Developing flexible automation for mushroom harvesting (*Agaricus bisporus*)

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Innovation Report

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ABSTRACT

A framework for analysing crop processes and their suitability to automation was developed in order to address the challenges of labour costs and skills availability that UK growers face. Harvesting was found to be the function of greatest potential labour resource savings. The framework compared those crops with the highest Home Production Marketed value, in terms of target detection, target removal, seasonality and environmental factors. Agaricus bisporus (common mushroom) was the crop that was identified as the best candidate for automation.

Therefore a laboratory demonstration of a robot arm was designed and developed and experiments conducted showed that the cycle time to pick and place three mushrooms was 20 seconds (compared to a typical human pick rate of 12 seconds (HDC 1996)). The model could in theory, be operated 24 hours a day, giving a picking strategy advantage over a current single day-shift operation. The pick efficiency rate (i.e. success rate) was found to be 69% and if all biological factors are eliminated (e.g. elimination of air conditioning which dried out compost and fruiting bodies), the results suggest a 92% pick success rate is theoretically feasible using the model within optimum environmental conditions. Additionally, 85% of these mushrooms successfully picked had no bruising damage; this results in an overall 78.2% success rate, or 21.8% scrap rate, compared to a 5-10% scrap rate produced by human pickers (Noble 2004), (Komatsu 2005), (Howard 2007).

The performance of the robotic harvester was tested within a simulated commercial environment using a discrete event simulation of a UK farm. Results of experiments conducted to compare the performance of a robotic harvesting operation to the current labour intensive operation show that the system would require between 31 and 34 robot harvesters to replace the current 28 humans.

The initial investment cost for the proposed fully automated harvesting and growing system, using an Automated Storage and Retrieval System, for the UK farm was found to be from £3.56-3.71m. The payback period for the replacement of the 28 Flexible Full Time Harvesters currently employed was found to be 8 years. The Internal Rate of Return (IRR) was found to be 4%. If the existing growing sheds and tray transport system at the UK farm was kept in service and just the automated harvesting unit was employed, the payback period reduced to 5.5 years and the IRR was found to be 10.5%.

The financial analysis provides unimpressive results; however, limitations of these traditional financial appraisal methods were identified from this work. The non-financial benefits provide a more compelling reason to go ahead with the proposed solution as the persistent labour supply and direct labour cost issues are currently forcing the UK growers out of business.

This work provides growers with a reliable automated harvesting solution and the ability to determine the suitability of its application within their own operations.

DECLARATION

The work presented in this document is submitted as part of my Engineering Doctorate Portfolio. Except where acknowledged it is my own work. This work has not been previously submitted for any other award.

ACKNOWLEDGEMENTS

I wish to acknowledge the support and guidance given to me over my period of study by my academic supervisor Professor Ken Young, Warwick Manufacturing Group, University of Warwick; and from the Horticultural Development Company staff and the members of the Mushroom Panel.

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LIST OF ABBREVIATIONS

ASRS	Automated Storage and Retrieval System
DEFRA	UK Government, Department for Environment, Food and Rural Affairs
DES	Discrete Event Simulation
ENGD	Engineering Doctorate
FOV	Field Of View
HDC	Horticultural Development Company
HPM	Home Production Marketed
OEM	Original Equipment Manufacturer
WHRI	Warwick Horticulture Research International, University of Warwick
WMG	Warwick Manufacturing Group, University of Warwick

CHAPTER 1
INTRODUCTION

1.1 PROJECT SCOPE

The Horticultural Development Company (HDC) has identified a need for research and development in the use of automation to save labour. They decided to do this through the Engineering Doctorate (EngD) programme, to help UK growers remain competitive.

The scope of the project therefore fits within the crops that HDC is concerned with. A large part of their focus is on fruit and vegetables. Therefore although the scope of horticulture covers the culturing, utilising and improving of fruit and nut (pomology), vegetable (olericulture), flowering and ornamental plants (ornamental horticulture) and turf, the scope of this work is limited to fruit and vegetables.

The objective of this work was to identify a significant problem growers have and to investigate and develop potential commercial solutions to address the problem.

1.2 CHALLENGES FOR THE HORTICULTURE SECTOR

1.2.1 Retail supply chain

UK fruit and vegetable growers are predominantly operating within supermarket, or multiple retail supply-chains, that currently control over 70% of the market value (Fenlon 2004). The supermarket supply chain has taken over the more traditional channels to market for growers (e.g. from a more diverse range including cooperatives and wholesale markets). The trend has proved challenging to domestic growers for the following reasons:

1. Supermarkets are better adapted to scheduling and obtaining economies of scale within their procurement function and consequently transport food commodity items from all over the world at a cost low enough to place competitive pressure on domestic supply.

2. Franks and Farrar (1999) note that the proportion of retail price captured by the grower at farm-gate has declined since 1987. The Farmer Survey (Friends of the Earth 2006) found that 35% of farmers surveyed received the same as or less than the cost of production for their produce, 39% said that their dealings with supermarkets were having a negative financial impact on their business and supermarket trading practices had forced 29% of all farmers to put investments and innovations on hold.

1.2.2 Foreign imports

In recent times the strengthening of Sterling between 1995 and 2007 has meant that domestic retailers were finding competitive advantage through the sourcing of imported goods and have no particular loyalty to domestic suppliers.

Growers have seen their competitive margins eroded because of the competition from the EU through the retail supply chains. In terms of Home Production Marketed (HPM) as a percentage of total supply to the UK, there has been a general declining trend since 1994 (DEFRA 2006).

1.2.3 Labour cost

In an attempt to maintain a profit from decreasing farm gate prices, growers have reduced a number of costs including: raw material (through higher yield attainment), energy (through computerised climate control); however labour costs have increased significantly.

Labour is a major requirement for the UK horticulture supply chain, particularly as many upstream processes still remain labour intensive. The contribution of labour to overall production costs for growers is generally at least 40%, (Napier *et al* 2005), (HDC 2006).

There is a minimum wage that must be paid to agricultural workers in the UK of £5.74 per hour for those workers with no agricultural qualifications at an initial level (DEFRA 2008a). This is traditionally high compared to many countries that have recently joined the European Union that have growers who are competing within the same supply chains as domestic growers.

1.2.4 Labour skills availability

Falling levels of employment in the sector has occurred generally with a slight increase in salaried managers (DEFRA 2007). Within the domestic skills base there has been a general long term trend of movement away from rural areas towards urban areas and urban-based jobs.

This trend has resulted in a shortage of indigenous agricultural labour and there is therefore a high dependency on migrant foreign labour as a seasonal or casual labour supply for UK growers. However, as standards of living rise across developing European and other countries, this supply of migrant labour is reducing as it moves to other countries and sectors: the labour supply agency Concordia reports a trend away from agriculture amongst potential workers from the A8 countries (e.g. Czech Republic, Estonia, Latvia, Lithuania, Slovenia, Slovakia, Poland, and Hungary), with the predicted result: UK growers not getting the workforce they require, the impact on agriculture being significant. They also see a similar trend from the A2 countries (e.g. Romania and Bulgaria). Improvement in wages in Latvia for example now means that many workers are deciding to stay at home to work instead (Orme 2007).

1.2.5 Implementing automation in horticulture

Automation has the potential of improving the quality of fresh produce, lowering production costs and reducing the requirement for manual labour, (Edan 1999). Therefore automation may provide a solution to the aforementioned issues of labour costs and skills availability, thus improving the competitiveness of domestic growers operating within the global retail supply chains.

Although many automated solutions exist in a research form, commercial application in such complex environments as found in horticulture is more difficult (Kassler 2001).

For commercialisation to occur, the automated solution must be cost effective. To achieve cost effectiveness the solution will require a reasonable payback period on investment, which will depend on the efficiency, the cost of the solution and the period of use. The efficiency and cost will depend on the task complexity and the work environment; the period of use will depend on the seasonality of the crop. Also, in order to attract OEMs to producing a solution there will be a need for a large grower base to make research and development costs viable; in this respect the focus of this work is on those crops, as shown in Figure 1, with the consistently highest value HPM from 1997 to 2006.

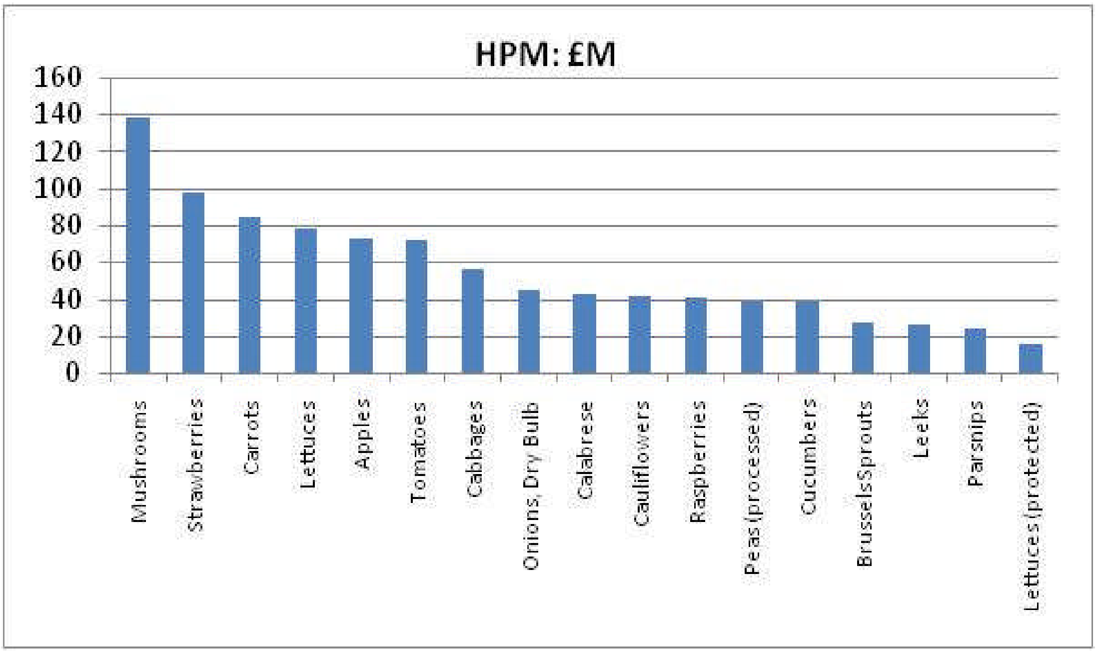

Figure 1: Comparison of crops with the largest mean HPM values from 1997-2006, (DEFRA 2008b).

1.3 MOTIVATION, PROJECT OBJECTIVES AND METHODOLOGY

1.3.1 Motivation and project objectives

Motivation was derived from a preliminary study conducted early on in the project that used informal interviews with growers and a literature review to establish the issues they had. The two most significant issues were found to be labour costs and skills availability, particularly within the harvesting function. They were found to be having a significant negative impact on the competitiveness of UK growers within a newly expanded European Union.

The study, documented in Napier *et al* (2005), included a review of crop characteristics, which was subsequently developed into a framework to compare crop types and prioritise a list of research activities suitable to the EngD programme. The result was that one crop was the most convincing candidate for research: mushrooms. Therefore the objectives of this project were: to design and develop a laboratory demonstration of a robot arm for harvesting Agaricus bisporus; to test the harvester for performance levels and compare these to current UK farm requirements; to provide understanding of how the harvester could be developed from research to commercial form; to test the harvester under commercial conditions; and to establish the business case for capital investment.

1.3.2 Methodology

During this research an initial literature review of horticultural crops was conducted. The data captured was used within a framework to assess crop characteristics, their individual growing and harvesting processes and their suitability to automation.

An automation project was subsequently carried out using a robot arm, which was available for use at Warwick Manufacturing Group (WMG), in order to address the issues that growers had in terms of labour costs and skills availability. The project was an experimental approach to ascertaining the capability of flexible automation using a fully functional laboratory demonstration of a robot arm for harvesting mushrooms. The automation platform was developed at WMG as a proof of concept prototype so that its performance could be measured in terms of cycle time and pick efficiency, without the need for direct experimentation within a grower's process or the requirement for capital investment by a grower in the project. The cost of components would indicate the cost of a commercial solution for growers.

An experimental approach to ascertaining the commercial applicability of the prototype was subsequently conducted using a discrete event simulation (DES) of a commercial automated mushroom harvesting system. The results of the laboratory demonstration were used as inputs to the simulation; additional inputs for the simulation were obtained from primary data gathering exercises conducted at two UK growers for process flows and growing and harvesting data. The results obtained from one farm were used to validate those results used within the DES from the other farm (for reasons of commercial sensitivity this second farm will be documented as *The Farm*). A sensitivity analysis was conducted using different levels of input factors within the simulation to obtain outputs. The outputs indicated the required level of primary and support equipment resource for a UK mushroom grower and therefore provided the input data for a financial analysis of a proposed fully automated mushroom farm.

1.4 PORTFOLIO STRUCTURE

The structure of this portfolio is based on five submissions, as shown in Figure 2.

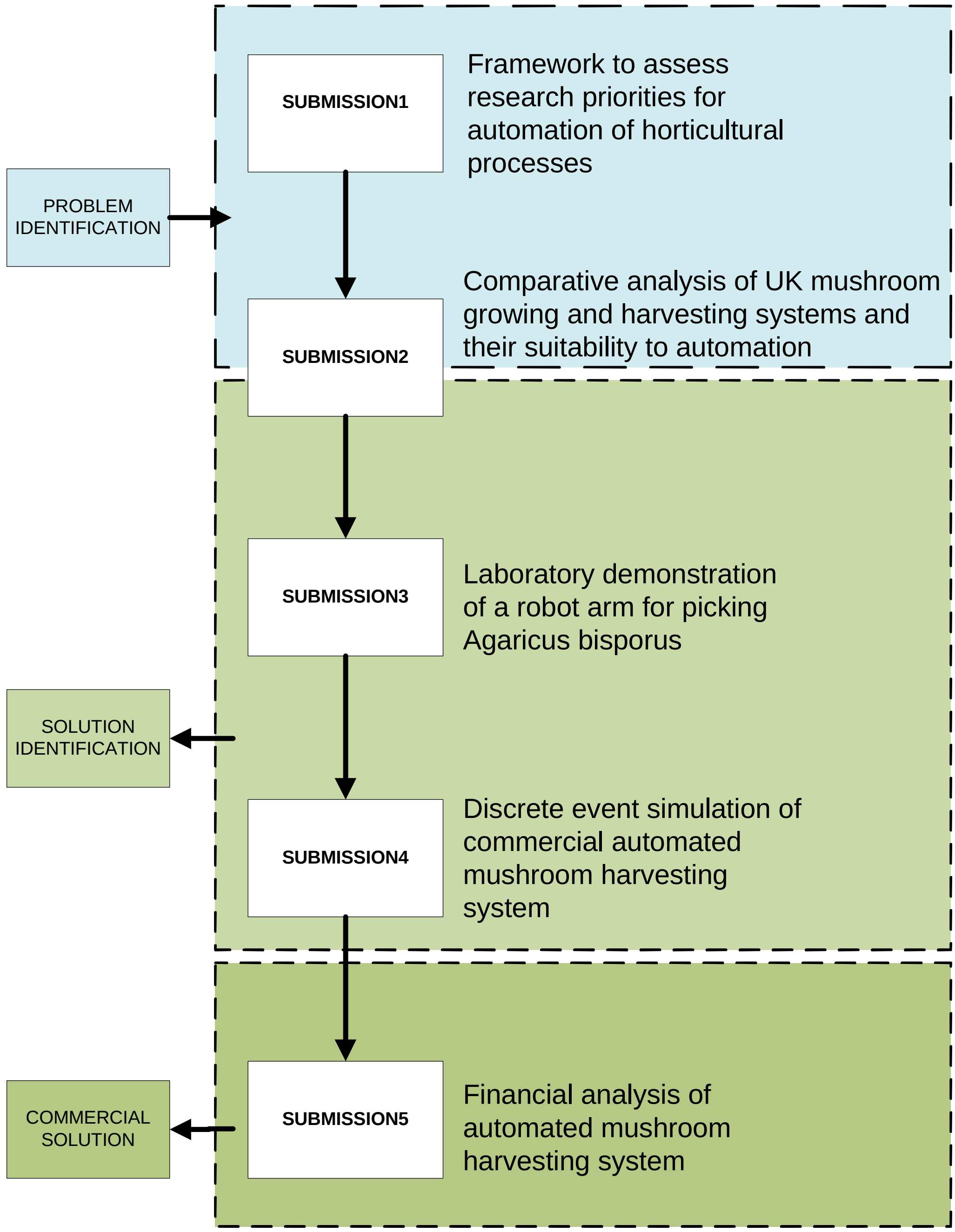

Figure 2: Portfolio structure

Submission 1 - A framework to assess research priorities for automation of horticultural processes

The first submission documents a literature review of horticultural crops and automated solutions for those crops. A comparison of research opportunities for the automation of horticultural processes for each crop type is made through the development and use of an assessment framework. From this a set of research priorities, suitable for the Engineering Doctorate Programme, has been compiled in order to identify the greatest benefits in labour saving through the application of automation within growers' operations.

Submission 2 - A comparative analysis of UK mushroom growing and harvesting systems and their suitability to automation

The different production systems for growing and harvesting mushrooms are analysed and compared in this submission, in order to provide data to assess the potential for the adoption of automation within the harvesting phase by UK growers, as a means to:

1. Maintaining competitive advantage through process efficiency gains and the reduction of direct labour costs.
2. Making an informed choice of how best to design an automated system.

Submission 3 – A laboratory demonstration of a robot arm for picking *Agaricus bisporus* for the fresh retail market

This work documents the research, design, development and implementation of a laboratory demonstration of a robot arm. A description of the experiments conducted to test for pick efficiency, cycle times and damage to mushrooms, using the integrated harvesting system is documented. The performance results are also included.

Submission 4 – A discrete event simulation of a commercial automated mushroom harvesting system.

This work documents the research, design, development and use of a discrete event simulation of a commercial automated mushroom harvesting system. The results of the project provide indication of the commercial applicability of the prototype harvester described in Submission 3.

Submission 5 – A financial analysis of an automated mushroom harvesting system

The results provided by Submission 3 and 4 are summarised and presented within a financial analysis for an automated harvesting solution for a UK mushroom grower.

CHAPTER 2
A REVIEW OF DEVELOPMENTS IN AUTOMATED SOLUTIONS FOR HORTICULTURE

2.1 CROP GROWING AND HARVESTING PROCESSES

In order to develop a successful commercial automated solution in horticulture it must fit within a combination of interrelated processes for each crop type.

UK horticulture comprises a large range of unique crop types, grown in fields and protected facilities. Their life cycles can be classified into four categories: seed (and spawn) production, crop establishment (e.g. sowing, transplanting), crop growing (e.g. crop walking for inspection, pest/disease/weed control, scheduling, irrigation, pruning) and harvesting (identifying, selecting and gathering of target). This process is summarised in Figure 3. Downstream activities may include storage, grading, weighing, washing and packing.

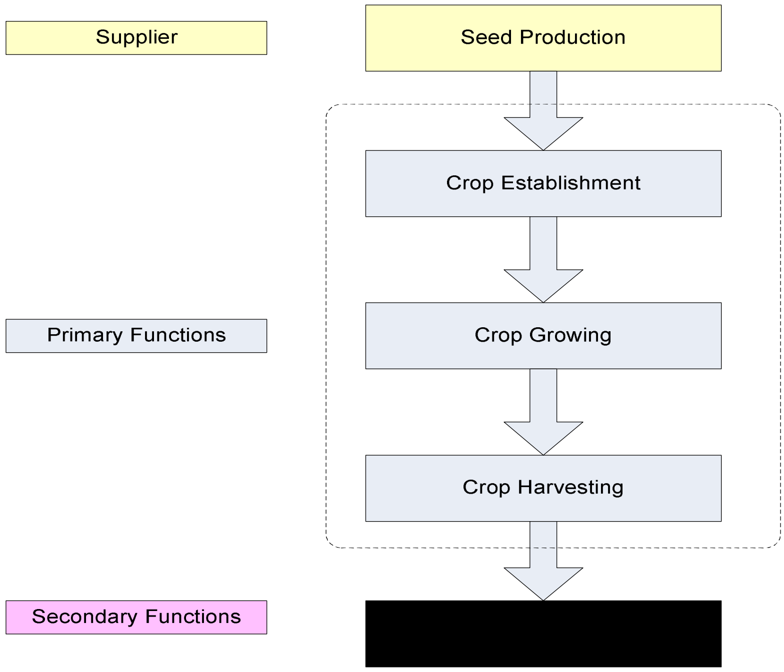

Figure 3: Growing cycle of crops

Uniformity of crops is important for a reduction in complexity of automation in all processes discussed subsequently in this section, and is enabled through appropriate genotype, seed quality, seedling establishment and growth control.

2.1.1 Seed production

Seeds may be procured from specialist suppliers or produced by the grower.

The quality of seeds produced, particularly for facilitating automated downstream processes, depends on precise germination to enable a reduction in variance in establishment and growth performance.

2.1.2 Crop establishment

Crop establishment tasks include sowing, addressing and gap filling, blocking, potting and spacing. Efficiency of downstream processes (e.g. growing, harvesting) are facilitated by uniformity of crops, enabled at the plant establishment phase. Uniformity allows a reduction in the complexity of automated tasks, by facilitating scheduling and prediction of harvest and reducing the need for repeat harvest or waste of plants remaining in the growing medium. Specialist growers exist in some sectors (e.g. hardy nursery stock, ornamentals, and brassicas) to fulfil this objective by selling plug plants to growers which are sown, germinated and raised in compost blocks or modules.

If seeds are sown directly into the field, seed mats provide protection, support, weed control, water saving mulch and pest and disease reduction for seedlings during establishment.

If plug plants are procured, once they are established and ready to continue growing on for market, they must be transplanted from their existing growing medium to pots, or the field.

2.1.3 Crop growing

As the plant grows, further improvements to the plant structure are possible through regulation of the environmental conditions (e.g. supplementary heating and lighting, plant spacing and weed control).

Pruning is carried out to control and improve performance and quality and is key for clonal propagation, this task is usually conducted by a skilled practitioner.

Plastic netting is used commercially to protect against root flies and leaf consuming caterpillars; the netting is placed over the crop immediately after seed sowing and gathered up before the harvesting phase.

The monitoring of plant growth and ambient conditions is critical and this is usually conducted by a senior, skilled participant, while crop walking.

2.1.4 Crop harvesting

Harvesting techniques vary considerably from crop to crop and for individual growers. The basis of the process involves the identification, selection, gathering and placement of the seed, fruit, flower, head, root, leaves or any other part of the plant and in some cases the plant as a whole.

Some crops require one-off harvesting, such as carrots and peas; methods are generally non-selective in these cases. Some crops must be repeat harvested, such as mushrooms, strawberries and cauliflowers for the fresh market; in these cases selective target discrimination is vital otherwise there will be wastage from premature action to unripe or unready crops. The level of task complexity tends to increase with these crop characteristics: a decision must be made regarding the quality (e.g. size and colour) of the target – to subsequently pass (select) or fail (reject) it; harvesters must avoid damaging adjacent objects within the local environment, including mother plants and the growing medium.

Seasonality of individual crops varies considerably and dictates the frequency and length of the harvesting period.

2.2 APPLICATION OF AUTOMATION IN HORTICULTURE

2.2.1 Seed production

Seeds production is generally outsourced to specialist suppliers and in this case is therefore not considered a core function for most fruit and vegetable growers.

2.2.2 Crop establishment

Automated solutions are used extensively in this sector to achieve the high levels of product uniformity required. Dedicated growers sell plug plants to plant suppliers which are sown, germinated and usually raised in compost modules. These automated processes rely on large-scale commercial solutions for sowing, addressing and gap filling, blocking, potting and spacing. Solutions for smaller scale in-house operations are also available to plant suppliers. Generally, these processes are well suited to automation as they are relatively simple and the environmental conditions are usually indoors and controlled. The automated solutions available include tray and pot fillers (i.e. solutions for filling trays and pots with growing media), seeders (i.e. solutions for placement of seed into growing media), transplanters (i.e. solutions for transplanting seedlings into growing media) and a variety of automated storage and retrieval systems within the process.

2.2.3 Crop growing

There are commercial solutions available for most activities within the growing process including irrigation, pruning and some forms of weed control, as documented in Submission 1. However one activity that has not seen commercial application of automated solutions is the monitoring of crop development.

There are prototype remote data collection devices and mobile field robots at a research stage of development that are theoretically capable of doing many of the tasks needed during the growing phase, however the criticality of requiring correct decisions to the grower's business may limit the uptake of high levels of automation because of a lack of trust, rather than the costs of the technologies, currently.

2.2.4 Crop harvesting

Of those crops identified in Submission 1 as having the largest HPM values, harvesting tasks for some (e.g. peas) have been automated for centuries, but for others (e.g. selectively harvested raspberries, cauliflowers and mushrooms) no commercial solutions exist yet. The application of automation with the harvesting process will be discussed in more detail in the next section.

As harvesting techniques vary considerably from crop to crop and for individual growers this limits the generic application of automation and therefore the attractiveness of development of solutions.

There are generic technologies available for many tasks and for several crop types, including vehicle platforms, industrial robot arms, sensors and actuators. It is the end effector (i.e. gripper) that is usually crop specific, although in the case of cauliflowers the target identification and selection activity is so complex that it has so far precluded any practical method of automation.

The harvesting tasks that need to be incorporated into each automated process, for each crop type, can be classified into the following categories: target detection, target removal. Figure 4 includes the various factors that may affect the level of complexity and cost required to automate both categories. These factors will be discussed in detail in the following sections.

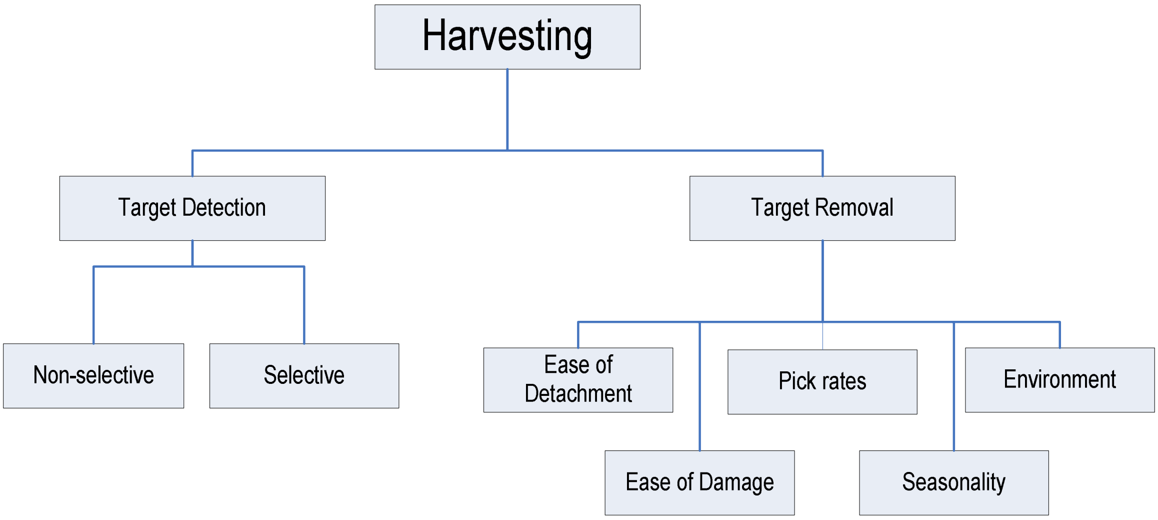

Figure 4: Classification of factors affecting harvesting tasks

2.2.4.1 Target detection

The complexity of the automation required for detecting the target depends on whether it is to be selectively harvested, or not.

If non-selective harvesting is to be conducted, the level of sensory feedback may not need to be sophisticated. In the case of field vegetables there may be prior knowledge of the plants' locations, particularly if they were transplanted mechanically, equidistant and in rows. Therefore if there is consistency in the growth rates and position of each plant, harvesting may be conducted in a single pass and indiscriminately. Some form of localised positioning may be required, such as a tactile sensor or non tactile sensor (e.g. GPS or laser distancing device). Inspection and grading of these targets would be conducted at a subsequent stage of the entire process – either in the field or within a pack house. Therefore, non-selective harvesting usually implies one-off picking sweeps that clear the growing area of all targets and residue, whereby residue is discarded at a later stage in the process.

If selective harvesting is to be conducted, the complexity of the process usually increases. The sensory input requires data on the unknown location of target, as a discrete value from the residue. Selective harvesting therefore implies consideration of the adjacent environment. Many crops require the target to be detached from a mother plant and therefore each entity on an individual plant must be discrete and recognisable. Many crops also require the target to be of a certain quality; therefore those entities considered outside of the prearranged parameters are discounted and left in situ until they are of the required quality (e.g. size and colour). Therefore selective harvesting may also imply multiple harvesting of a crop.

The characteristic of tomatoes for example is that, like mushrooms, the fruiting bodies are of distinctly unique, precise and repeatable colours from the residue, therefore colour vision systems may be used to select the target and obtain location data; greyscale vision systems would also be sufficient for mushrooms. In the case of cucumbers, the targets are of distinctly unique and repeatable shapes from the residue and therefore grey scale vision systems using shape or template matching recognition tools may be more appropriate to gain target location data. In both cases however the vision system will be required to gain data on the targets' size in order to determine whether it is a target or at a 'pre-target' stage and therefore still regarded as residue.

In the case of some field vegetables, vision systems combined with line tracking algorithms may gain data on the location of the rows of the possible targets.

In the case of field vegetables with an obscured target (e.g. from foliage) the task is particularly complex. For example, leaves may have to be physically moved away from the target to gain fuller data on shape and size; environmental conditions may cause the target to move from its identified position. Also, the ambient lighting conditions will be variable. The complexity in automating these tasks is at the higher end of the scale.

Alternative technology has been used in research that does not rely on visual sensors (e.g. X-ray, ultrasonic, thermal imaging). However the cost and practical factors have limited the commercial attractiveness in most cases (e.g. for cauliflowers and apples). For crops where target detection success rates are relatively low, it has been proposed that collaboration of a human operator and a robot may increase detection rates significantly compared to a fully autonomous system (Bechar and Edan 2003).

2.2.4.2 Target removal

The following criteria are used to classify targets' characteristics in their removal from the growing environment: Ease of detachment, Ease of damage, Pick rates, Seasonality and Environmental factors.

a) Ease of detachment - detachment methods differ widely for individual crop types. As a general rule, for those targets that require selective harvesting the method of detachment will require more complexity than for those that do not. Some, including the root vegetables, onions and leeks, can simply be lifted from the ground, whereas others such as cucumbers, tomatoes and fruit crops must be individually selected and carefully detached from the mother plant.

b) Ease of damage - the individual handling requirements of crops being harvested will be determined by their - or the surrounding residue's - susceptibility to damage, either from the process of removal or the subsequent process of placement. Bruising and other damage may occur as a result, however ultimately, it is the quality requirements that will determine the suitability of the method.

The fruit or vegetable is considered compliant or non-rigid where deformations are produced during handling and Erzincanli and Sharp (1997), identify the need for a new range of end effectors suitable for handling non-rigid products in the food industry, incorporating minimised deformation and maximum hygiene. They note that humans handle these types of materials by combining information from the 'inbuilt' product behavioural models together with data from sensory mechanisms, including sight and touch. They also refer to several research projects involving end effectors for handling fruit and vegetables, including one designed with fingers covered with a 20mm thick layer of expanded PVC which conforms to the shape of the target, thus avoiding high-contact pressures. Whilst there is generic applicability inherent in this design, the majority of horticultural research outputs have tended to be crop specific to date. The ease of detachment and ease of damage factors will affect the complexity of the solution and therefore its cost.

c) Pick rates - the frequency of picking will determine the cycle time (pick rate), and therefore is a contributing factor to the payback on investment that may be achieved. In the case of crop types that are easily damaged, the task of handling the target must account for dynamic stresses on the target from acceleration and velocity, the time the target is handled and the potential for impact on the target. For those crops that are difficult to detach, pick rates will be relatively low.

d) Seasonality - the use of specific solutions is linked to the growing cycle of the crop, therefore if a crop has no seasonal patterns the automated harvesters may be used on a constant basis. In the case of those targets that are seasonal, the period of use is limited relative to individual cropping cycles; those crops with a longer harvesting period would tend to suit automation more than those that require a solution to work for a matter of days or a few weeks (e.g. apples); for the rest of the year the equipment is either idle, or must have an ability to be applied in other applications. If the machine is idle this will affect the payback on the solution and therefore its attractiveness to the growers and also the equipment manufacturers (OEMs). Therefore seasonality is a contributing factor to payback on investment.

e) Environmental factors - control of the ambient environmental conditions will also determine the complexity of the automated application. Those environments with limited variability (e.g. controlled indoor environments for protected crops), result in more accurate and precise predictions and therefore the need for flexibility is reduced. In the case of outdoor applications the ground, lighting, temperature, humidity and residue will generally be uncontrollable and stochastic in nature. The requirement for accurate, timely sensory feedback data, in order to adapt to continuously changing conditions is critical. Finally, the harshness of the environment will determine the suitability of automated equipment - and necessary protection for that equipment - that may be applied. Therefore environmental factors contribute to the complexity and cost of the solution.

2.3 IDENTIFICATION OF RESEARCH PRIORITIES.

In order to summarise the findings and compare the crop types by the harvesting task categories outlined in *Section 2.2.4*, a framework described in Submission 1 has been developed, as shown in Figure 5. For each task category a score has been given from 1-3. For example, Cauliflowers have been given a score of 1 (pre-weighting) for Ease of Target Detection, as the task of measuring the size of the target (i.e. the white cauliflower curd), which is generally covered by foliage, is so complex that to date no practical solution has been found. However, for those crops that require non-selective target detection (e.g. root vegetables, onions and leeks) they may be lifted from the ground en-masse without the need for individual target location; therefore these crops have been given a score of 3 (pre-weighting). For a detailed discussion of the individual crop characteristics in relation to process automation please refer to Submission 1.

Also a weighting has been applied to each of the task categories to reflect the relative impact on automation projects. The Economic Value, Existing Automation and Target Detection categories have been given a weighting of 2, the Target Removal categories: Ease of Damage, Ease of Detachment, Pick Rates and Seasonality have been given a weighting of 1 each, Environmental Conditions has been given a weighting of 2. For a detailed discussion of the weighting factors please refer to Submission 1.

When crop types that already have commercial solutions available are eliminated from the analysis (i.e. those crops in shaded background in Figure 5), mushrooms score the highest, followed by cauliflowers, tomatoes and apples. Calabrese, cucumbers, strawberries and raspberries score relatively low.

Economic Value	High 3	Medium 2	Low 1
Existing Automation	None 3	Research 2	Commercial 1
Ease of Target Detection	High 3	Medium 2	Low 1
Ease of Damage	Low 3	Medium 2	High 1
Ease of Detachment	High 3	Medium 2	Low 1
Pick Rates	High 3	Medium 2	Low 1
Seasonality	All year 3	Medium 2	Low 1
Environmental conditions	Controlled 3	Medium 2	Harsh 1

Weighting Factor	**2**	**2**	**2**	**1**	**1**	**1**	**1**	**2**	
Crop	Economic Value	Existing Automation	Ease of Target Detection	Ease of Damage	Ease of Detatchment	Pick Rates	Seasonality	Environmental Conditions	**Total**
Apples	6	4	4	3	2	1	1	2	**23**
Brussels Sprouts	2	2	6	3	3	3	2	2	**23**
Cabbages (All)	6	2	6	3	3	2	3	2	**27**
Calabrese	4	2	4	2	2	2	2	2	**20**
Carrots	6	2	6	3	3	3	1	2	**26**
Cauliflowers	4	4	2	3	3	3	3	2	**24**
Cucumbers	4	4	4	1	1	1	2	4	**21**
Leeks	2	2	6	2	2	2	2	2	**20**
Lettuces	6	2	6	2	3	2	3	2	**26**
Mushrooms	6	4	4	1	2	1	3	6	**27**
Onions (dry bulb)	4	2	6	3	3	3	1	2	**24**
Parsnips	4	2	6	3	3	3	1	2	**24**
Peas (green)	4	2	6	3	3	3	2	2	**25**
Raspberries	4	6	4	1	1	1	1	2	**20**
Strawberries	6	4	4	1	1	1	1	2	**20**
Tomatoes (All)	6	4	4	1	1	1	2	4	**23**

Figure 5: Analysis of harvesting task categories for crop type

Therefore from Figure 5, Mushrooms score the highest of the crop types overall and are considered the best candidate for research development. No commercial automated harvesting solutions exist yet, but research has shown the task is possible, if the development, production and implementation costs can be minimised. Target detection can be achieved relatively simply, using machine vision. Protection of equipment is less of an issue in a controlled environment, reducing the development costs. In some mushroom farms (e.g. tray systems), the crop can be taken to the harvester therefore the complexities of moving and positioning the harvesting equipment are reduced. There are issues regarding ease of damage of the target and the individual pick rates would therefore not be high relative to human picking, however as the harvesting can be continuous, this may not be a major disadvantage.

CHAPTER 3
DEVELOPMENTS IN AUTOMATED SOLUTIONS FOR MUSHROOM HARVESTING

3.1 COMMERCIAL CROP GROWING AND HARVESTING SYSTEMS FOR THE FRESH MARKET

The majority of edible and medicinal mushrooms are cultivated commercially (rather than gathered from the wild); this guarantees proper identification and relatively pure products. Commercial mushroom production is generally conducted intensively in specialised growing buildings with a controllable environment. The complete process of growing *Agaricus bisporus* involves the following operations:

1. Selection of mushroom spores or strains,
2. Maintenance of mycelial cultures,
3. Development of spawn or inoculum,
4. Preparation of growing medium (compost/substrate),
5. Spawn inoculation and colonization of substrate,
6. Crop management for optimum production,
7. Crop harvesting,
8. Sorting, weighing, packing,
9. Transportation.

All commercial growers are faced with the following costs:

1. Fixed assets – land, buildings, environmental equipment, shelving or trays.
2. Labour – maintenance, pickers (time rates, piece rates or bonus pay scheme), crop managers (highly skilled and experienced in order to plan and supervise well), packers.
3. Interest costs – bank loans, overdrafts.
4. Materials and supplies – including fuel, water, compost, spawn, casing soil, supplement and pesticides.
5. Marketing costs – packing materials, transport, commission.
6. General expenses – levy payments (e.g. to the HDC) and insurance costs.

Industry wide surveys of growers have been conducted very infrequently, figures obtained from Hinton (1982) show that the costs of production for England and Wales (as at October 1981) were broken down as shown in Table 1:

Cost	**%**
Materials and fuel	39.7
Labour	35.8
Growing	*23.5*
Picking and packing	*56.9*
Maintenance	*8.2*
Administration	*9.8*
Cleaning	*0.8*
Pensions	*0.8*
Other (haulage, equipment hire, tray repairs)	13.7
Overheads (marketing, administration, depreciation, loan interest)	10.8

Table 1: Cost of production, (Hinton 1982)

By far the largest costs were comprised of *Materials and fuel* and *Labour*. Growing made up 23.5% and Picking/packing made up 56.9% of *Labour* costs. At the time of this survey however there was not the degree of mechanisation inherent with modern packing houses on mushroom farms, which means the labour intensity of packing would have decreased over time in those farms. However, van Roestel (1988) found that labour costs were 45% of the total costs in mushroom farms in 1984 (fresh only, handpicked). These estimates broadly concur with more recent estimates obtained from informal interviews with growers at a workshop entitled: *Mushrooms: Addressing the problems of the mushroom industry in the UK*, held at Warwick Horticulture Research International (WHRI), University of Warwick, in 2004, as discussed in Submission 2.

3.1.1 Composting and crop growing

Unlike other crops considered in Submission 1, mushrooms do not manufacture their own food through the process of photosynthesis; rather, a fungal mycelium secretes enzymes which digest the compost-based substrate, and the result is then absorbed by the mycelium, from which fruiting bodies grow.

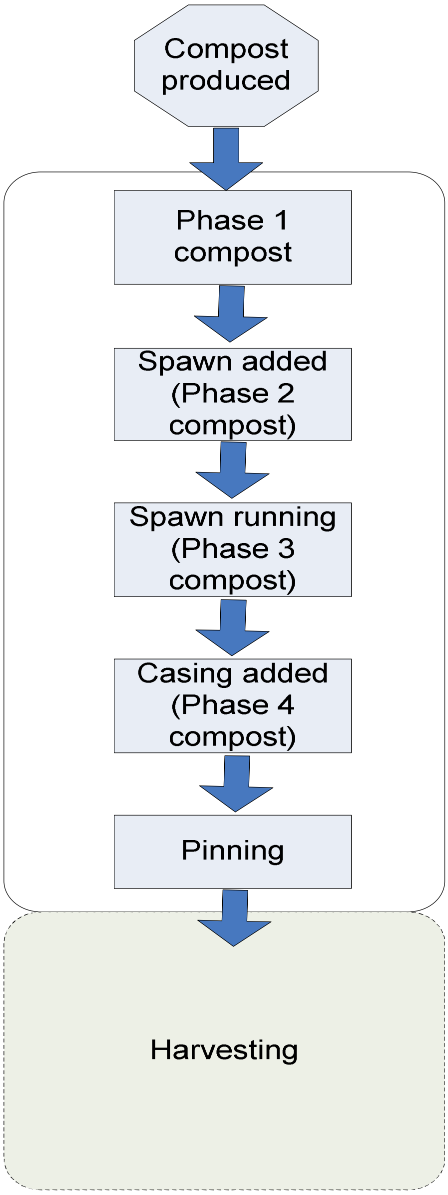

Figure 6: Process flow of mushroom growing

The growing medium starts its lifecycle as compost, made from horse or chicken manure mixed with gypsum and wheat straw, as shown in Figure 6. This compost is usually bought in from specialist composters (some larger growers produce on site). This mixture is then watered and turned regularly to give uniform decomposition and texture throughout, needed for consistent mushroom growth. The turning process usually lasts for 6-8 days – depending on the nature of the straw provided, the ambient temperature, humidity and moisture content, which produces Phase 1 compost.

Phase 1 compost is subsequently peak heated, or pasteurized: this process releases ammonia and transforms it into nitrogen that is used by the mushroom crop and also kills pests and fungal competitors. Peak heating lasts 5-7 days whereby Phase 1 is converted into Phase 2 compost by adding mushroom spawn.

Spawn production is conducted by specialist companies whereby mushroom mycelium is cultured under sterile conditions on grains of moist wheat, rye or millet to produce spores or mushroom spawn. The mushroom grower buys the many different strains of spawn in bags or bottles.

The spawn is generally mixed mechanically into the peak heated Phase 1 compost. Subsequently the temperature is maintained at 24°C and humidity at 98%. Spawn grows through the compost for 14-21 days. The process of converting Phase 2 into Phase 3 compost is completed when it looks similar to Figure 7, whereby it can be seen that the white threads of mycelium have grown within the compost. The compost may be procured at this point, already spawn run by the specialist composters, for a premium mark-up on price.

Figure 7: Phase 3 compost (spawn run)

The Phase 3 compost is subsequently cased, or covered, with a 4cm layer of wet peat and spent lime mix, which is vital in order to stimulate mushroom production (formation of fruiting bodies), thereby producing Phase 4 compost. The ambient temperature is lowered to 20^{o}C and fresh air is introduced; the humidity is lowered to 85-90%. This process usually takes 15-20 days from casing to pinning (the point of growth whereby primordial fungal fruiting bodies start to appear from the mycelium, which has by this time also colonised the casing layer).

Approximately 4-5 days after the pinning stage has commenced (by the introduction of more air), the mushrooms grow to a large enough size to be harvested. It should be noted that the times reported from casing to picking varies from grower to grower, due to growing conditions and harvesting strategies.

Some compost suppliers specialise in the production of compost in trays at the pinning stage, just a couple of days before the first flush.

3.1.1.1 Comparison of growing systems

The compost can be contained in bags, blocks, trays and shelves (refer to Figure 8) which in turn can be placed in specially designed growing houses, sheds, polytunnels and caves.

Figure 8: Mushroom growing systems

The percentage of mushrooms grown in the UK by mushroom growing system types can be seen in Figure 9: shelf and tray farms dominate.

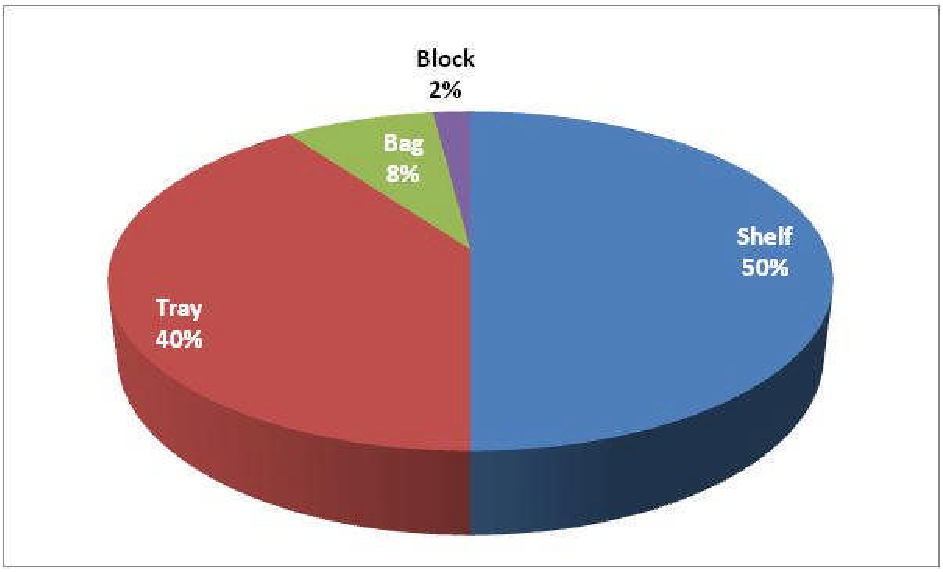

Figure 9: Percentage of mushrooms grown by mushroom growing system (Franks and Farrar 1999)

The tray system generally uses trays of around 4 x 8 ft to contain the compost. Legs on the base corners (as can be seen in Figure 8), allow stacking of trays, air to circulate and space for watering and harvesting when stacked and in production. Full trays are heavy and require lifting aids, also the growing crop requires care when it is transported to avoid damage to the crop and spreading of disease. The early Phase compost may also be treated in a separate area before the trays are moved for the final stages of growth. In this way trays may be more intensively stacked (as they do not need to be accessed at this point) and other sheds are thus freed up for more production.

The shelf system generally contains the compost within metal troughs within shelves, which run the length of the growing shed. The shelves are filled in bulk with compost and casing is applied in the growing room. Alternatively the shelves may be used to contain compost blocks which may be procured already spawn run (i.e. at Phase 3).

3.1.2 Harvesting

Mushrooms grow in a series of flushes, over a 3-4 day period, before all mushrooms are picked. After a period of around a week of further pinning the next flush will begin. This cycle continues after this point with diminishing returns, in terms of yield.

From interviews with growers, in order to minimise pest and disease problems and the reduced yield from later flushes, many only take crops from two flushes before removing the spent compost, cleaning the area and growing another crop.

A significant variable in deciding the flush strategy is the time to wait to harvest the first flush from the next crop, which is most heavily influenced by the phase of compost used to fill the mushroom growing area.

From Table 2 it can be seen that there is much variation throughout the growing and harvesting cycle: from 44 to 61 days, depending on the individual grower. This is reflected in data from Franks and Farrar (1999) that shows the Earliest Start Time to Flush 1 is 46 days and the Latest Start Time is 62 days.

Days	Earliest	Latest
Turning to Phase 1	6	8
Peak heating to Phase 2	5	7
Spawn running to Phase 3	14	21
Casing to pinning	15	20
Pinning to flush	4	5
Total Growing	**44**	**61**
Flush 1	3	4
Pinning	7	10
Flush 2	3	4
Total Growing and Harvesting	**57**	**79**

Table 2: Growing and harvesting cycle (Earliest and Latest days)

The traditional production plan of a UK grower is smooth, aiming for predictable continuity of production and weekly work patterns, depending on the length of the growing and harvesting cycles. Therefore in each week the same proportion of growing sheds are emptied and filled as are producing their various flushes. If this pattern is altered the labour and the growing area and room requirements would alter.

Picking too many mushrooms from an individual tray or shelf area in a single shift also tends to lower the yield of subsequent flushes, so daily picking intensity over the flush must remain smooth. This makes staggering the growth of the fruiting bodies very important so that equal amounts of mushrooms are ready for picking each day of the flush, rather than all mushrooms being ready for picking simultaneously.

If left to grow, mushrooms double in size every 24 hours. Picking mushrooms at an early stage when they are smaller results in a decrease in yield per time taken to pick a mushroom (i.e. it will weigh less), therefore an increase in picking costs and a decrease in production output, which therefore inflates production costs. However, large mushrooms are not the only size required. Care must be taken to pick the correct mushroom in the correct order also: neighbouring mushrooms are picked around the target in order to allow the target mushrooms to grow to the required size; if clusters of mushrooms are left to grow they will deform each other.

The grades of mushrooms in size terms are characterised as shown in Table 3.

Mushroom Category Name	Cap Diameter (mm)
Baby Buttons	20-30
Buttons	25-35
Closed Cups	35-45
Small Open Cups	40-60
Medium Open	50-70
Large Open	65-115
Extra Large Open	110+

Table 3: Mushroom category names by cap diameter, (Shackleford 2006).

In terms of direct labour, time spent picking per shed per flush must be optimised, or efficiency lowers because of the non-value adding activities (e.g. moving or waiting). Pickers need regular work or they cannot be kept as core labour, therefore staggering the crop harvesting is important in this regard also. Pickers need to possess a good degree of skill or they will bruise mushrooms and also create health and safety issues. Pickers work with an uncomfortable posture for much of the day if picking in-situ.

When the compost is ‘spent’ and further flushes are not likely to be large enough in yield, it is generally heat sterilised in its current position (i.e. cooked out) and then distributed as Spent Mushroom Compost (SMC) to other crop growers for spreading on land as a soil improver. The growing houses are also steam cleaned to avoid a build up of pest and disease, whereby they are ready for further growing and flushing cycles.

3.1.2.1 Comparison of harvesting systems

The harvesting system will depend on the growing system used. If mushrooms are grown using the shelf production system they are harvested in-situ (i.e. in the growing shed as shown in Figure 10a). If the tray production system is used mushrooms can be harvested in-situ, or at a centralised picking point somewhere else on the farm (i.e. in a picking parlour as shown in Figure 10b).

a) In-situ harvesting within a shelf system   b) Centralised picking parlour within a tray system

Figure 10: Mushroom harvesting systems

Trays are easier to move than shelves; therefore they facilitate more functionally optimised growing, with specialized areas for composting, treatment, growing and harvesting. In that respect, the environment in the harvesting area may be controlled to suit the automated equipment, unlike in the growing areas where high humidity will require the protection of electronic and vision systems. However, these ambient conditions in the harvesting area may not be favourable to the mushrooms, so a rapid process flow during the time the trays are out of the growing sheds is required before, during and after harvesting if quality is not to be jeopardised; another option is to have a compromise in the harvesting area between the two environmental requirements; or maintain growing conditions within the harvesting area and protect the equipment.

Goosens (1995) supports the argument that centralised picking is a better environment for current, and to be developed, picking machinery; and better quality control; with the option of picking in the growing houses retained as an aid to picking management and as an insurance against equipment breakdown. For example, if a tray has a small number of suitable mushrooms to be picked it may be more effective to pick from the growing rooms, rather than transporting it to the centralised picking area for a few minutes of picking time. The maintenance of the trays is vital otherwise substrate may be lost or mushrooms damaged during the harvesting process.

Downstream activities are also facilitated using centralised tray picking as the handling of mushrooms in pre-packs, trays or individually can be organized and mechanised in a fixed location much more rigorously than from shed to shed, whereby movements are restricted within the shed and at the entrance to the shed.

The advantage of using a shelf system over trays is that the compost substrate can be more easily controlled through mechanisation (i.e. using a ruffling machine to achieve flatter substrate surface level and finer texture) to enable 'straighter' growing mushrooms that may be harvested more easily.

Franks and Farrar (1999) conducted an economic analysis of the production systems and found tray and shelf systems to be comparable although the Net margin and Net farm income values in Table 4 support the argument for using the tray system.

Pence per lb	**Shelf**	**Tray**	**Bag**	**Block**
Net revenue	82.2	81.0	81.1	75.1
Gross margin	60.5	59.3	41.1	42.6
Total costs	71.8	71.0	85.4	74.3
Net margin	5.0	6.3	-11.0	-2.6
Net farm income	5.7	7.9	-8.2	8.8

Table 4: Economic analysis of systems (pence per lb of mushrooms grown), (Franks and Farrar 1999)

3.2 AUTOMATED SOLUTIONS FOR MUSHROOM GROWING AND HARVESTING

The growing tasks have been mostly automated for both tray and shelf farms, including compost preparation, compost filling, compost ruffling (smoothing) and casing. However the task of harvesting the crop has not been automated commercially.

There have been a variety of research projects conducted for selective harvesting (e.g. Reed et al 2001, McKeown 2004). However none have become commercial solutions. From informal interviews with growers the main reasons for this seem to be:

1. There was a perception of inconsistency in picking performance, from one day to the next.
2. There was a perception of inconsistency in quality.
3. There were many stories quoted about how the Dutch growers for the fresh market have had failures in regards to Automated Storage and Retrieval Systems (ASRS) and other automated processes, combined with the fact that the Dutch are not using automated picking in this sector when they are usually receptive to such equipment.
4. There was a general climate of risk averseness in the industry.
5. There was until recently a healthy economic climate (in regards to returns and migrant labour supply) and growers became complacent.

For any solution to become a commercial success it therefore needs to overcome these perceptions from the growers.

A harvesting solution using flexible, proven, generic technologies would be cheaper to develop, implement and maintain than proprietary equipment, whist enabling more consistency in performance. The centralised picking option within a tray production system would facilitate this option, as the harvesters may be located in a fixed position within a more controlled environment than if they were moved around the growing sheds.

CHAPTER 4
DEVELOPING FLEXIBLE AUTOMATION FOR MUSHROOM HARVESTING

4.1 OVERVIEW

Two projects were conducted during this research. These were the laboratory demonstration of a robot arm for harvesting mushrooms and the discrete event simulation of an automated mushroom farm.

The following section presents the description of these projects, their design process, the results obtained through their use and their applicability to the sponsoring companies (through the HDC).

4.2 A LABORATORY DEMONSTRATION OF A ROBOT ARM FOR HARVESTING MUSHROOMS

The laboratory demonstration of a robot arm used a fully integrated robotic harvesting system, comprising flexible industrial components, for tray production systems operated by UK mushroom growers.

4.2.1 Project need

In order to convince the growers that there is a realistic opportunity for gaining extra profit through direct labour cost savings, a laboratory harvesting demonstrator has been developed and experiments conducted, using component technology that is mature and proven in other industry sectors that require reliability and precision: thus limiting inconsistency of performance. The cost of flexible off-the-shelf components - more suited to centralised harvesting of trays from a fixed position - is less than the proprietary form of the previous solutions; support is more readily available in terms of maintenance and technical help from the equipment manufacturers and suppliers; programming skills and engineering expertise is less of a requirement.

Experiments using the laboratory harvesting demonstrator were conducted to test for performance levels and compare these to current UK farm requirements.

The experiments were also conducted to provide understanding of how the harvester could develop from a research project into a commercial solution, in terms of component costs, costs of adapting the solution to a commercial farm system and likely support equipment costs (e.g. required number of trays, environmental protection for automated equipment).

4.2.2 System requirements

In order to emulate the performance of a human mushroom harvester, using automation, it is important to understand what are the tasks performed. They can be broadly categorised into the following task requirement list:

1. Target identification and selection
    a) Obtain an image of the growing area

b) Identify mushrooms on the growing medium and their position

c) Identify mushrooms' cap diameters and estimate their size from this

d) Identify mushrooms' proximity to other mushrooms and the tray sides

e) Select target(s) to pick, based on desired size and relative ease of removal

2. Removal of targets

   a) Make contact with mushroom cap and grip it

   b) Move cap away from neighbouring mushrooms

   c) Twist mushroom cap to release from compost substrate

   d) Pull in an upwards motion

3. Trimming, weighing and sorting of mushrooms into containers (as found from Submission 2, this may be achieved by the placement of target into a receptacle whereby the stipes are trimmed and mushrooms weighed and sorted downstream of the harvesting process; there are commercial solutions available).

In order to achieve the same performance as a human picker, the general system requirements are as follows:

1. Mushrooms will be harvested from trays. Tray sizes are different for each farm, therefore for logistics purposes (i.e. moving full trays of mushrooms grown at

WHRI to the laboratory at WMG) the tray growing area will be 600mm x 400mm.

2. The system must be capable of picking target mushrooms with cap diameters of between 35-60mm, to reflect high value Closed and Open Cup mushrooms; the system must be capable of discerning between the two general category sizes.

3. Currently a typical picking cycle consists of picking three mushrooms, cutting the stipes (i.e. stalks) and placing them into a receptacle in approximately 12 seconds by a human harvester (HDC 1996), the solution must be capable of achieving equivalent cycle times.

4. Scrap rates (i.e. mushrooms that have had portions of the cap or stipe removed, or have been bruised in a way that does not meet quality standards) are 5-10% (Noble 2004), (Komatsu 2005), (Howard 2007). The solution must achieve or exceed current standards.

4.2.3 System description

4.2.3.1 Target identification and selection

The identification and selection of target mushrooms in the Cartesian X-Y axis is performed using a machine vision system, running Cognex Intellect software, to communicate to the robot controller (for a complete description of the vision system, its different components and its operation, please refer to Submission 3 of the portfolio).

Once the target has been identified and selected by the vision system a laser sensor is positioned by the robot directly over the target mushroom cap, at a constant height, within the range of the laser. The sensor operates according to the triangulation principle: a laser diode projects a visible point of light onto the surface of the target mushroom cap, the light reflected off the cap is projected onto a CCD array. The measurements obtained are processed digitally within the laser control unit and communicated to the robot controller. At this point the 3D coordinates of the target are known.

4.2.3.2 Target removal

The next task is to remove the target mushroom from the growing medium without damaging it, the growing medium or neighbouring mushrooms.

To achieve this task an end effector (gripper) was designed and built based on a vacuum suction system previously described by Reed and Tillet (1994), Noble *et al* (1997) and Reed *et al* (2001) and adapted to handle 3 mushrooms in a pick cycle, in order to emulate the picking sequence of human harvesters (HDC 1996); 3 suction cups were considered as the maximum within the pick cycle in order to minimise the time each mushroom undergoes vacuum pressure and therefore reduce the risk of bruising to the targets.

From Figure 11, the end effector frame is bolted directly to the end of the robot arm.

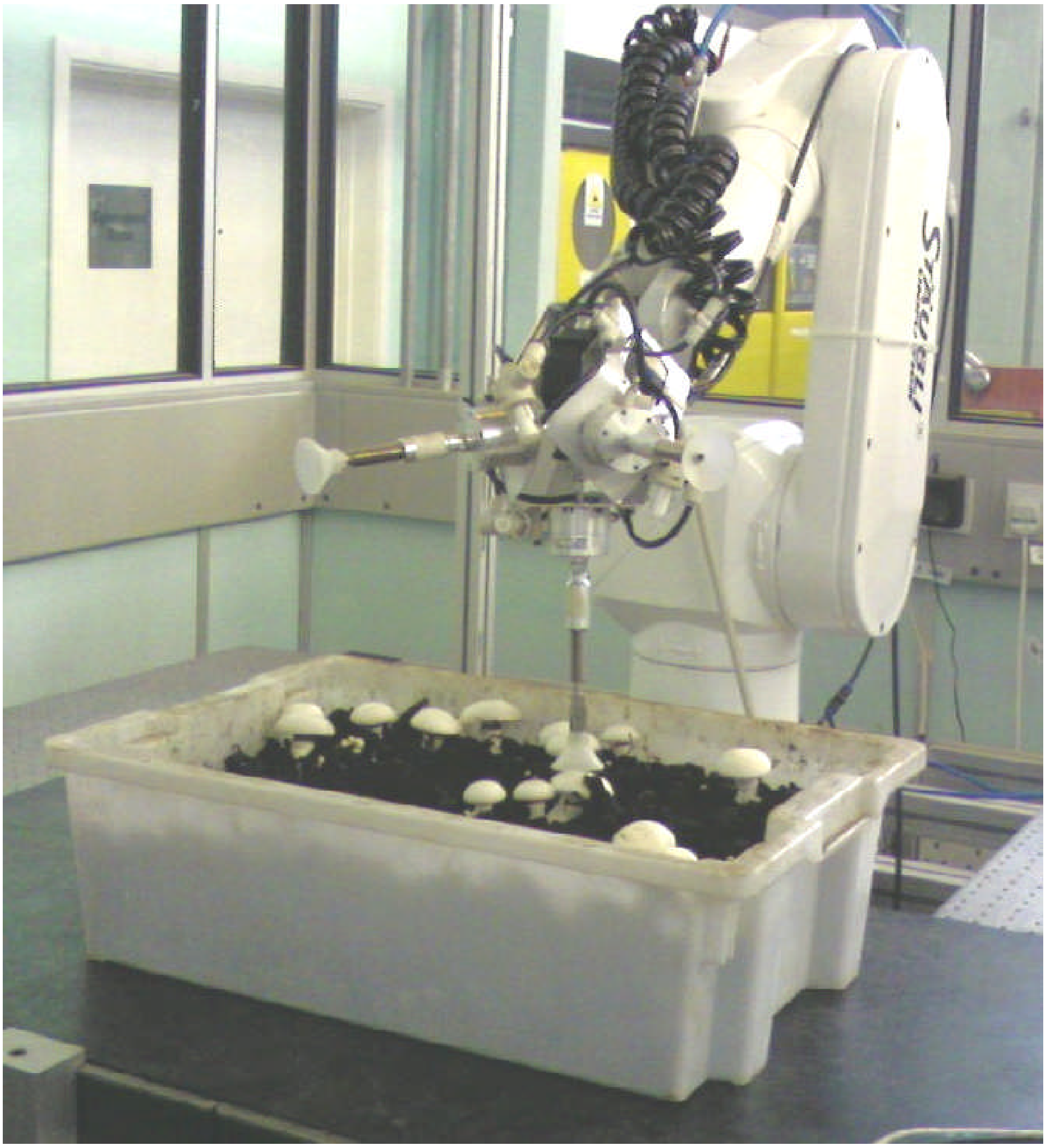

Figure 11: Laboratory demonstrator model of a robot arm for harvesting *Agaricus bisporus*

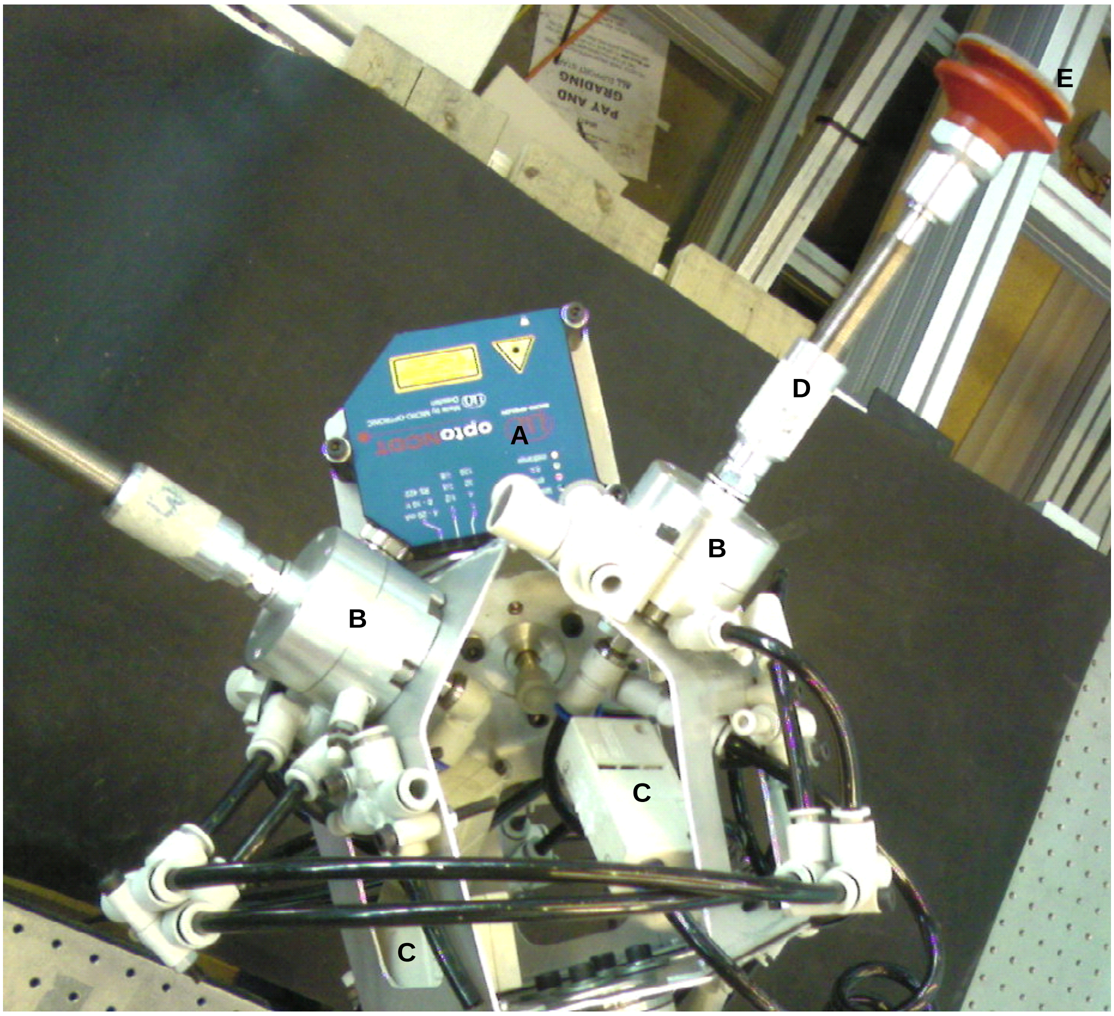

Figure 12: End effector for harvesting *Agaricus bisporus*

From Figure 12, the laser sensor (A) is bolted to another plate which is welded to the top of the frame.

The rotary actuators (B) are bolted to the side plate as are the vacuum ejectors (C); and the compliant vacuum suction cup assembly (D) is threaded onto the rotary actuator. The vacuum cup assembly is comprised of a hollow shaft; onto this a second hollow, lightweight-spring mounted shaft is screwed. This avoids any uncontrolled upwards pulling motion of the target once the suction cup, engaged with the mushroom cap, has deformed when the vacuum is formed. An adapter is then threaded onto the other end of the spring mounted shaft to connect the suction cup.

The silicon nitrile suction cup (E) has foam padding on the contact surface that is used to connect to the target mushroom cap, to reduce the possibility of bruising of the target mushroom.

The rotary actuators are supplied with two air inputs from the main air supply via a valve manifold, which is bolted to the arm of the robot. One valve port allows the shafts of the rotary actuators to simultaneously turn clockwise and the second port allows them to turn anti-clockwise. Speed controllers allow the air to be controlled locally to each rotary actuator input port.

An additional three valves within the manifold allow air from the main supply to pass through one of three vacuum ejectors housed within the frame. These ejectors create vacuum pressure that passes through a port in the back of each of the rotary actuators and down the vacuum suction cup assembly to the vacuum suction cup. An air filter between each vacuum suction cup assembly and ejector are included in the design to prevent mushroom detritus from entering the ejectors. Speed controllers allow the air to be controlled locally to each ejector – this then allows the main air supply pressure to be increased to suit the rotary actuators, without increasing the supply to the ejectors and vice versa.

A further three ports in the valve manifold allow air to blow directly through the back of the rotary actuator to the vacuum suction cup, thereby forcing the mushroom cap from the cup at the point of placement – this avoids sticking problems.

The valves are controlled by the robot controller.

4.2.3.3 Robot arm and control unit

An anthropomorphic, flexible robot (Staubli RX60BL) with 6 Degrees Of Freedom (DOF), with a reach of approximately 700mm and payload of 1.5 Kg. was used to manipulate the end effector. The weight of the end effector was at the limit of the robot's capacity. The robot was freely available for use at WMG at the time.

The robot's V+ programming language was used to move the robot and control the sensors and actuators within the end effector. The V+ system was also used to control the vision system. Figure 13 shows the logic of the complete system for picking up to three target mushrooms per cycle. Figure 15 shows the logic of the complete system for placing the targets.

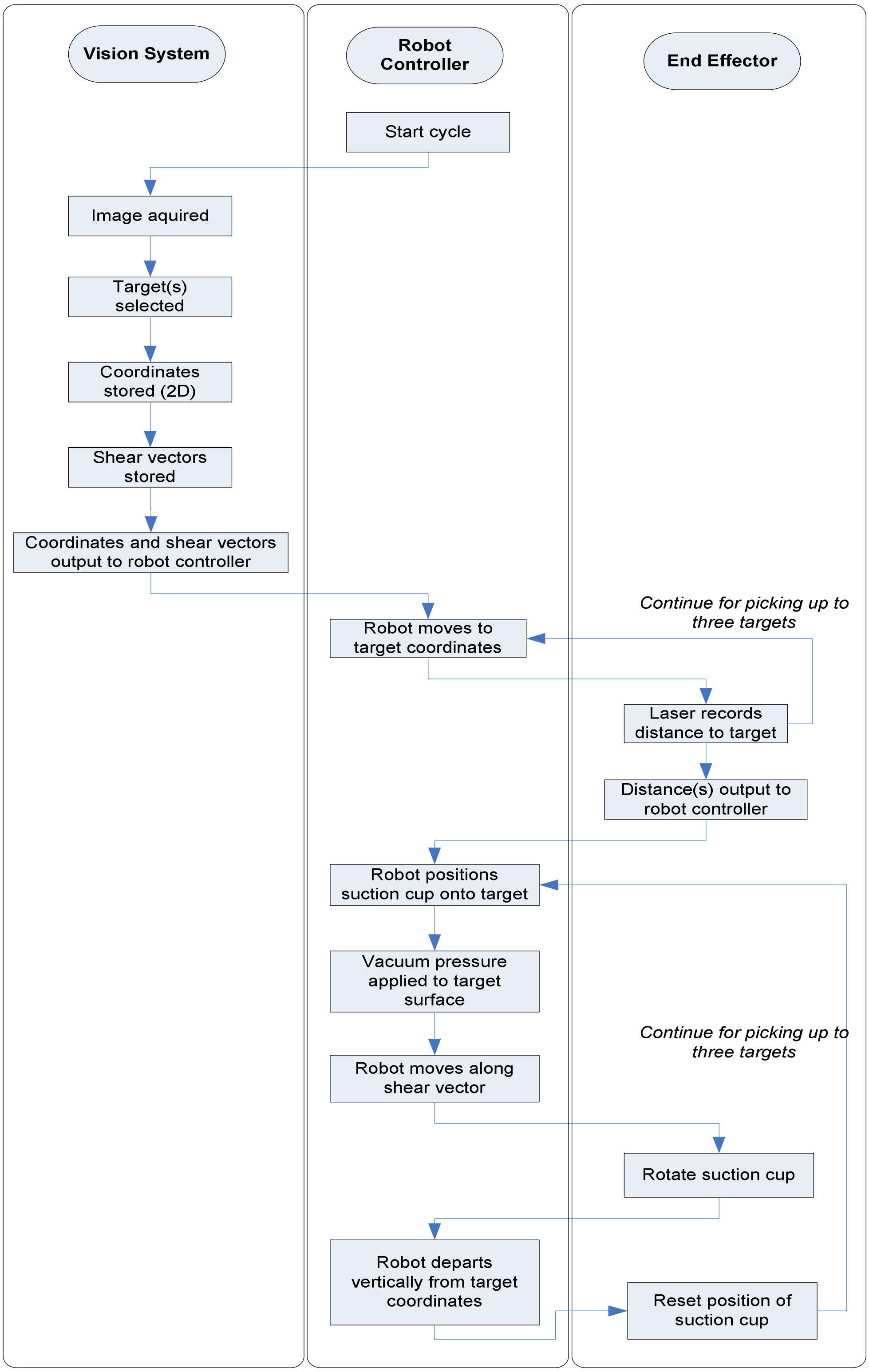

Figure 13: System logic for identification, selection and picking of a target mushroom

From Figure 13, the V+ robot control program initially requests target mushroom coordinates from the vision system, which was described in *Section 4.2.3.1*. Once these coordinates are received the robot positions the laser, mounted on the end effector frame, above each of the selected mushrooms in sequence, in order to gain distance readings, as detailed in *Section 4.2.3.1*. The value from each target is received and read by the V+ program from the laser. The value is translated within the V+ program to distance (mm), then to real world coordinates; then the first suction cup is positioned onto the cap of the target mushroom.

At the point of completing the cup movement to the target, the V+ program sends a digital output signal (SIG) to the valve manifold, enabling air supply to the vacuum ejector of the appropriate cup. This creates a vacuum onto the mushroom cap surface.

The robot then moves in the shear direction (i.e. horizontally away from the mushroom cluster) received from the vision system for that mushroom target.

At the point of completing the shear vector movement, the V+ program sends another signal to the valve manifold enabling air supply to the rotary actuators, thus allowing a twisting of the target mushroom (of 180 degrees around the stipe as shown in Figure 14), in a clockwise direction, to facilitate its separation from the mycelium with the minimum of damage to either the target or the mycelium and substrate; thus emulating the actions of a human picker.

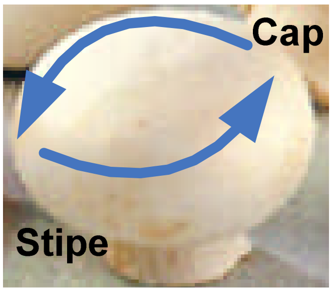

Figure 14: Twisting action of target mushroom facilitated by rotary actuators

The robot then departs 100mm vertically, to avoid colliding with neighbouring mushrooms or the tray sides: the target mushroom is thus removed from the growing surface.

At this point air is cut to the input ports of the rotary actuators by the V+ program and air is applied through the opposite input ports to allow them to reset to an origin position (i.e. they are turned 180 degrees in an anticlockwise direction).

The next suction cup is positioned over the next target. The pick cycle continues until all targets identified by the vision system for that pick cycle (up to three mushrooms) have been attempted (or until there are no more suitable mushrooms left on the growing medium).

After all targets in that cycle have been picked, the robot moves to the point of placement (e.g. into a receptacle or conveyor), whereby each cup assembly is sequentially positioned above.

At the point of placement of a picked mushroom (the logic is shown in Figure 15), the V+ program then sends a signal to the valve manifold to stop vacuum to the appropriate cup. A signal is subsequently sent to the manifold to send a supply of air directly to that cup, thus stopping the cup and mushroom cap sticking. The individual mushroom drops into the receptacle and the next cup is positioned above the receptacle. The cycle repeats until all mushrooms are placed. At this point the picking cycle may restart. The target identification task may commence at the point where the robot arm has moved from the Field Of View (FOV) towards the drop position.

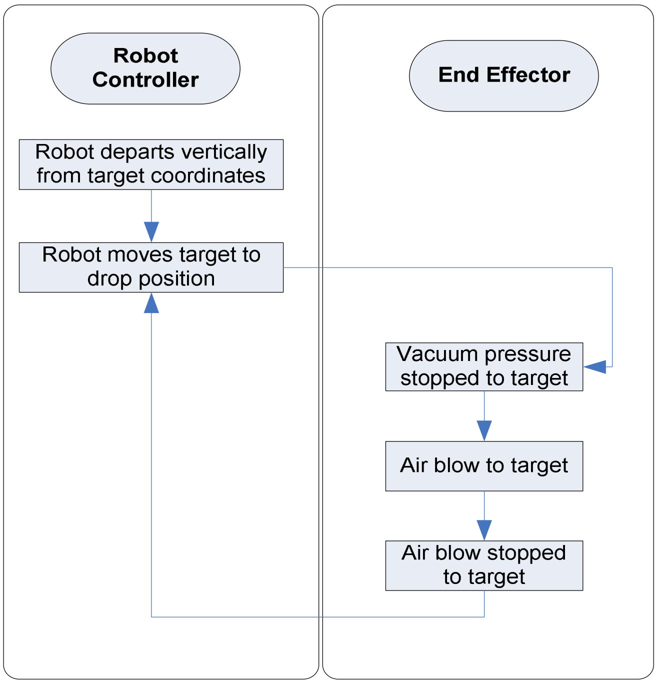

Figure 15: System logic for target mushroom placement

4.2.4 Test conditions

The aforementioned systems were set up and integrated as a working prototype at Warwick Manufacturing Group (WMG), University of Warwick, in order to model the harvesting phase of a mushroom farm, using trays as the growing medium. The complete model (lighting, vision, robot, end effector, picking area) is shown in Figure 16.

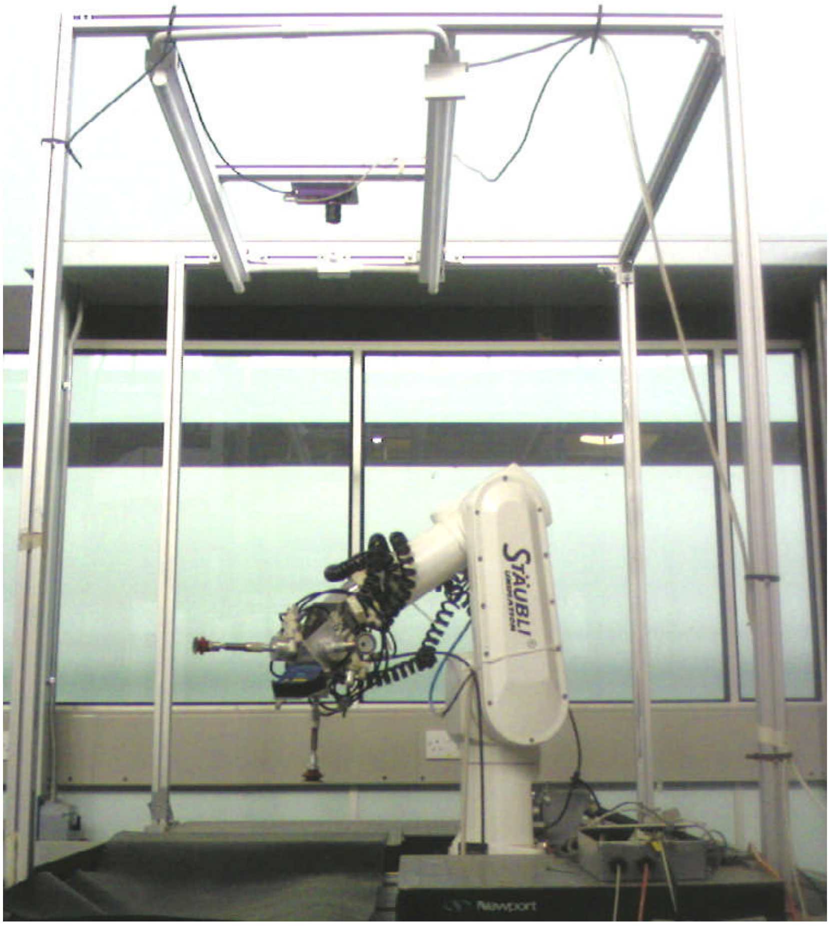

Figure 16: Complete integrated working prototype

Trays of 600mm (length) x 400mm (width) x 180mm (depth) made from polypropylene were used to grow Sylvan A15 Agaricus bisporus by the Mushroom Unit at Warwick Horticulture Research International (WHRI). This was an acceptable size tray to transport from Wellesborne mushroom growing unit to WMG. The trays were positioned under the robot when mushrooms were ready to be picked (i.e. they had cap diameters of between 35-60mm).

Ambient, external lighting was minimised to the area to give standard lighting conditions and therefore standardise vision system behaviour. If a mushroom was identified, picked and placed into a receptacle it was deemed a success. If the mushroom was not picked and placed successfully, it was removed by hand from the harvesting area and deemed a failed pick.

Two separate trials were conducted over a total of 6 days, which amounted to 211 suitable mushrooms on the trays at the trials, in total.

4.2.5 Results of experiments

Results of the experiments showed that the vision system identified 90% of all mushrooms on the tray and provided the ability to select targets by mushroom product categories typically used within the industry. This result could be improved with less variable ambient lighting.

The cycle time to pick and place three mushrooms, as shown in Figure 17, was found to be 20 seconds, or 6.7 seconds per mushroom. This would increase if the system identified less than three mushrooms within an inspection. This result compares to a typical human pick rate of 12 seconds (HDC 1996). The robot could in theory, be operated 24 hours a day, this would give a picking strategy advantage over a current single day-shift operation in terms of cycle times over a 24 hour period. This also avoids the need to 'over-pick' (i.e. prematurely pick mushrooms within a shift to avoid them growing too big before the next shift starts. Continuous operation of automated equipment will also shorten the payback period on investment.

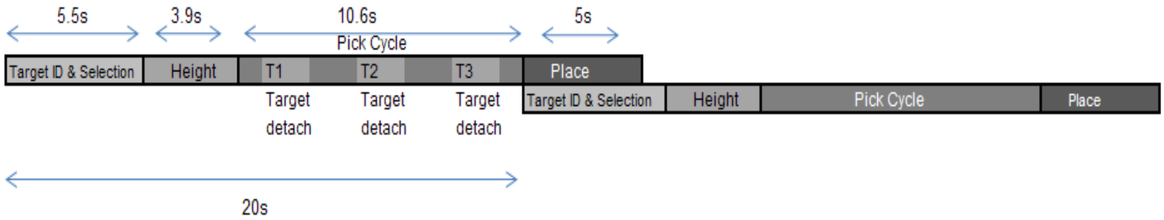

Figure 17: Gantt chart showing task breakdown and timings

The pick efficiency rate was found to be 69%. The most significant factor affecting successful picks was found to be the angle of growth of mushroom from the substrate: 12% of mushrooms were missed because they were growing at an acute angle; this tended to preclude the creation of vacuum pressure between the suction cup and the mushroom cap and in those cases where vacuum pressure was achieved, the twisting action produced an undesired splitting of the mushroom stipe; human harvesters would also find these targets more difficult to detach successfully. If all biological factors are eliminated, there was found to be an 8% failure rate from neighbouring mushrooms being picked simultaneously, or being knocked over. The results therefore suggest a

92% pick success rate is theoretically feasible using the model within optimum biological conditions. This compares to a 5-10% scrap rate produced by human pickers (Noble 2004), (Komatsu 2005), (Howard 2007).

Immediately following picking, mushrooms were stored in a fridge at 5 degrees Centigrade for 24 hours whereby they were inspected for markings and damage. 85% of mushrooms successfully picked had no bruising damage; the components of the system are theoretically able to achieve the same performance as the solution proposed by Reed et al (2001), whereby there was no bruising caused by the picking action.

With the addition of a protective covering for the vacuum ejectors the demonstrator model could be used within a commercial environment in the current configuration. The robot arm is produced to IP65 standard protection; as is the laser; vision sensor; all communications, pneumatic and electronic connections; and component assemblies.

The total component cost is £6,508.18 and the cost of the robot was £23,000, producing a total of £29,508.18

4.3 A DISCRETE EVENT SIMULATION (DES) OF A COMMERCIAL AUTOMATED HARVESTING SOLUTION

4.3.1 Project need

The performance of the laboratory demonstration prototype recorded in Submission 3 needed to be tested under commercial conditions in order to establish how many robotic harvesters would be required to replace the human pickers currently employed at a commercial grower (for reasons of commercial sensitivity the grower will be referred to as The Farm), what support equipment will be required and how the primary equipment might interact with other systems on the farm.

Simulation has been found to be a useful and powerful tool for designing and analysing manufacturing systems (Law and Kelton 1991). Manufacturing environments such as mushroom production systems are amenable to modelling as discrete event systems (Fishman 2001). Through its ability to predict systems performance simulation reduces the need for growers to invest in a prototype harvester and removes the need to experiment with the farm's processes and facilities, which would be very expensive to validate, in terms of time and cost.

4.3.2 System description

An analysis of experimental simulation techniques was conducted based on the criteria of: complexity and type of system modelled, ease of use of tool and level of expertise available. The system model was relatively complex, with stochastic input variables. Therefore the decision was taken to use Discrete Event Simulation software.

Witness (Lanner Group) was the Discrete Event Simulation software (DES) used to perform the experiments described in Submission 4. It was available for use at Warwick Manufacturing Group (WMG). It is also relatively easy to learn to use as it requires very little programming skill (Robinson 1994); and there was support at WMG from expert users.

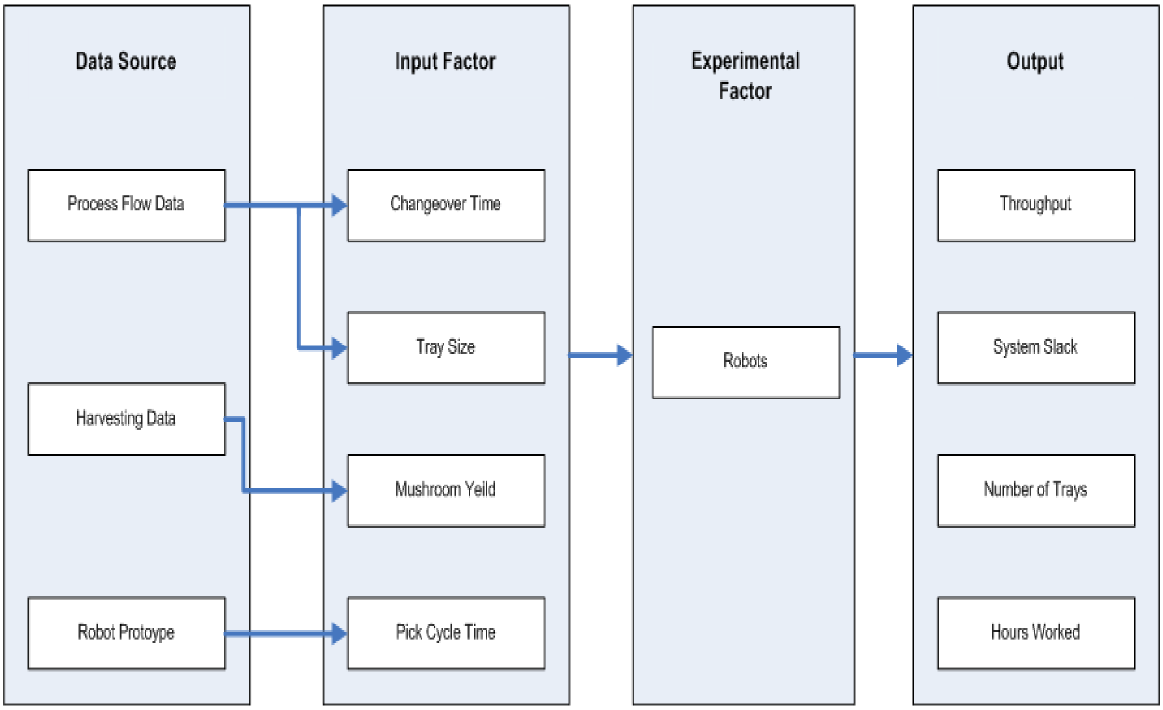

Figure 18: Modelling phase of simulation

There was found to be no current accurate published data for mushroom farms, therefore a primary data gathering exercise was conducted to record the system process logic from The Farm, the current mushroom harvesting data (e.g. flush density) and the current human performance data. The robot harvesters could then be incorporated into the virtual system through the use of the prototype's performance data recorded from Submission 3. It was then possible to compare the performance of the human and robot harvesters.

The data sources were incorporated into the simulation within the modelling phase to produce input factors as shown in Figure 18. The values of the four inputs factors may be changed individually to observe the effect on outputs in terms of throughput achieved, how long it takes, how many trays require harvesting and the utilisation rates of the harvesters in order to achieve the level of throughput. Also, DES indicates the sensitivity of system outputs to various combinations of values for each input factor. The number of robots required to achieve the output values can therefore be established.

4.3.2.1 Inputs

Pidd (1998) defines inputs as controllable factors and stochastic elements. The inputs to be used within this simulation, as shown in Figure 18, include:

1. Number of mushrooms harvested from each tray

   The empirical data observed over a flushing period from a sample tray was used to form a distribution of values. The pseudo random number generator within the DES used stream 1 to generate values within the distribution and also the antithetic of that stream to reduce bias in the generation of random numbers within the distribution. The empirical distribution was used and compared to the Production Manager's intuitive estimate of what quantities of mushrooms are harvested from a tray and a third distribution, based on a 'best practice growing' value of the empirical data.

2. Pick cycle time of robot operations

The empirical evidence gathered from the laboratory demonstrator model as recorded in Submission 3 was used to test the system's capabilities; the value was changed to reflect lower and higher cycle times that may occur in a commercial environment.

3. Tray size

Three tray sizes were considered – the ones used in Submission 3 (600mm x 400mm), one based on a standard UK Pallet size (1200mm x 1000mm) and the trays currently used at The Farm (2123.4mm x 1106mm).

4. Tray transfer times

Trays require loading and unloading to and from the robot and the system may require resetting between trays; as this was currently an undetermined factor, the assumption made was that the total transfer times would be between 15 – 60 seconds to cover the probable real outcomes.

4.3.2.2 Experimental factors

Experimental factors will produce outputs when combined with the various inputs. For example, robots are represented as 'machines' within the simulation and are the major constraint (i.e. bottleneck) of the harvesting function. The quantity of robots will determine the throughput capability of the system, based on the input variables; and will also determine the frequency of trays entering the system, the ASRS requirements and the building space required.

4.3.2.3 Outputs

The required outputs of the simulation which attempt to provide results from which conclusions were drawn are:

1. Hours worked.
2. Slack in system: the idle time for bottleneck processes (e.g. robot harvesters).
3. Throughput of product (e.g. lbs/week is a typical metric in mushroom farms).
4. Quantity of appropriate size trays required to achieve throughput.
5. Frequency of trays into the system in order to maintain continuous harvesting.

4.3.3 Test conditions

The simulation was designed to represent 1 week's activity, to reflect the even demand patterns associated with best practice mushroom growing.

Over the simulated week, 1388 trays are harvested 6 times. This totals 8328 tray pick occurrences to produce 38,000 lbs of yield (i.e. representing The Farm's weekly throughput level).

4.3.4 Description and results of experiments

Experiment 1 – A change in the value of input factor Pick cycle time (t)

This experiment was conducted in order to compare the current labour intensive operation using 28 humans to harvest the required amount of mushrooms, with the proposed automated system based on cycle times achieved using the laboratory demonstration model (6.7 seconds per mushroom). It was also conducted to ascertain the sensitivity of the system outputs to a change in the input factor of Pick cycle time (t): the Pick cycle time was tested from 5.0 - 7.3 seconds per mushroom.

Using the Pick cycle time of 6.7 seconds per mushroom, it was found that 29 robots were required to replace the 28 human pickers currently employed at The Farm The utilisation rate of the robot harvesters was found to be 93 per cent. When an extra robot was included the utilization rate was 89 per cent. The mean time between trays being picked was 14.7 hours, slightly higher than the 12 hour target; however this would not be a significant threat.

Through the process of linear differentiation it was possible to extrapolate the results to other farms operating different throughputs in order to ascertain the required quantities of robot harvesters.

A further investigation involved changing the Pick cycle time for 1 mushroom from 5.0-7.3 seconds per mushroom. It was found that for every additional second to pick and place three mushrooms it will incur at least one extra robot to achieve the same throughput. This suggests that the output of the simulation: *Throughput per week* is sensitive to a change in the input factor *t*.

Experiment 2: A change in the quantity of mushrooms harvested per tray (flush density)

This experiment was conducted to ascertain the sensitivity of the system outputs to a change in the input factor of mushrooms harvested per tray (d).

This input factor was treated as a stochastic element. The quantities of mushrooms harvested from the observed sample tray at The Farm were used to form an empirical continuous integer distribution to reflect probable values for the population of trays at The Farm. This was considered more realistic than using a mean value or an arbitrary distribution for all trays. Details of the formulation process for this distribution are recorded in Submission 4.

The distribution (dist01) was also compared to the farm manager's intuitive estimate of quantities of mushrooms harvested from a tray (uniform) and a further distribution (dist02), which was based on *dist01* with the exclusion of lower values to reflect 'best practice' growing.

From Experiment 1 when *dist01* is used 29 robots are required to replace the 28 human pickers, this value increases to 42 when *dist02* is used and to 55 when *uniform* is used.

The results suggest that the system outputs are extremely sensitive to a change in the input factor (d) over the three values. The range of required harvesters between the observed value and the intuitive value is significantly large and suggests further investigation including more tray samples may be needed to validate the results.

If a combination of the values for the two input factors *t* and *d* are used the range increases: from 22 (t = 5.3s, d=dist01) to 60 (t = 7.3s, d=uniform).

Notably, when the results are compared to the findings of HDC (1996), the empirical values (dist01) produce closer results than the farm manger's intuitive estimate: suggesting a degree of subjective optimism on the manager's part. Therefore the distribution *uniform* was excluded from further consideration. Also when the results are compared to Vedder's (1978) estimate of the weight of Closed and Open cups the results of the empirical values *dist01* reflect the weekly yield more closely than the distribution *dist02*, therefore *dist02* was excluded from further consideration.

Experiment 3: A change in the value of mushrooms harvested from the tray, corresponding to mushrooms harvested from different tray sizes

This experiment was conducted in order to compare three sizes of trays (s) to be used within the proposed automated system.

In the previous experiments the trays were assumed to be the same trays as the observed sample tray used at The Farm (i.e. Tray 3 = 2123.4mm x 1106mm). Therefore in practical terms, using the same robot as the laboratory demonstrator, would require the tray to be repositioned under the robot multiple times, for all parts of the tray to be reached by the robot.

In this experiment *Tray 1* is the same size as those trays used in the demonstrator model experiment described in Submission 3: the area dimensions are 600mm x 400mm. This equates to 0.102 times the size of that currently used at The Farm. Therefore it is possible to test the system using *Tray 1*, by changing the amount of trays entering the system in this case to 13608 (in order to maintain current yields, using *Tray 1*), and reducing the quantity of mushrooms picked per tray, by proportionally changing the values used in the distribution *dist01*.

Tray 2 is of the same area dimensions of a standard UK Pallet: 1200mm x 1000mm. This equates to approximately half the size (0.51 times the size) of that currently used at

The Farm. The ASRS system, including shelves and conveyors, will be less customised and therefore less expensive if the system is based around a standard tray size. Therefore it is possible to test the performance of the system when using *Tray 2*, by increasing the amount of trays in each batch (i.e. by a factor of 1/0.51 to 2722 trays); and reducing the quantity of mushrooms picked per tray, by proportionally changing the values used in the distribution *dist01*.

For *Tray 1*, if the Pick cycle time (t) of 6.7 seconds is used with the empirical distribution (dist01), with 29 robots, the mean time that a tray is being picked for is 3.6 minutes.

As there are 6805 trays required to be picked every 12 hours, this means that the robot harvesters must be fed 567 trays every hour in total. Over the 7 day period there will be 81660 tray movements performed by the ASRS.

The results suggest that using *Tray 1* is impractical when considering the trays must be transported from the growing shed to the harvesters, which will take time. There would be too much movement in the ASRS and not enough mushrooms in each tray to warrant the extra investment required for the ASRS, or indeed any movement at all from the growing shed. The robots would not be operating efficiently, particularly if change over times are incorporated into the system. It is assumed therefore that it would most likely be more efficient to harvest the mushrooms from the trays in-situ. For this reason *Tray 1* was excluded from further consideration.

For *Tray 2*, if the Pick cycle time (t) of 6.7 seconds is used with the distribution *dist01*, with 29 robots, all trays in the first batch are picked once within 14.2 hours. The mean time that a tray is being picked for is 17.6 minutes. In total all 16330 tray picks are completed within 166.65 hours. The results suggest that the ASRS would have to cope with moving a mean of 96 trays per hour to and from the robot harvesters.

When the Pick cycle time factor (t) is changed from 5.0s to 7.3s, there is no significant difference in the number of robots required to achieve the required weekly throughput of 38,000lbs to *Tray 3*. Therefore the outputs of the simulation are not particularly sensitive to a change in the input factor: Tray Size (s) over the two levels: *Tray 2* and *Tray 3*.

Practically, these results indicate a higher throughput of trays per hour using *Tray 2* instead of *Tray 3*, this suggests the need for rapid changeover times between trays to keep the system harvesting mushrooms and not having robots idle for large proportions of the time while they wait for Trays.

Also, *Tray 2* is a larger tray than that used in the laboratory demonstrator experiment (Tray 1) which would also mean extra time to travel the further distances over the growing area to harvest mushrooms; therefore extra time should be considered a distinct possibility; as would the need for a robot with a larger reach than the one that was used in Submission 3. A Kinematic Simulation of a larger robot (ABB IRB 2400L) has been carried out using *Tray 1* and *Tray 2* for comparison. The results show that it takes an additional 0.8 seconds to cover the extra distance required for *Tray 2*, which means that the overall cycle time to pick three mushrooms, recorded for *Tray 1* will increase from 20 seconds to 21.6 seconds for Tray 2 (or 7.3s per mushroom).

From this experiment it is possible to determine the simulation output: *Number of Trays* required to keep robots harvesting continuously. From the primary data gathering exercise to establish The Farm's process logic, it was found that each tray will be in a state of growing and harvesting for 45-54 days, this suggests that if using *Tray 2*, The Farm will require from 6.4 and 7.7 times the number of trays in the harvesting phase (8923 and 10708 trays in total), in order to keep the robot harvesters operating continuously.

<u>Experiment 4: Changeover time addition</u>

This experiment was conducted in order to ascertain the sensitivity of the system outputs to the addition of changeover times (c) to transfer trays to and from the robots.

Experiment 3 ignores any requirement for the transfer of trays to and from the state of being harvested by a robot. This would include the physical movement time and also any software start-up or reset procedures that may need to be carried out in between tray pick visits; this will add extra time to the Pick cycle time for each tray. This may be significant if the number of trays is to increase to accommodate the smaller *Tray 2* within the system. The assumption is made that a range of values of 15-60s would realistically represent the additional time required for changeover of trays.

Using *Tray 2*, there is a general increase of 1 extra robot over the change over time values (c) on the quantity of required robots to achieve throughput.

4.3.5 Summary of results

From the results therefore, it is possible to create a scenario of probable input factor levels as in Table 5.

Number of robots	Changeover (c)	
Pick cycletime (t) (secs)	Low 15-30s	High 45-60s
6.7	**31**	**31**
7.0	**32**	**33**
7.3	**33**	**34**

Table 5: Scenario of probable input factors for UK Pallet Tray

Table 5 shows that over the range of Pick cycle times (t) 6.7-7.3s with low changeover times of 15-30 seconds and a distribution (dist01) of mushrooms picked per tray the range of robots required to achieve current throughput levels with a reasonable amount of slack time in the system for maintenance and breakdowns is from 31-33. If the changeover times per tray are high, the range is from 31-34 robots.

Therefore in order to achieve the current levels of throughput at The Farm the results of the experiments from the simulation suggest that there will be a requirement for between 31 and 34 robots, depending on the various input factors outlined in Submission 4.

4.4 FINANCIAL BENEFITS

4.4.1 Direct labour

Based on the cost analysis of the proposed fully automated harvesting and growing system presented in Submission 5, the system costs are shown in Table 6

Component	Unit Cost (£)	31 Robot System (£)	34 Robot System (£)
Robot	30,275	938,525	1,029,350
Vision System	2,445	75,780	83,114
End Effector	4,064	125,973	138,164
Building (Racking)	145,750		
Building (Harvesting)	85,000		
Safety System		28,861	31,491
ASRS	1,974,184		
TOTAL including trays (lower param: 8923)		3,561,457	3,674,436
TOTAL including trays (upper param: 10708)		3,598,942	3,711,921

Table 6: Cost summary of automated system

The upper and lower parameters are based on the number of trays required in the system, which in turn is based on the length of the growing and harvesting cycle of The

Farm. Values are given for the range of scenarios based on results of Submission 4 for the required number of robots to achieve current throughput (31-34 robots). Based on the range of initial investment costs presented in Submission 5 the payback analysis based on the elimination of the direct labour costs is shown in Table 7.

Labour savings per annum	**Initial cost**			
	31 robots		34 robots	
	lower param.	upper param.	lower param.	upper param.
	3561456.82	3598941.82	3674436.22	3711921.22
462756.00	**7.70**	**7.78**	**7.94**	**8.02**

Table 7: Payback Analysis of fully automated system

From Table 7 the payback range is between 7.70 and 8.02 years which is not attractive.

If The Farm was to keep its existing growing facilities and use the current method of transporting trays to and from the harvesting area using a forklift truck, the growing building, racking and the storage and retrieval machines could be eliminated from the initial cost. Three employees would be needed to operate the forklift truck over a three shift period every 24 hours. Table 8 shows the payback period for this scenario. In this case the payback range is from 5.49 to 5.85 years, still not particularly attractive.

Labour savings per annum		**Initial cost no ASRS**			-£1,287,234
		31 robots		34 robots	
		lower param	upper param	lower param	upper param
		2274222.82	2311707.82	2387202.22	2424687.22
414333.88		**5.49**	**5.58**	**5.76**	**5.85**

Table 8: Payback Analysis of automated harvesting system, excluding full ASRS

Table 9 shows the maximum rate of return required by the investor for the project to just break even, investigated using the Internal Rate of Return Method over a 10 year period.

With Full ASRS			
31 Robots		34 Robots	
Lower limit	Upper limit	Lower limit	Upper limit
4.4	**4.2**	**3.7**	**3.5**

Table 9: IRR for system requiring 31 to 34 robots

The IRR is low for 31 robots and produces a lower result if 34 robots are required. However if the system is implemented without the full ASRS and growing facilities Table 10 shows the IRR results:

Without Full ASRS			
31 Robots		34 Robots	
Lower limit	Upper limit	Lower limit	Upper limit
10.9	**10.5**	**10.6**	**10.3**

Table 10: IRR for system excluding full ASRS

From Table 10, the IRR is still low for a system requiring 31 to 34 robots to achieve current throughput. It would probably not be attractive to most investors for such a high risk project over a 10 year period.

4.4.2 Other benefits

The aim of financial justification is to evaluate an investment project for its capacity to provide a satisfactory contribution to the value of the company's shareholders. While this is easier to do using the methods described in the previous section, on their own they may not provide a true perspective. Non-financial benefits will add to the provision of a clearer scenario. Such benefits are significant, but are difficult to measure in terms of monetary benefit. Therefore there is a need to link them to the company objectives (i.e. remaining profitable in the medium to long term future)

4.4.2.1 Real options

If this project is assessed using the IRR method and has a negative value (or relatively low value) against expectations, the result would suggest not going ahead with the project. Shank (1996) points out the limitations in this regard: the proposed solution may create new opportunities to increase the firm's overall future value. Real options account for this wider perspective on investment decisions. Broyles (2003) recognizes that real options provide an opportunity for voluntary future investment when at least a part of the required investment expenditure is not perfectly positively correlated with the project's present value. In that respect, the growers may embrace an uncertain future – if they possess the option to exploit changing circumstances they will have the flexibility to respond with more agility. If the option is not taken the labour supply and harvesting cost issues may detrimentally affect the UK growers' capacity to maintain their current market share. The growers have the option to invest in the project and they also have an option to delay the decision until the most appropriate time; however in the case of the UK mushroom industry something needs to be done more immediately if the growers are to regain their competitive advantage over foreign imports. The traditional financial analysis methods used in the previous section assume the status quo; if the current market conditions and labour issues prevail the share of the market for UK growers will shrink further.

4.4.2.2 Continuous harvesting

The system is considered reliable enough to be left continuously operating without operator supervision, therefore reducing the requirement for direct harvesting labour and eliminating the requirement of growers to ‘over pick’ crops, associated with a single shift operation. Over picking results in higher picking costs, as smaller mushrooms are cropped; and causes a reduction in yield from the growing area as energy from the mycelium is wasted on the smaller mushrooms. Therefore if The Farm was to employ a night shift to enable continuous picking, the labour costs would be significantly higher than they are currently, which makes the proposed system more attractive.

4.4.2.3 Opportunity to invest in new facilities

By the very nature of the automated environment, investment in the proposed system will have a cross-functional impact across the organisation and savings may be obtained from a reduction in overhead costs (e.g. from a better insulated building than used currently). Benefits from new and improved buildings would also extend to a reduction in pests and disease associated with older facilities. Also, if the company decided to build new infrastructure they would have the opportunity to relocate nearer to market, thereby reducing transport costs to the customer.

4.4.2.4 Human resource implications

Automation will reduce the manual input required in the current labour intensive harvesting process. This will reduce direct labour costs and alleviate the skills availability problems for growers; it also frees up existing core labour so they can be utilised in more value adding activities across the farm's functions. In this way the labour resource is used more productively and the work is more diverse for the employee (e.g. with the introduction of job rotation). Also the harvesting supervision and training resource will be reduced as there will not be such a requirement in the proposed system.

4.4.2.5 Marketing opportunities

The customer may be more reassured by the knowledge that the marketed crop is being processed using the latest technology developed for industries such as automotive and aerospace.

4.5 RELEVANCE TO INDUSTRY

Industrial relevance of the work completed is demonstrated in two ways: the identification of interest from the horticulture and other industry sectors and the commitment of resources from the sponsoring company and its clients.

4.5.1 Identification of interest from the horticulture and other industry sectors

The project has featured in the HDC News journal on several occasions to highlight the benefits of the project to growers. It has also been presented at the HDC seminar:

Addressing the Problems of the UK Mushroom Industry in the UK and the *Robotics in Horticulture* seminar at WHRI. Additionally the project has featured on BBC Radio 4 Farming Today, BBC Midlands Today and BBC South East Today. Other industries have taken an interest in the project and the work was published in the machine vision journal: Europhotonics. The project has also featured extensively on the Internet including websites such as NewScientist, ScienceDaily and the UK Trade and Investment Office.

4.5.2 Commitment by sponsoring company

Commitment to the project and its outcomes is demonstrated by the level of investment made by the sponsoring company. Significant amounts of money were designated to the various projects throughout the period of the Engineering Doctorate programme. The client companies of the HDC also treated the programme as a significant part of their future development plans by allocating the necessary resources for each of the various projects that involved them directly.

4.5.3 Other relevant issues

The proposed system provides growers with an innovative way of harvesting mushrooms for the fresh market. The projects developed have generated knowledge that is commercially exploitable through the various publications and presentations. The work completed indicates priorities for automation researchers to develop solutions for other fruits and vegetables based on the task complexity, the technology currently available and the costs of these.

CHAPTER 5
INNOVATION SUMMARY

5.1 OVERVIEW

The innovation that has been created from this Doctoral research comes from two main areas:

1. The Automatic Harvesting System.
2. The testing of the commercial potential of the Automatic Harvesting System using discrete event simulation of a commercial mushroom farm.

5.2 MAIN INNOVATIONS

5.2.1 Innovations from the automatic harvesting system

The solution that has been developed for the automated harvesting of mushrooms for the fresh market comprises application of known technology, that addresses problems where commercial solutions are not available and research projects do not provide all the required features for a commercial application.

The result of developing this solution is a new system that offers an improvement over traditional labour intensive harvesting methods and also existing research proposals. The system provides mushroom growers with the opportunity to adopt harvesting methods that were previously not possible.

The main innovations for the developed systems are:

a) Non-tactile target identification and selection system

The system is a module that provides growers with an automatic system for identifying target mushrooms on the growing area and prioritising them for harvesting depending on their size and position relative to other mushrooms and the tray sides.

The system enables the size and coordinates in three dimensional space to be established and the surrounding area around that target to be known, without the need to physically contact the target cap, which is easily damaged.

The system offers a method of identification and selection which will not damage the target; it also offers pick cycle time savings from eliminating the need for careful handling of the target cap in this phase of the harvesting process, existing solutions have relied on the detection of the mushroom cap after the end effector has connected with it and therefore necessitates a very slow final descent of the end effector to the target.

b) Automatic harvesting of mushrooms using flexible industrial automation

The automatic harvesting system employs integrated system components that are known and proven technologies. This offers an improvement over existing systems that have relied on customised, mechatronic components, which are not easily reproduced or available for use on a large scale. The solution developed from this research can be reproduced in modular form to harvest from different sized trays using an optimal size robot manipulator and can harvest a range of target sizes through the use of dedicated suction cups. The components allow repeatable precision of the system's operation, increasing the trust of growers in its use.

The system offers an improvement over traditional labour intensive harvesting methods through its ability to harvest on a continuous basis. Therefore the system is not constrained to shift working and consequently eliminates the requirement for 'over picking' of smaller mushrooms, therefore reducing the picking costs and increasing the overall yield of the crop (Vedder 1978). The proposed system also eliminates the requirement for human pickers to work with an uncomfortable posture for much of the day if picking in-situ.

5.2.2 Innovation in the method by which the commercial potential of the automatic harvesting system was tested, using discrete event simulation of a commercial mushroom farm.

The discrete event simulation of a commercial mushroom farm provides mushroom growers with the opportunity to assess the commercial applicability of an automated harvesting system within their operation, without the need for direct manipulation of the existing production process. This method eliminates the need for implementation of a commercial prototype, therefore saving the growers the cost of capital investment outlay and validation time. The risk of disruption to existing systems is also eliminated.

The unique and novel application of a discrete event simulator to a mushroom farm allowed the testing of stochastic factors inherent within the growers' operations through the use of distributions of empirical values. The sensitivity of the simulation outputs to the input factors were established individually and in combination, to ensure reliable prediction of results and establish the margin of error. The method allows growers to make a better informed decision about the use of automation in their individual operations and automation equipment suppliers to develop a marketing strategy in which the business benefit of investing in the harvesting system can be demonstrated to potential customers.

5.2.3 Additional benefits

5.2.3.1 System reliability

The proposed system presents a precise and reliable harvesting system that differs from other solutions as it does not require supervision or repositioning. The system is considered reliable enough to be left continuously operating without operator supervision, therefore reducing the requirement for direct harvesting labour and eliminating the requirement of growers to 'over pick' crops, which results in higher picking costs and a reduction in yield.

5.2.3.2 Simplification of maintenance

Contrary to existing harvesting solutions, the components used in this system are all readily available from suppliers and relatively easily replaced. The more significant system components such as the laser and robot arm and control unit may be covered by a maintenance contract with the suppliers.

5.2.3.3 Facilitating automation development for growers

The methodology used to predict commercial applicability of this project for a UK grower is flexible enough to be adapted to the operating policies of any mushroom grower operating a tray production system. It can help management with the decision to invest in an automated harvesting system by predicting the amount of equipment resource required for that farm.

5.2.3.4 Recognition of the need for cultural change

The traditional UK mushroom industry approach to automation issues tends to be sceptical. Growers must be willing to actively participate in the automation projects to facilitate the correct level of information required by the project engineers.

Growers also need to be receptive to adopting technologies that are not specifically designed to work within the existing production environment, but that can offer advantages over those designed for it (i.e. the use of industrial components and using new production methods to suit industrial automation). The advantages that industrial automation technologies provide include the level of performance that traditional equipment has failed to deliver, particularly in the aspects of development costs, reliability and ease of maintenance. Such technologies including robotic arms, machine vision sensors and laser sensors are capable of providing the levels of flexibility and reliability that growers demand. These tools have been developed and validated for successful and proven operation in the manufacturing sector, particularly for automotive manufacturers. Additionally, industrial automation has been developed with a robust use of standards to facilitate successful integration of components.

5.2.4 Contribution to knowledge

From this work a study has been conducted to show the horticultural processes that will benefit most in terms of direct labour savings from the implementation of automation. The results of the study demonstrated that mushroom harvesting was the process that would benefit most significantly from the implementation of automation, followed by cauliflowers, tomatoes and apples.

In order to achieve the objective of reducing labour costs and skill availability pressures within the harvesting phase for mushroom growers, an evaluation has been conducted which shows that there is a clear link between solution design, performance and trust from end users. This work allows equipment manufacturers supplying to growers to see that the solution's design will have an impact on trust in its ability to deliver and therefore will dictate the level of investment in the solution by growers. It provides manufacturers with: an awareness of the needs, concerns and priorities of their customers in the horticulture sector; an awareness of the need for full testing of solutions to gain growers' trust in their application; a method for commercial validation of an automated harvesting system.

This work also allows growers to make an informed decision beyond the initial factors of purchase, in terms of including commercial applicability to individual farms, training and maintenance requirements and support equipment cost, which is critical when assessing a harvesting solution.

Additionally this work demonstrates that introducing automation into horticultural processes requires a change in culture from the growers, particularly farm managers, in the way they perceive their role in automation projects. They should be open to accept and participate in the projects. Their involvement in the design and implementation of automation projects is essential as their active participation increases the information available to the project team, which facilitates relevance to the application of the solution in terms of achieving required performance. This level of participation also instils in them a culture of ownership of the new equipment, in turn encouraging them to take responsibility for the equipment, for its correct operation and for its maintenance.

Commercial application in such complex environments as found in horticulture is difficult (Kassler 2001), (Bechar and Edan 2003), demanding in some cases a compromise of system features between growers and system developers. Each requirement has to be prioritised and rigorously justified to deliver solutions that address both the user and process requirements and minimises the complexity and cost of the designs.

The experimental work has presented several significant results that provide valuable knowledge that can be successfully implemented in the broader horticultural automation fields:

The flexible industrial automated equipment used for the laboratory demonstration of a robot arm for picking *Agaricus bisporus* is capable of achieving pick cycle time and pick efficiency rates similar to previous automated research prototypes that were based on customised components using tactile target identification and selection methods and also human harvesters, when compared over a 24 hour period of production (i.e. current labour shifts are between 8-12 hours per 24 hour period).

The method used for evaluating the commercial applicability of a commercial automated harvesting system through the use of discrete event simulation found that there are large differences in outputs, created as a result of a change in the input factor: *flush density*. There are no published figures on standard pick rates currently, with anecdotal data from growers ranging from 33-60 lbs per harvester, per hour, depending on the size of the mushrooms picked, the farm, the picker and the time of day they are measured. Therefore this data was captured during a primary data gathering exercise conducted at two UK farms. This data was used within the DES in the form of a continuous integer distribution of the cumulative totals of each observed value within the DES, in order to reflect the possible amounts of mushrooms that could be harvested from a similar sized growing area in all trays on The Farm. It was found to produce significantly lower input values than the intuitive estimate made by the farm manager.

This highlights the significance of the quality of the data used for this input factor within the DES and suggests that using poor data will have a clear impact on the results of the simulation in terms of obtaining a correct value for the quantity of robot harvesters and support equipment required to achieve the throughput.

CHAPTER 6
CONCLUSIONS

As a result of this work an analysis was conducted to identify those horticultural processes which would benefit most greatly from the application of automation. The analysis found that mushroom harvesting was the process which was the best candidate for further research work.

In order to assess whether automation could deliver the requirements of mushroom growers a laboratory demonstration model was designed and tested. The results of experiments to test the performance of the model were used as input data within a discrete event simulation. Experiments were conducted using the simulation to test the commercial applicability of the model within a UK mushroom grower's simulated operation.

The work conducted for this Engineering Doctorate programme demonstrates the innovative use of automation technologies in the horticulture sector, particularly for harvesting mushrooms for the fresh market. The novel automation platforms demonstrate that it is possible to develop systems with high levels of precision and reliability, through the application of a modular approach using industrial automation components. These platforms are as follows:

6.1 NON-TACTILE TARGET IDENTIFICATION AND SELECTION SYSTEM

The Non-Tactile Target Identification and Selection System is a flexible automation platform using a vision system and laser sensor to identify the target location and prioritise picking. The system is a new method for locating the target mushroom cap and prioritising picking without the need for tactile methods, which prior research harvesting solutions were dependent on. The system enables the target to be harvested directly by the end effector with the advantage over existing systems in terms of reduced cycle time and reduced damage to the crop.

6.2 AUTOMATIC HARVESTING OF MUSHROOMS USING FLEXIBLE AUTOMATION

The automatic mushroom harvesting system uses the Non-Tactile Target Identification and Selection System and an integrated target removal platform using industrial automation components. This system demonstrates the benefits of reliable and simple to use automation which were not available to previous research solutions and which enables unsupervised and overnight operation of the equipment. This reduces costs associated with direct harvesting labour and largely eliminates the requirement for hard to find labour. This also reduces the high picking costs associated with ‘over picking’ using manual labour.

6.3 DISCRETE EVENT SIMULATION (DES) OF A COMMERCIAL MUSHROOM FARM USING THE AUTOMATIC MUSHROOM HARVESTING SYSTEM

The automatic mushroom harvesting system's commercial applicability was tested under simulated conditions. The discrete event simulation provides growers with further insight into the operation of the primary equipment and the requirement for support equipment. The method provides a novel way for growers to make a business case for capital investment in an automated mushroom harvesting system without the need to invest in a commercial prototype or disrupt current operations.

In summary, the primary objective of designing a commercial automated solution for the harvesting of *Agaricus bisporus* has been met. Innovation is demonstrated in the technologies developed for the system and in the approach to commercial validation of the system through the use of DES of a commercial harvesting system.

CHAPTER 7
FUTURE IMPLICATIONS AND RECOMMENDATIONS FOR FUTURE WORK

There is a clear limitation in this work arising from the limited sample of trays used as harvesting input data and therefore the ability of the discrete event simulation to obtain accurate predictive information for the harvesting system. Therefore further work should involve establishing a larger sample of input data for the input factor: *flush density*, using more sample trays from more farms and over more flushes (i.e. to accommodate the autocorrelation effect on later flushes that arises from harvesting strategies employed on earlier flushes).

The continued lack of trust in any automated harvesting solution is also evident from growers, particularly in current times of financial uncertainty. Further work to alleviate this cultural threat to the implementation of any commercial solution would involve the production of a commercial model of an automated harvesting system to prove the solution would work on a farm.

A further limitation of this work is that it provides a solution for trays farms only. In practice the proportion of tray farms existing in the UK is less than 50%, with the majority of farms operating a shelf production system. Therefore the next area of study from this work is to assess the potential to adapt the system to be used within shelf production systems. Notably, a Dutch company (Methore 2008) has developed a research prototype that may potentially be a commercial solution for shelf systems.

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