated variables**		**Locations**	
(Structure)	**(each is Double)**		**(Cell array)**	
- **Amount**- Total amount of peppers that were not harvested - **MissedList**- indexes of paths missed and the amount of peppers missed in every path	- TotalPeppersHarvested - sum of all peppers harvested. - PathsHarvested- amount of paths completed - HarvestAvg- the average time per one pepper in seconds.		- the locations (x,y,z) of each worker during simulation.	

Output Structure- RobotsData

PathsMissed	Measures	HarvestingOperations	PathsSummeryInfo	TimeInfo
(Structure)	**(Structure)**	**(Cell array)**	**(Array)**	**(Structure)**
- **Amount** - amount of paths that were not completed (paths waiting for the robot at the end of simulation) - **PathsList**- indexes of paths missed	- **SumPepper** - **StdPepperPath** - **AvgTimePath** - **StdTimePath** - **AvgTimePepper** - **StdTimePepper** - **CycleTimePepper**	For each path: **1. Detailed timing** (path priority , pepper num, was harvested?, select pepper time, cut time, empty container, move between paths, total time, total time without move between paths) **2. PathID** **3. RobotNum** started the harvest **4. Total peppers** harvested by robots **5. TotalTime** (without moving to and from the path) **6. Harvest time** (Time [5] /Peppers [4]) **7. TotalTime** (including move between paths)	For each path: **1. pathID** **2. TotalPeppers** **3. Harvest repetition** (first, second, third harvest...) **4. BeginTime** **5. EndTime** **6. TotalTime** **7. ResourceType** (2-robot) **8. RobotNum** **9. Simulation day** of harvest	- TotalTime: in which simulation time the robots work was finished (in hours) - Details: (array) Each line is: harvesting day, RobotNum, total time the robots worked in hours and utilization (once with move between paths and once without). - DayLength: for each date, the length of the work day- according to time defined or the maximum robots work.
TotalPepperMissed	**Summery Results- separated variables**		**Locations**	
(Structure)	**(each is Double)**		**(Cell array)**	
- **Amount**- Total amount of peppers that were not harvested - **MissedList**- indexes of paths missed and the amount of peppers missed in every path	- TotalPeppersHarvested - sum of all peppers harvested. - PathsHarvested- amount of paths completed - HarvestAvg- the average time per one pepper in seconds.		- the locations (x,y,z) of each robot during simulation.	

Output Structure- SummeryInfo

PathSummery	PeppersHarvested	PeppersMissed	HarvestAverage
(Array)	**(Double)**	**(Double)**	**(Double)**
1. Path ID 2. Peppers harvested by human workers 3. Peppers harvested by robots 4. Total missed peppers for path 5. Total amount of peppers in path 6. Is the path completed? 1=yes	Total peppers missed by both resources at the entire greenhouse	Total peppers missed by both resources at the entire greenhouse (Due to lack of time)	Total time of both resources / Total peppers harvested

Output Structure- MissedPeppersByRobots

DetailedInfo	Total amount
(Array)	**(Double)**
1. Path ID 2. Peppers harvested 3. Total peppers should be harvested on path 4. Total missed peppers for path 5. Harvest repetitions- how many times the path was harvested	Total peppers missed by robots at the entire greenhouse

Appendix N: Calibration results on September 26th

		0.5 overlap		0.4 overlap		0.3 overlap		0.4+20% cut time		0.3+20% cut time	
	RealData	**1**	**Accuracy**	**2**	**Accuracy**	**3**	**Accuracy**	**4**	**Accuracy**	**5**	**Accuracy**
SumPepper	60469	64030	94.1%	62842	96.1%	64880	92.7%	64030	94.1%	60756	99.5%
StdPepperPath	160.136	191.253	80.6%	178.853	88.3%	160.534	99.8%	191.253	80.6%	142.906	89.2%
AvgTimePath	1810	1727	95.4%	1739	96.1%	1868	96.8%	1898	95.1%	1969	91.2%
StdTimePath	496.873	313.730	63.1%	303.652	61.1%	281.783	56.7%	380.646	76.6%	291.718	58.7%
AvgTimePepper	3.292	2.995	91.0%	3.072	93.3%	3.196	97.1%	3.290	99.9%	3.597	90.7%
StdTimePepper	0.423	0.481	86.1%	0.473	88.2%	0.444	94.9%	0.479	86.7%	0.446	94.6%

Appendix O: Calibration test results on 26-28/9/2012

26/09/12	RealData	1	2	3	4	5	6	7	8	9	10	Average	Std	Upper CI	Lower CI	Accuracy
SumPepper	60469	62406	59648	62756	60522	59864	62162	61504	58468	60044	60756	60813	1376	59828	61798	99.4%
StdPepperPath	160.1	145.2	143.7	152.8	142.4	147.7	148.6	135.7	146.3	146.0	142.9	145.1	4.5	141.9	148.3	90.6%
AvgTimePath	1809.8	2002.1	1950.9	2007.0	1966.4	1955.5	1997.6	1982.4	1929.8	1956.7	1969.0	1971.7	25.1	1953.8	1989.7	91.1%
StdTimePath	496.9	298.1	290.6	314.1	288.0	299.1	304.9	275.5	296.2	294.7	291.7	295.3	10.3	288.0	302.6	59.4%
AvgTimePepper	3.292	3.561	3.631	3.550	3.606	3.626	3.567	3.578	3.664	3.617	3.597	3.600	0.036	3.574	3.625	90.7%
StdTimePepper	0.423	0.495	0.482	0.467	0.513	0.495	0.467	0.445	0.548	0.459	0.446	0.482	0.032	0.459	0.505	86.0%

27/09/12	RealData	1	2	3	4	5	6	7	8	9	10	Average	Std	Upper CI	Lower CI	Accuracy
SumPepper	69683	69394	69532	73206	71536	70182	73380	71022	69800	69656	70878	70859	1464	69811	71906	98.3%
StdPepperPath	119.4	116.3	118.0	118.7	124.0	112.2	132.7	124.0	117.8	111.8	120.5	119.6	6.2	115.2	124.0	99.8%
AvgTimePath	1622.9	1715.8	1717.2	1763.5	1741.2	1724.8	1766.2	1739.4	1723.3	1722.9	1736.7	1735.1	18.0	1722.2	1748.0	93.1%
StdTimePath	415.2	224.5	232.2	233.6	242.0	216.7	260.5	243.3	231.5	218.8	240.5	234.3	13.0	225.0	243.6	56.4%
AvgTimePepper	3.796	4.080	4.075	3.975	4.016	4.055	3.971	4.041	4.074	4.081	4.043	4.041	0.041	4.011	4.071	93.6%
StdTimePepper	0.693	0.645	0.674	0.628	0.637	0.599	0.708	0.626	0.607	0.641	0.658	0.642	0.032	0.620	0.665	92.7%

28/09/12	RealData	1	2	3	4	5	6	7	8	9	10	Average	Std	Upper CI	Lower CI	Accuracy
SumPepper	10623	10678	10834	9844	10404	9956	9740	10220	11296	10452	11080	10450	525	10075	10826	98.4%
StdPepperPath	92.2	121.0	82.5	96.3	84.4	70.9	70.4	111.8	85.3	85.1	91.7	89.9	16.2	78.3	101.5	97.5%
AvgTimePath	1488.9	1684.7	1691.7	1617.2	1654.7	1626.4	1595.9	1632.5	1709.6	1653.8	1693.5	1656.0	37.9	1628.9	1683.1	88.8%
StdTimePath	358.1	240.7	154.6	173.4	156.8	137.5	128.3	215.0	153.5	166.5	181.5	170.8	34.4	146.2	195.4	47.7%
AvgTimePepper	3.784	4.260	4.216	4.436	4.294	4.411	4.424	4.313	4.086	4.272	4.127	4.284	0.120	4.198	4.369	86.8%
StdTimePepper	0.343	0.712	0.555	0.865	0.665	0.497	0.519	0.637	0.498	0.583	0.450	0.598	0.125	0.509	0.688	25.6%

All three days	RealData	1	2	3	4	5	6	7	8	9	10	Average	Std	Upper CI	Lower CI	Accuracy
SumPepper	140775	142478	140014	145806	142462	140002	145282	142746	139564	140152	142714	142122	2209	140542	143702	99.0%
StdPepperPath	147.2	145.7	137.8	146.8	140.7	137.6	149.5	142.6	136.0	137.3	139.5	141.3	4.6	138.0	144.6	96.0%
AvgTimePath	1679.4	1817.9	1800.6	1839.7	1816.0	1800.5	1835.8	1818.9	1797.8	1802.4	1818.0	1814.7	14.7	1804.2	1825.3	91.9%
StdTimePath	453.7	290.6	274.3	293.3	279.0	272.7	299.2	283.1	270.6	272.4	280.4	281.6	9.9	274.5	288.6	62.1%
AvgTimePepper	3.579	3.866	3.897	3.823	3.862	3.897	3.829	3.861	3.903	3.897	3.860	3.869	0.029	3.849	3.890	91.9%
StdTimePepper	0.635	0.667	0.646	0.668	0.644	0.607	0.670	0.633	0.610	0.629	0.619	0.639	0.024	0.623	0.656	99.3%

Appendix P: Validation results on four harvesting periods in the season of 2012

30/4-2/5	RealData	1	2	3	4	5	6	7	8	9	10	Average	Std	Upper CI	Lower CI	Accuracy
SumPepper	200642	186452	189716	188758	184766	186354	188152	178716	186356	182612	180590	185247	3593	182677	187817	92.3%
StdPepperPath	221.5	203.1	216.3	199.3	228.3	198.7	211.6	192.7	204.5	203.5	216.5	207.4	10.6	199.8	215.0	93.6%
AvgTimePath	2644.2	2111.8	2135.6	2126.1	2101.7	2107.4	2120.5	2059.7	2110.2	2086.4	2073.3	2103.3	23.8	2086.3	2120.3	79.5%
StdTimePath	1097.0	414.8	445.7	405.9	468.3	406.9	436.4	388.6	416.8	415.6	442.4	424.1	23.6	407.3	441.0	38.7%
AvgTimePepper	3.980	3.432	3.411	3.413	3.447	3.426	3.415	3.492	3.431	3.462	3.479	3.441	0.028	3.420	3.461	86.5%
StdTimePepper	1.876	0.693	0.746	0.662	0.888	0.665	0.644	0.761	0.739	0.927	0.879	0.760	0.103	0.687	0.834	40.5%

11-14/6	RealData	1	2	3	4	5	6	7	8	9	10	Average	Std	Upper CI	Lower CI	Accuracy
SumPepper	288380	273446	264606	269730	270586	264326	264102	262480	266098	265874	270178	267143	3583	264579	269706	92.6%
StdPepperPath	260.4	271.4	217.4	264.6	241.3	228.4	224.9	221.6	230.6	253.3	266.8	242.0	20.4	227.4	256.6	92.9%
AvgTimePath	2595.6	2710.2	2645.1	2680.2	2686.0	2643.6	2642.8	2629.7	2655.3	2653.8	2685.7	2663.2	25.7	2644.9	2681.6	97.4%
StdTimePath	721.4	592.7	468.4	582.0	525.3	498.5	489.9	484.3	499.4	552.8	583.8	527.7	46.5	494.5	561.0	73.1%
AvgTimePepper	2.736	3.013	3.039	3.021	3.018	3.040	3.042	3.046	3.034	3.034	3.022	3.031	0.012	3.023	3.039	89.2%
StdTimePepper	0.558	0.264	0.267	0.259	0.252	0.258	0.252	0.232	0.273	0.279	0.280	0.262	0.014	0.251	0.272	46.9%

10-16/8	RealData	1	2	3	4	5	6	7	8	9	10	Average	Std	Upper CI	Lower CI	Accuracy
SumPepper	335396	333676	333710	330804	329858	327838	336432	328348	331436	329330	333274	331471	2755	329500	333442	98.8%
StdPepperPath	197.5	211.7	200.9	198.7	199.9	191.8	194.7	200.6	199.0	198.0	207.2	200.2	5.7	196.2	204.3	98.6%
AvgTimePath	3282.9	3125.3	3121.4	3099.8	3096.0	3081.0	3140.2	3081.8	3105.3	3088.8	3120.8	3106.1	20.1	3091.7	3120.5	94.6%
StdTimePath	728.2	471.4	446.4	439.3	439.4	426.3	432.8	444.4	439.5	443.1	463.0	444.6	13.4	435.0	454.1	61.0%
AvgTimePepper	2.995	2.866	2.862	2.867	2.872	2.876	2.856	2.872	2.867	2.870	2.865	2.867	0.006	2.863	2.871	95.7%
StdTimePepper	0.580	0.138	0.129	0.147	0.142	0.129	0.122	0.140	0.136	0.134	0.137	0.135	0.007	0.130	0.141	23.3%

11-13/9	RealData	1	2	3	4	5	6	7	8	9	10	Average	Std	Upper CI	Lower CI	Accuracy
SumPepper	117995	128508	122082	122374	121604	125114	122778	128274	122808	119568	126986	124010	3043	121832	126187	94.9%
StdPepperPath	131.1	161.4	134.1	130.4	136.6	129.6	127.2	148.3	129.3	124.0	142.4	136.3	11.5	128.1	144.5	96.0%
AvgTimePath	1799.8	1738.6	1696.0	1697.2	1690.6	1714.4	1697.5	1736.8	1696.4	1677.4	1728.7	1707.4	21.0	1692.3	1722.4	94.9%
StdTimePath	528.8	324.7	260.3	254.6	266.4	254.1	248.1	292.2	253.8	244.7	280.5	267.9	24.8	250.2	285.7	50.7%
AvgTimePepper	4.576	4.059	4.168	4.161	4.171	4.111	4.148	4.062	4.144	4.209	4.084	4.131	0.050	4.095	4.168	90.3%
StdTimePepper	1.130	0.829	0.885	0.769	0.901	0.789	0.800	0.807	0.744	0.756	0.833	0.811	0.052	0.774	0.848	71.8%

Appendix Q: Verification results of robot with 80% detection capability

Path	Pepper amount	First harvest	% from peppers	Second harvest	% from peppers	Third harvest	% from peppers	Harvested peppers	Missed peppers	% from peppers	Harvest repeats
141	456	374	82.0%	65	79.3%	-	-	439	17	3.7%	2
142	716	578	80.7%	106	76.8%	-	-	684	32	4.5%	2
143	452	372	82.3%	58	72.5%	-	-	430	22	4.9%	2
144	608	479	78.8%	108	83.7%	-	-	587	21	3.5%	2
145	456	364	79.8%	71	77.2%	-	-	435	21	4.6%	2
146	458	367	80.1%	74	81.3%	-	-	441	17	3.7%	2
147	408	323	79.2%	68	80.0%	-	-	391	17	4.2%	2
148	478	381	79.7%	84	86.6%	-	-	465	13	2.7%	2
149	430	341	79.3%	64	71.9%	22	88.0%	427	3	0.7%	3
150	780	618	79.2%	127	78.4%	-	-	745	35	4.5%	2
151	480	391	81.5%	72	80.9%	-	-	463	17	3.5%	2
152	522	429	82.2%	70	75.3%	-	-	499	23	4.4%	2
292	362	289	79.8%	57	78.1%	-	-	346	16	4.4%	2
293	478	375	78.5%	91	88.3%	-	-	466	12	2.5%	2
294	396	315	79.5%	60	74.1%	16	76.2%	391	5	1.3%	3
295	516	411	79.7%	87	82.9%	-	-	498	18	3.5%	2
296	542	439	81.0%	83	80.6%	-	-	522	20	3.7%	2
297	484	396	81.8%	66	75.0%	-	-	462	22	4.5%	2
298	372	281	75.5%	78	85.7%	-	-	359	13	3.5%	2
299	722	589	81.6%	107	80.5%	-	-	696	26	3.6%	2
300	396	319	80.6%	61	79.2%	-	-	380	16	4.0%	2
301	324	265	81.8%	47	79.7%	-	-	312	12	3.7%	2
302	514	407	79.2%	79	73.8%	20	71.4%	506	8	1.6%	3
303	522	420	80.5%	84	82.4%	-	-	504	18	3.4%	2
304	470	387	82.3%	68	81.9%	-	-	455	15	3.2%	2
Averages:			80.3%		79.4%		78.5%			3.5%	<5%

Appendix R: Sensitivity of robots maximum cost with changed capabilities (detection, harvest repeat and acceleration)

Four fixed workers:

	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12
R_{DET}	70%	50%	90%	70%	50%	90%	70%	50%	90%	70%	50%	90%
R_{REPEAT}	100%						70%					
Acceleration	0.2			0.1			1.0			0.2		
Number of Robots	4	5	4	5	6	5	3	4	3	5	6	5
Cost per robot [€]	45,634	34,329	50,819	32,823	31,090	37,819	46,776	43,474	75,337	31,367	24,972	31,065

Five fixed workers:

	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12
R_{DET}	70%	50%	90%	70%	50%	90%	70%	50%	90%	70%	50%	90%
R_{REPEAT}	100%						70%					
Acceleration	0.2			0.1			1.0			0.2		
Number of Robots	4	5	4	5	6	5	3	4	3	5	6	5
Cost per robot [€]	28,604	20,174	31,832	18,041	16,869	30,045	28,928	26,694	33,229	16,532	14,966	16,613

Appendix S: Economic model- yield sensitivity analysis

Base cost, only human workers:		244,858€		Averaged yield	204,066€		Low yield	278,215€		High yield
		Robots	Price	Investment space	Robots	Price	Investment space	Robots	Price	Investment space
50%	3	5	39,504	49,380	4	31,281	31,281	6	43,618	65,428
	4	4	34,329	34,329	3	18,685	14,013	5	41,057	51,321
	5	3	20,174	15,131	2	-	0	4	32,713	32,713
	6	1	-	0	-	-	-	3	17,951	13,463
	7	-	-	-	-	-	-	2	-	0
70%	3	4	53,880	53,880	3	44,546	33,410	5	57,353	71,691
	4	3	45,634	34,226	2	26,817	13,408	4	52,041	52,041
	5	2	28,604	14,302	1	-	0	3	41,236	30,927
	6	1	-	0	-	-	-	2	24,848	12,424
	7	-	-	-	-	-	-	2	-	0
90%	3	4	60,191	60,191	3	49,652	37,239	5	64,974	81,217
	4	3	50,819	38,114	2	30,827	15,414	4	59,409	59,409
	5	2	31,832	15,916	1	-	0	3	49,828	37,371
	6	1	-	0	-	-	-	2	30,799	15,400
	7	-	-	-	-	-	-	1	-	0

Appendix T: Economic model- greenhouse size sensitivity analysis

1.3 hectare			4.3 hectare			8.6 hectare		
Workers	Robots, R_{DET}=50,70,90%	Price (€)	Workers	Robots, R_{DET}=50,70,90%	Price (€)	Workers	Robots, R_{DET}=50,70,90%	Price (€)
1	2	32,020	3	5	39,504	6	10	50,928
1	2	34,114	3	4	53,880	6	8	68,160
1	2	37,049	3	4	60,191	6	8	74,471

10 hectare			15 hectare			20 hectare		
Workers	Robots, R_{DET}=50,70,90%	Price (€)	Workers	Robots, R_{DET}=50,70,90%	Price (€)	Workers	Robots, R_{DET}=50,70,90%	Price (€)
7	11	53,194	7	11	53,194	7	11	53,194
7	10	62,700	7	10	62,700	7	10	62,700
7	9	76,190	7	9	76,190	7	9	76,190

תקציר

חממות לגידולים חקלאיים דורשות כוח אדם רב. אחת הבעיות העיקריות בחקלאות, הנובעת מדרישה זו, היא מחסור בכוח אדם והעלות הגבוהה של העובדים. אחד הפתרונות המוצעים הינו פיתוח רובוט לביצוע פעולת קטיף שישולב בחממות. הכנסה של רובוטיקה לתהליך הקטיף מעלה את הצורך לחקור ולהשתמש בסימולציה על מנת לבחון את שילובו האופטימלי למערכת. היות ויכולות הרובוט מוגבלות, יש צורך לשלב את הרובוט לתהליכים בחממה במקביל לעובדים. מטרת המחקר הינו הערכת וניתוח הרכבים שונים של שילוב אדם-רובוט לקטיף יעיל תוך שימוש במודל כלכלי עבור השילובים המוצעים.

במהלך המחקר פותח מודל סימולציה למידול פעולות קטיף ידני ורובוטי של פלפלים על סמך מודל קודם, ה- GWorkS אשר פותח להערכה ושיפור הפעולות לוגיסטיות בחממות לגידול ורדים בהולנד. מודל הסימולציה שפותח בתזה יושם בסביבת Simulink ו-SimEvents של Matlab. אימות ותיקוף המודל בוצע מול נתוני הקטיף הידני בפועל מחממה בהולנד עם ממוצע של 92% דיוק של זמן קטיף ממוצע בשביל. באמצעות מודל הסימולציה, הרכבים שונים של עובדים ורובוטים נבחנו לביצוע הקטיף של עונה שלמה, ראשית בגודל חממה קבוע של 43 דונם עם יכולות רובוט בסיסיות (זיהוי של 70%, הצלחה בקטיף 100% ותאוצת זרוע של 0.2 מטר לשנייה בריבוע) ולאחר מכן עם גדלי חממות שונות, כמויות פלפלים קיצוניות ויכולות רובוט משתנות על מנת להעריך כדאיות של שינויים עתידיים במבנה החממה, בהרכב הכדאי של המשאבים לעונת הקטיף ובשיטות העבודה הננקטות.

ניתוח כלכלי של כל הפתרונות המשלבים עבודת אדם ורובוט בוצע באמצעות מודל שנבנה בהתבסס על המתודולוגיה של פרויקט EU קודם (CROPS Ref: C0399), שכולל השוואה של העלות השנתית בין כל פתרון של שילוב רובוט-אדם לבין קטיף ע"י אדם בלבד.

התוצאות הראו כי עבור חממה בגול 43 דונם, בשילוב רובוט עם יכולות בסיסיות (זיהוי של 70%, הצלחה בקטיף 100% ותאוצת זרוע של 0.2 מטר לשנייה בריבוע), פתרונות של שילוב אדם ורובוט כוללות בין 3-6 עובדים עם 4-1 רובוטים בהתאמה. המחיר המקסימאלי שמשתלם לשלם עבור כל רובוט מסוג זה הינו €53,880. כאשר יכולות הרובוט משתפרות ליכולות זיהוי של 90% ותאוצת זרוע של 1 מטר לשנייה בריבוע, המחיר יכול לגדול ל€79,866. לפי התוצאות, השיפור הכי משמעותי שניתן להשיג (כאשר ההצלחה בקטיף של הרובוט מוגדרת 100%), הינו קיצור זמני הקטיף (הגדלת תאוצת הזרוע) שיפור שיכול להגדיל את המחיר המקסימלי לתשלום על רובוט ב€12,900.

מילות מפתח: שיטות עבודה בחקלאות, ניתוח נתונים, סימולציה, קטיף פלפל, רובוט לקטיף, שיתוף פעולה אדם-רובוט, ניתוח כלכלי.

אוניברסיטת בן גוריון בנגב

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המחלקה להנדסת תעשייה וניהול

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חיבור זה מהווה חלק מהדרישות לקבלת תואר מגיסטר בהנדסה

מאת: זוהר מלמד (אלקובי)

יוני 2016

מנחים: פרופ' יעל אידן, Dr. Bert van ’t Ooster

מחבר	____________	תאריך	____________
מנחה	____________	תאריך	____________
מנחה	____________	תאריך	____________
יו"ר ועדת תואר שני מחלקתית	____________	תאריך	____________

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