Functionalized Soft robotic gripper for delicate produce harvesting powered by imitation learning-based control

D1.1 SoftGrip Use Case Descriptions, functional requirements and standards

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1 INTRODUCTION

The SoftGrip project aims to deliver an innovative soft gripper solution for the autonomous picking of delicate white button mushrooms cultivated on what are known as 'Dutch shelves' within an environmentally controlled growing room. Currently mushrooms are harvested by hand, by teams of skilled harvesters as retailers demand very high quality, blemish-free fresh produce. Hand-harvesting is the only way to deliver this high quality of produce at the moment, and it requires the availability of large workforce. The working conditions can be challenging – harvesters work indoors in a warm humid environment and, depending on the crop, the working hours can sometimes be unpredictable, requiring weekend work or late shifts. Harvesters also have to meet harvesting targets to ensure the viability of the business. Trainee harvesters who do not reach the minimum harvesting target after training are unlikely to be retained for employment. These factors mean that it can be difficult to retain staff, who may leave to take up work with more acceptable working hours and conditions.

The use of robots to harvest mushrooms has long been a subject of research, given the ongoing challenge with sourcing and retaining labour, for what is in fact quite a skilled and essential element of a successful mushroom business. As a result, there are several automated aspects now to mushroom harvesting operations (e.g. automated trimming, transport of harvested mushrooms, and their placement in product containers) however the actual picking of the mushroom off the mushroom bed is still done by hand as to date prototype robot grippers have tended to leave visible pressure marks on the mushrooms, or require additional handling operations that cause damage, making them unsuitable. This deliverable will outline the key requirements that SoftGrip will need to address in order to successfully harvest mushrooms that are of an acceptable quality and standard to meet the demands of fresh market.

Work Package 1 (WP1) in the SoftGrip project is entitled '**Technical Functional Requirement Analysis'.** This WP has four Tasks, the first of which is entitled '**Task 1.1 Use case analysis, functional requirements and standards**. It is led by partner Teagasc, and is contributed to by all partners. It is the first task in the project and has a duration of three months (M1-M3). It is a critical task and **Deliverable D1.1** is a report documenting the **'SoftGrip use case description, functional requirements and standards'**. It outlines the framework within which SoftGrip will operate and will be a reference document for all partners and all tasks in terms of the starting position description. It sets the approach to be taken to identify all the important system requirements and needs, the impact on key users, and how each component of the system will address those needs to reach essential threshold values that have been identified.

2 MUSHROOM GROWING SYSTEM FUNCTIONAL DESCRIPTION

2.1 MUSHROOM TUNNEL STRUCTURE AND DIMENSIONS

Every mushroom farm in Ireland has several mushroom growing tunnels to accommodate their mushroom production cycle. The majority of farms in Ireland produce 3 flushes of mushrooms which means each crop has a duration of 6 weeks. With this cycle, the minimum amount of tunnels required is 6 to maintain a consistent filling cycle. However, as farms expanded over the last two decades, many units consist of multiple growing tunnels. Figure 1 is a photo of (A) the most common mushroom tunnel in Ireland and (B) modern mushroom production facility.

Mushroom crops are grown in these units on 'Dutch Shelving' (Figure 2). This shelving is made from either galvanised steel or aluminium (aluminium is the preferred option as it does not corrode, unlike galvanised steel). The shelves are either 1.2m or 1.34m wide and the length of these shelves vary between 30m to 60m long. The depth of these shelves is 20cm. The shelves have a sideboard (2cm wide) which holds the compost in place. These sideboards are bolted to the shelves and have convex shape which allows a ruffling machine to drive down the shelves as can be seen in the photos below. See also: Teagasc Ruffling video.

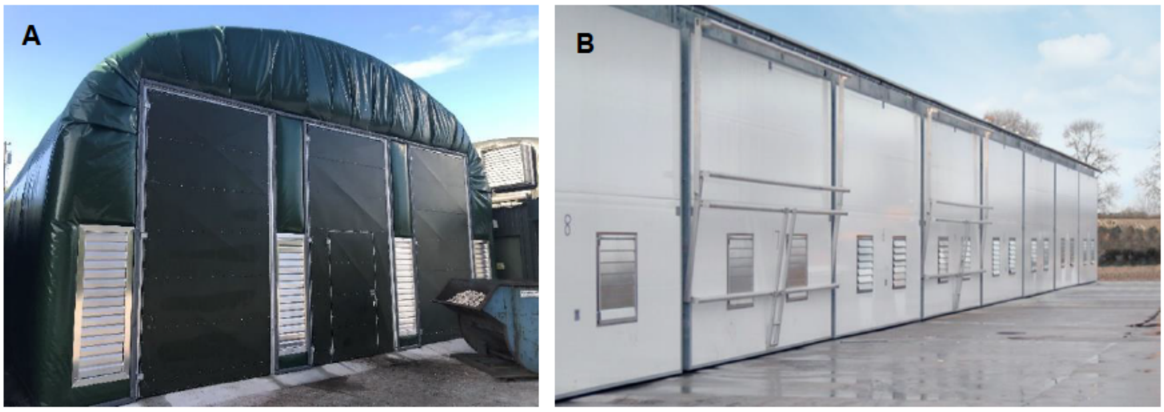

Figure 1. A: the most common type of mushroom tunnel in Ireland and B: a modern mushroom production facility.

Figure 2. Examples of Dutch shelving in mushroom tunnels.

Examples of mushroom tunnel growing area sizes:

- 540m² = 1.2m wide x 30m long x 3 rows of shelving x 5 shelves high
- 324m² = 1.2m wide x 30m long x 3 rows of shelving x 3 shelves high
- 603m² =1.34m wide x 30m long x 3 rows of shelving x 5 shelves high
- 288m² =1.2m wide x 30m long x 2 rows of shelving x 4 shelves high
- 648m² =1.2m wide x 45m long x 3 rows of shelving x 4 shelves high

Example of mushroom tunnel dimensions (Figure 3):

- Distance between rows of shelving – 1300mm
- Distance between shelves and wall – 1324mm
- Distance between sideboard and shelf above – 400mm
- Distance between shelves and doors at the front of the tunnel – 1.5-4m
- Distance between shelves and doors at the back of the tunnel (Filling end) – 1.5-3m

Example of a mushroom crop on a shelf is shown in Figure 4.

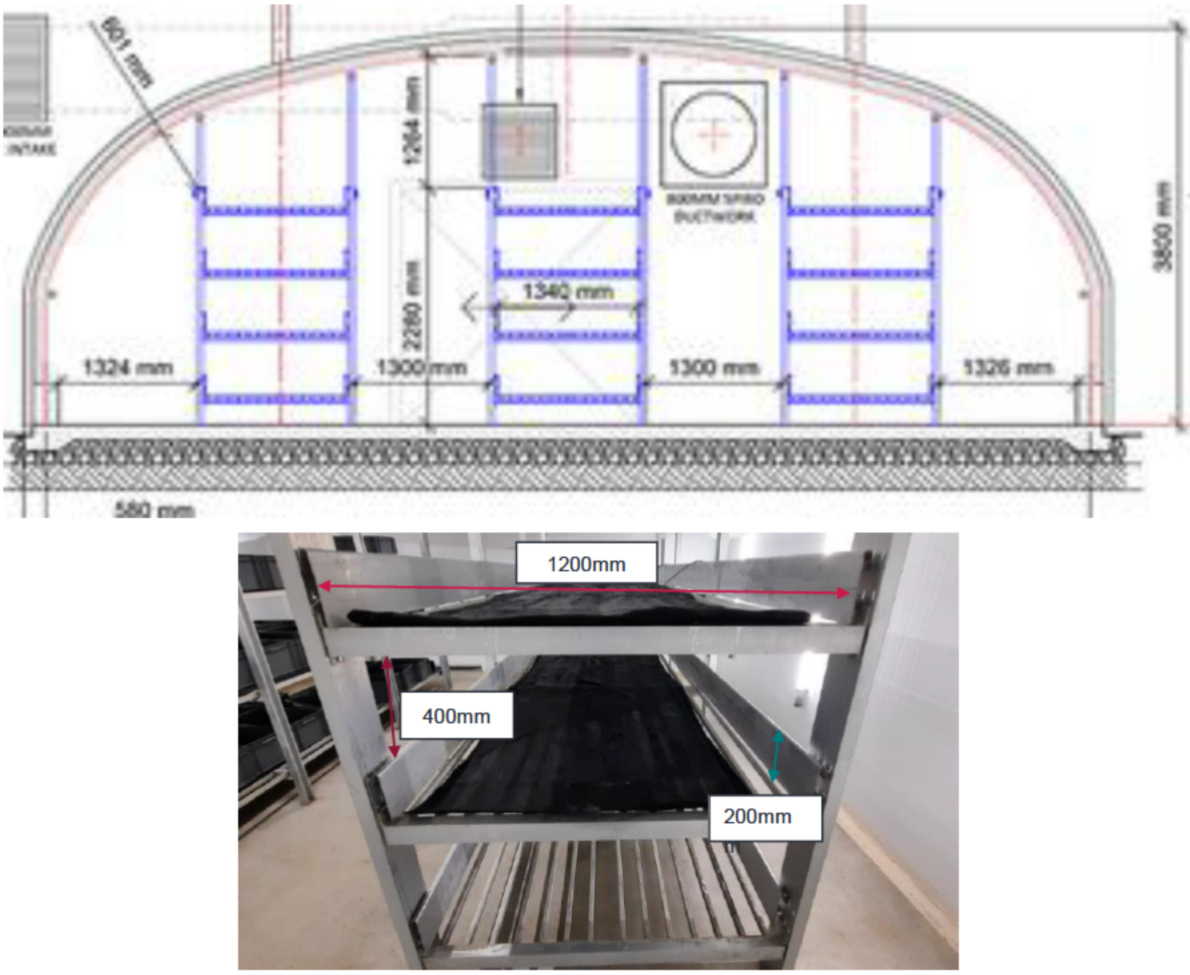

Figure 3. Mushroom tunnel and shelf dimensions. Shelves can be either 1200 or 1340 mm wide.

Figure 4. Mushroom shelf filled with 20cm of compost and 5cm of mushroom casing.

2.2 MUSHROOM GROWING ENVIRONMENT

Mushroom growing is a complex process in which the growing room climate is monitored and controlled to recreate the conditions of a typical autumn morning. This is the perfect environment for mushroom growth. Table 1 below provides the environmental parameters during each flush of mushrooms.

Table 1. Growing environment in mushroom tunnels during the growth of three flushes of mushrooms (RH: Relative Humidity).

1st Flush					
RH set points (RH %)	90/91	88/90	88/90	88/90	87/89
CO_2 Set Points (ppm)	1400/1800	1400/1800	1400/1800	1400/1800	1400/1800
Expected Air Temp (°C)	16/19	16/19	16/19	16/19	16/19
2nd Flush					
RH set points (RH %)	85/87	85/87	85/87	85/87	
CO_2 Set Points (ppm)	1000/1600	1000/1600	1000/1600	1000/1600	
Expected Air Temp (°C)	16/20	16/20	16/20	16/20	
3rd Flush					
RH set points (RH %)	83/85	83/85	83/85		
CO_2 Set Points (ppm)	1000/1400	1000/1400	1000/1400		
Expected Air Temp (°C)	17/21	17/21	17/21		

2.3 MUSHROOM YIELD IN KILOGRAMS PER CROP, PER FLUSH AND PER DAY

An average yield on a white mushroom crop is 35 kg/m² for a standard fill rate of 86 kg of compost per m². Table 2 below provides a breakdown of yield per flush in kgs per tonne of compost, total kgs produced (based on a growing room of 540 m² and 46.5 ton of compost and a fill rate of 86 kgs of compost per m²) and kgs per meter squared.

Table 2. Average yield of mushrooms for 1st, 2nd and 3rd flush based on a crop in a single growing room of 540 m² with 46.5 ton of compost and a standard fill rate of 86 kgs of compost per m².

	1st flush	2nd flush	3rd flush	Total
Kgs mushrooms/tonne of compost	218	136	54	**408**
Kgs mushrooms/crop (46.5 tonnes of compost)	10,127	6,329	2,532	**18,988**
Kgs mushrooms/m²	**18.8**	**11.7**	**4.7**	**35.2**

Table 3 provides the percentage of the crop picked each day during the 1st, 2nd and 3rd flushes. This table is based on a 540 m² growing room. The harvesting percentage for each day of the flushes vary for every crop, however these percentages are a reasonable estimate.

Table 3. Percentage of mushrooms picked each day of each flush in a single growing room of 540m² with 46.5 ton of compost and a standard fill rate of 86 kgs of compost per m².

	Day after casing	% of Flush	kgs/day based on 540 m²	Yield kg/m²	Flush
Friday	17	2%	203	0.4	1st Flush
Saturday	18	10%	1,013	1.9	
Sunday	19	30%	3,038	5.6	
Monday	20	41%	4,152	7.7	
Tuesday	21	17%	1,722	3.2	
Wednesday	22		**Total 1st Flush**	**18.8**	
Thursday	23				
Friday	24				
Saturday	25				
Sunday	26				
Monday	27	12%	760	1.4	2nd Flush
Tuesday	28	33%	2,089	3.9	
Wednesday	29	39%	2,468	4.6	
Thursday	30	16%	1,013	1.9	
Friday	31		**Total 2nd Flush**	**11.7**	
Saturday	32				
Sunday	33				
Monday	34				
Tuesday	35				
Wednesday	36	10%	253	0.5	3rd Flush
Thursday	37	50%	1,266	2.3	
Friday	38	40%	1,013	1.9	
Saturday	39	Cookout	**Total 3rd Flush**	4.7	
Sunday	40	Empty			
	Total Crop Yield for 540 m² =		**18,988**	**35.2**	

2.4 PICKING FORECAST/SCHEDULE

A single mushroom crop in a growing room generally lasts for six weeks. After this period, the room is emptied and cleaned and it is ready to have another crop filled for the next six weeks. This process goes on throughout the year. Each growing room therefore produces 8-9 crops per year. Table 4 shows the activities occurring in a standard growing room over the six-week period of a crop. With six growing rooms, being filled at weekly intervals, the farm will have a steady output of mushrooms all through the year. Most farms will have multiples of six growing rooms on their farm in order to ensure this steady output of produce throughout the year.

Table 4. Activities occurring in a standard mushroom growing room with a six-week cycle.

Day 1 Week 1	Day 6 Week 1	Day 18-22 Week 3-4	Day 28-31 Week 4-5	Day 37-39 Week 6	Day 40 Week 6	Day 41 Week 6
Fill Crop	Ruffle	1st Flush	2nd Flush	3rd Flush	Cook Out	Empty

Table 5 below is a picking forecast per day for a two-week period for a mushroom farm with 6 tunnels, each with a growing area of 540 m² per tunnel. It is clear that crops overlap each day, but production remains steady throughout the week. This production forecast varies from farm to farm depending on farm size (number of tunnels), size of tunnels, day of filling and quantity of compost filled per week.

Table 5. Picking forecast for a two-week period for a mushroom farm with 6 x 540 m² tunnels.

	Picking Schedule Kgs per day over a 2 week period (540m² Tunnel)										1st Flush	2nd Flush	3rd Flush	
Tunnel	Monday	Tuesday	Wednesda	Thursday	Friday	Saturday	Sunday	Monday	Tuesday	Wednesda	Thursday	Friday	Saturday	Sunday
1		Fill Crop					Ruffle							
2			253	1266	1013	Cookout	Empty		Fill Crop					Ruffle
3	760	2089	2468	1013						253	1266	1013	Cookout	Empty
4	4152	1722						760	2089	2468	1013			
5					203	1013	3038	4152	1722					
6												203	1013	3038
	4912	3811	2721	2279	1216	1013	3038	4912	3811	2721	2279	1216	1013	3038
	18990							18990						

The picking schedules for the 1st, 2nd and 3rd flushes of mushrooms are given in Tables 6, 7 and 8, respectively.

Table 6. Picking schedule for the first flush of mushrooms in a standard 540 m² tunnel.

1st Flush Picking Schedule							
				Harvest Type	Min Size	Max Size	Harvester Pick Rate
Day 1	Start Time	12:00	1st Pass	Large	50mm	55mm	8 - 10 kg/hour/harvester (203kgs/6 hours harvesting = 34kgs per hour/4 harvesters)
	Finish Time	18:30	2nd Pass	Seperation	20mm	35mm	
	No. of Harvesters	4	3rd Pass	Last Pass	45mm+		
			4th Pass				
	(30 minutes break)		5th Pass	Start and finish time vary depending on crop			
Day 2	Start Time	10:00	1st Pass	Large	50mm	55mm	16 -18 kg/hour/harvester (1013kgs/7.5 hours harvesting = 135kgs per hour/8 harvesters)
	Finish Time	18:30	2nd Pass	Seperation	20mm	35mm	
	No. of Harvesters	8	3rd Pass	Seperation	20mm	35mm	
			4th Pass	Large	50mm+		
	(1 hour break)		5th Pass	Last Pass	45mm+		
Day 3	Start Time	06:30	1st Pass	Large	50mm	55mm	22-24 kg/hour/harvester (3038kgs/11 hours harvesting = 276kgs per hour/12 harvesters)
	Finish Time	18:30	2nd Pass	Seperation	20mm	35mm	
	No. of Harvesters	12	3rd Pass	Graze Pick	50mm	55mm	
			4th Pass	Graze Pick	50mm+		
	(1 hour break)		5th Pass	Graze Pick	45mm+		
Day 4	Start Time	06:30	1st Pass	Large	55mm	60mm	30-32 kg/hour/harvester (4152kgs/11 hours harvesting = 377kgs per hour/12 harvesters)
	Finish Time	18:30	2nd Pass	Graze Pick	55mm+		
	No. of Harvesters	12	3rd Pass	Graze Pick	50mm+		
			4th Pass	Graze Pick	45mm+		
	(1 hour break)		5th Pass	Graze Pick	40mm+	if quality poor	
Day 5	Start Time	06:30	1st Pass	Large	45mm+		20-22 kg/hour/harvester (1722kgs/7 hours harvesting = 246kgs per hour/12 harvesters)
	Finish Time	14:30	2nd Pass	Graze Pick	40mm+		
	No. of Harvesters	12	3rd Pass	Graze Pick	35mm+		
			4th Pass	Take Down			
	(1 hour break)		5th Pass	Leave Solid Mushrooms 10-20mm			

Table 7. Picking schedule for the second flush of mushrooms in a standard 540 m² tunnel.

2nd Flush Picking Schedule					Harvest Type	Min Size	Max Size	Harvester Pick Rate
Day 1	Start Time	10:00	1st Pass	Large	50mm	55mm	15-17 kg/hour/harvester (760kgs/6 hours harvesting = 126kgs per hour/8 harvesters)
	Finish Time	17:00	2nd Pass	Seperation	20mm	35mm	
	No. of Harvesters	8	3rd Pass	Seperation	20mm	35mm	
			4th Pass				
	(1 hour break)		5th Pass	Start and finish time vary depending on crop			
Day 2	Start Time	06:30	1st Pass	Large	50mm	55mm	21 - 23 kg/hour/harvester (2089kgs/8 hours harvesting = 261kgs per hour/12 harvesters)
	Finish Time	15:30	2nd Pass	Seperation	20mm	35mm	
	No. of Harvesters	12	3rd Pass	Seperation	20mm	35mm	
			4th Pass	Large	50mm+		
	(1 hour break)		5th Pass	Last Pass	45mm+		
Day 3	Start Time	06:30	1st Pass	Large	60mm+		25 -27 kg/hour/harvester (2468kgs/8 hours harvesting = 309kgs per hour/12 harvesters)
	Finish Time	15:30	2nd Pass	Graze Pick	55mm+		
	No. of Harvesters	12	3rd Pass	Graze Pick	50mm+		
			4th Pass	Graze Pick	45mm+		
	(1 hour break)		5th Pass				
Day 4	Start Time	06:30	1st Pass	Large	55mm+		14-16 kg/hour/harvester (1013kgs/6 hours harvesting = 169kgs per hour/12 harvesters)
	Finish Time	13:30	2nd Pass	Graze Pick	50mm+		
	No. of Harvesters	12	3rd Pass	Graze Pick	45mm+		
			4th Pass	Graze Pick	40mm+		
	(1 hour break)		5th Pass	Take Down			

Table 8. Picking schedule for the third flush of mushrooms in a standard 540 m² tunnel.

3rd Flush Picking Schedule							
				Harvest Type	Min Size	Max Size	Harvester Pick Rate
Day 1	Start Time	12:00	1st Pass	Large	50mm+		17-19 kg/hour/harvester (253kgs/3.5 hours harvesting = 72kgs per hour/4 harvesters)
	Finish Time	16:00	2nd Pass	Large	45mm+		
	No. of Harvesters	4	3rd Pass				
			4th Pass				
	(30 minutes break)		5th Pass	Start and finish time vary depending on crop			
Day 2	Start Time	10:00	1st Pass	Large	45mm	50mm	30-32 kg/hour/harvester (1266kgs/5 hours harvesting = 253kgs per hour/8 harvesters)
	Finish Time	16:00	2nd Pass	Large	40mm+		
	No. of Harvesters	8	3rd Pass	Large	35mm+		
			4th Pass				
	(1 hour break)		5th Pass				
Day 3	Start Time	08:00	1st Pass	Large	40mm+		24-26 kg/hour/harvester (1013kgs/5 hours harvesting = 203kgs per hour/8 harvesters)
	Finish Time	14:00	2nd Pass	Large	35mm+		
	No. of Harvesters	8	3rd Pass	Take Down			
			4th Pass				
	(1 hour break)		5th Pass				

2.5 HARVESTER PICK RATE

Harvester pick rates differ significantly from harvester to harvester. Factors which influence pick rate are:

- Harvester speed;
- Product mix (% baby button mushroom, % value pack, etc) which is required by the marketing company);
- Mushroom Size specification – Some marketing companies require a relatively small closed cup mushroom (35-50mm) where as other marketing companies allow closed cup mushrooms up to 60mm;
- Quality – Poor quality mushrooms on the bed may result in the harvester needing to dump mushrooms which will slow down pick rates.

An average harvester weekly pick rate is 25 kgs/hour based on a 40-hour working week. This means an average harvester has the ability to pick 1000 kgs of mushrooms per week. Some farms can achieve better average pick rates due to a more advantageous product mix or mushroom size specification. Table 9 shows the pick rates for a sample team of harvesters who pick in a 1st flush over a 1-week period. The huge variation in picking speeds and kgs/m² (yield) can be seen.

Table 9. Pick rates for a sample team of 16 harvesters picking a 1st Flush of mushrooms over one week (BB = baby buttons; VP = value pack).

Harvester	Total Kg picked per week	Kg/m2	kg/h	Hour Rate based on kgs picked	BB%	VP%	close clup %	Total hours
A	1176	21.4	30.9	12.47	12	2	86	38
B	1189	21.6	30.5	12.07	12	5	83	39
C	1113	20.2	26.5	10.96	14	4	82	42
D	1162	21.1	28.3	11.11	14	3	83	41
E	1146	20.8	29.4	12.07	12	5	83	39
F	1144	20.8	26.6	10.42	15	4	81	43
G	1077	19.6	26.3	10.89	15	4	81	41
H	1136	20.7	27.7	11.47	15	5	80	41
I	1017	18.5	24.8	10.61	14	4	82	41
J	1045	19.0	28.2	11.9	15	3	82	37
K	912	16.6	24.6	11.01	16	3	81	37
L	1031	18.7	25.8	11.35	16	3	81	40
M	1010	18.4	26.4	11.73	16	2	82	38.2
N	950	17.3	24.4	10.24	14	4	82	39
O	891	16.2	24.1	10.63	14	3	83	37
P	859	15.6	22.0	9.55	13	2	85	39

2.6 PICKING AREA PER HARVESTER

Each harvester is designated sections of the mushroom crop. The harvester has full responsibility for the yield (kg) and quality of the harvested mushrooms from these allocated sections for the duration of the flush. Harvesters are allocated sections based on:

- The harvester's recent picking performance (kgs/hour) – A harvester who has low pick rates will be allocated picking area based on his/her ability e.g. a new harvester will get a smaller area to harvest compared to an experienced harvester.
- How heavy the crop is – If a section is very heavy, the grower will select a fast and experienced harvester to pick this section to ensure the area is picked correctly and to ensure no quality defects will occur.
- Stage of the crop – At the early stages of the crop, harvesters can be given larger sections as the crop may only need to be 'separated' with a low volume of mushrooms that require harvesting.
- Manual or Automatic picking trolley – Manual picking trolleys (Figure 5) require harvesters to manually move the picking trolley along the shelves. These harvesters would require a small section in comparison to harvesters with automatic trolleys (Figure 6), which are electrically powered and move automatically.

Figure 5. Manual picking trolley

Figure 6. Automatic picking trolley

2.7. GENERAL HARVESTING RULES

The main principles of mushroom harvesting that result in high quality mushrooms can be summarised as follows:

- Light touch
- Upward twisting motion
- No double handling
- All mushrooms in line for trimming
- The cut is square to the stalk
- Mushrooms are placed gently in punnets/packaging
- No mushroom throwing into the packaging
- No mushroom transfer
- No over-topping of the punnets.

In addition:

- Always move forward during harvest. It will allow the harvester to see the state of the beds clearly and make the right decision on what to harvest. While operating electric picking lorry, harvesters may harvest in both directions, i.e. forward and backwards.
- Always harvest mushrooms from the edge of the shelf towards the centre to avoid knocking over or damaging nearer mushrooms.
- Always harvest mushrooms with left hand and cut the stalk with right hand in case of right handedness. In case of left handedness, harvest mushrooms with right hand and cut stalk with left hand. Never transfer mushrooms from one hand to another or transfer mushrooms from punnet to punnet.
- Harvest mushrooms with twist and pull motion using the 'One Touch Picking Technique'. However, do not use twisting pulling motion for brown mushrooms, because mushrooms can leave without the stalk. Breaking motion has to be used for brown mushrooms.
- Do not roll and squash mushrooms in the hand.
- Always cut the mushroom stalk according to product requirements.
- During the final pass of the day harvest all weak mushrooms with long stems and stretched veils, irrespective of their size, to reduce Grade 2 the following day. Make sure there are 'no dead men' on the beds – (mushrooms uprooted/knocked over and lying on the bed).
- On the final day of pick off leave solid 10-15 mm mushroom on the bed, 10 cm apart from each other, which will develop into future interflush mushrooms, and will improve the quality of second and third flushes.

2.8 SEPARATION OF THE CROP

Separation is a vitally important process to maximise the yield and quality of mushrooms from a crop. Separation is the process of 'thinning' of the crop of mushrooms on the bed which is done mainly on day 1 and day 2 of the first and second flushes and involves looking at the crop and deciding which mushrooms should be sacrificed to maximise the yield and quality from the remaining mushrooms for the following days (Figure 7). For brown mushrooms light separation is done mainly in day 1. The farm manager plays a crucial role in managing the crop to ensure there is a good even spread of mushrooms that can be harvested easily. Certain terms are used to describe different features of a mushroom crop and the separation process and these are explained below.

Figure 7. Separating out small mushrooms to give other mushrooms room to grow.

Clump: A 'clump' is an area with 5 and more mushrooms in the same area touching each other (Figure 8).

Figure 8. A mushroom clump

Leader: A 'leader' is the largest mushroom in the clump that protrudes on top of other mushrooms. There can be number of leaders in the clump (Figure 9).

Figure 9. A clump with a number of leader mushrooms.

Stagger/Spread: The 'stagger' or 'spread' of mushrooms is the variety of different sizes of mushrooms across the bed, usually 4-6 sizes.

Figure 10. A spread of different sized mushroom sizes across the bed.

Pass: A 'pass' is one complete movement across the harvesting area allocated to a harvester. For example, in a growing room with shelves at three levels, a harvester would typically be allocated five x 2 sets of 'windows' for the day as their harvest area (a window is the 1.5 m wide distance between two upright shelf supports) (Figure 11). Harvesters would make several passes across their allocated area during the day.

Figure 11. Allocated area for a harvester to work on.

Optimum size: Optimum size is the maximum size the mushroom can grow without quality deterioration. It refers to the point of harvesting that guarantees the best return in yield and price for every mushroom. Optimum size may differ from mushroom to mushroom. For example optimum size for a mushroom that has no room to grow may be a cap of 20-30 mm.

Graze picking: Graze picking is the term used to describe the harvesting system that involves harvesting each area of bed more frequently (e.g. five faster passes throughout the day with each pass harvesting a specific size instead of a single slower pass harvesting a range of different mushroom sizes at the same time). Graze picking ensures that mushrooms are harvested at their optimum sizes over a number of passes and it provides a higher yield for the bed area.

Objectives of the separation process:

- Create stagger
- Maintain stagger
- Improve quality throughout the flush
- Increase yield and revenue per house
- Control of disease

Reasons for the separation process:

- A mushroom respires – it takes in oxygen (O_2) releases carbon dioxide (CO_2)
- If CO_2 builds up around the mushrooms they begin to suffocate and die. That will also trigger them to open, and shed their spores before they die.
- If the mushrooms are left in dense clumps they have to compete against each other for O_2. The result will be that they grow long stalks and try to open, producing 'leggy' mushrooms that become weaker and are of poor quality.
- If mushrooms are not separated out of tight clumps (Figure 7), the less room there is for the mushrooms to grow. Because mushrooms grow so fast, (doubling in size every 24 hours) mushrooms clumps will grow into each other and become misshapen and of poor quality.

- The tighter the clumps, the harder they are to pick, so pick rates suffer.
- The tighter the clumps the smaller the size of mushroom that has to be picked to open up the clump, reducing the yield.
- The tighter the clumps of mushrooms are, the more difficult it is to get water into the casing bellow the crop of mushrooms. Water can sit on top of the clumps where it can trigger the development of bacterial blotch disease, which cause brown coloured blemishes on the mushrooms, and any affected mushrooms would then be discarded as waste.
- Mushrooms consist of 95% water. The more the water applied to a crop, the bigger and better it will be.

Separation strategy: The separation strategy for a given crop depends on the following conditions:

- Flush number
- Day of the crop
- Pinning level (underpinned, over-pinned, normally pinned)
- Mushroom stagger (absence/presence)

2.9 MUSHROOM SELECTION FOR HARVESTING

The photo below (Figure 12) is of the 2nd day of a 1st flush. The dots in green are the mushrooms to be picked first as these mushrooms have reached their optimum size. The dots in blue are the principle mushrooms which **must not be harvested on this day** of harvesting as these mushrooms have the potential to grow to a larger size (55mm). The dots in red are those mushrooms which need to be picked small as part of the separation pass in order to allow the other mushrooms reach their optimum size. Figure 13 shows how significant mushroom yield can be lost if smaller mushrooms are harvested – as can happen with less skilled harvesters.

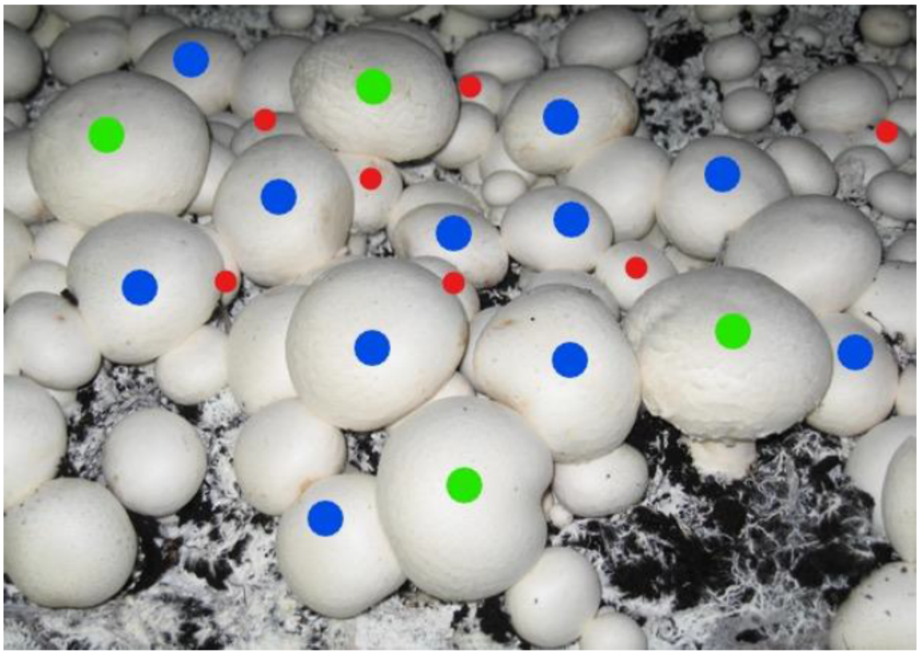

Figure 12. Selecting mushrooms for harvesting: Green = First Pass Mushrooms which require picking; Blue = Principle Mushrooms for tomorrow – must not be picked today as they can grow to optimum size; Red = Separation Mushrooms – mushrooms that must be picked from the clump to allow others reach their optimum size.

Figure 13. The 6 mushrooms of 55 mm on the left weigh the same as the 9 mushrooms of 45 mm on the right.

2.10 MUSHROOM QUALITY DEFECTS

Quite often a lovely crop of good quality white mushrooms is seen on the bed or they look well harvested and ready for transport in the farm fridge but later they may be rejected by the pack house or the customer depots. This can be the result of poor mushroom handling. When the mushrooms are handled incorrectly, or too frequently, the damage is not apparent immediately after the pick but only appears post-harvest, after a couple of hours or in a day or two.

Unlike most vegetables, mushrooms do not have a cuticle to protect them from physical damage. Mushrooms are very delicate and are quite vulnerable. If they are handled incorrectly or too frequently they will show denting, bruising or damage.

The main causes of mushroom handling damage are:

- Poor picking method – pulling of mushrooms, rough handling, rolling the mushroom in the palm.
- Double handling.
- Incorrect trimming of the stems.
- Incorrect placement in containers.

During grading at the packhouse the following parameters are taken into account:

- Compliance with the sizing and quality requirements of the customer
- Shape of mushroom
- Colour of mushroom (white/off-colour)
- Open/Closed mushroom
- Extent of feathering
- Level of peat adhering to the mushroom
- Extent of cap damage
- The 'cuppiness' of flat mushrooms
- Presence of disease and flies

Some of the important terms are described below.

Sizing: Size bandings must be strictly adhered to, as customers will reject if product is outside agreed size range.

Control measures: A measuring-ring or calliper should be used at the beginning of the shift and during the day if required to ensure correct size is being harvested (Figure 14). Picking one specified size and using one type of packaging at a given time will ensure the uniform sizing in the punnet.

Figure 14. Accurate sizing of mushrooms requires skill and precision.

Feathering levels: Any “stress” during the early growing stages, for example sudden changes to temperature, humidity or air movements will cause damage to the skin of the mushroom. This damage becomes apparent as the mushroom reaches harvest size and is known as feathering (Figure 15). Light, clean, unsoiled, non-discoloured feathering is acceptable. Heavy or brown feathering is not permitted and will be rejected by customer. Note: Feathering is a natural characteristic on large flat mushrooms.

Control measures: Feathering is controlled during the growing process.

Figure 15. Unacceptable heavy feathering on a mushroom

Discoloration*:* Discoloration (Figure 16, left) directly leads to downgrading or rejection and is caused by:

- Heavy handling during picking and presentation of product in punnets.
- Dirty gloves (Figure 16, right)
- Rough handling during transportation.
- By abuse during packing (e.g. double handling, shaking punnets).

Control measures: Good training and supervision of harvesters will help ensure good picking and handling technique. Gloves should be changed regularly during the day. Between five and ten changes of gloves will be needed by a harvester per day, depending on the crop.

Figure 16. Left: Mushrooms showing handling damage; Right: Dirty gloves can leave marks on the mushrooms.

Disease and pests: Under certain conditions mushrooms are susceptible to certain diseases, the presence of these in any pack of mushrooms is a defect (Figure 17). The pests that are most likely are flies – there are two or three small mushroom fly pests that can infect mushroom crops and so can be in the mushroom tunnel when the crop is being harvested. Customers have zero tolerance of disease as well as of flies and will reject produce if an infestation of flies is located in the product. Some diseases that affect mushrooms may not be obvious on the mushrooms at harvest time but if spores are present on the mushrooms they can grow inside the punnet post-harvest.

Control measures: The crop management on mushroom farms should ensure that strict hygiene control is in place and that levels of disease and pests are kept under control.

Figure 17. Left: Mushrooms showing browning; Middle: mushrooms showing disease; Right: mushroom fly on a mushroom

Peat levels: Mushrooms grow on a bed of compost which is covered with a peat-based casing layer (Figure 4). Thus, the mushroom is rooted in the peat layer, which often results in the attachment of peat onto the stem and surface of mushrooms. Growers aim to ensure that mushroom pins form close to the surface of the peat layer and not deep within it, which can also result in peat on the mushrooms (Figure 18). The smaller the mushroom, the closer the mushroom cap to the casing layer; therefore, the greater amount of peat that may be present.

Control measures: More care should be taken during ruffling to ensure the mushrooms are presented well during the flushes. Vigilance is also needed during harvesting to eliminate fibres from the casing adhering to the mushrooms and ending up on the product.

Figure 18. Mushrooms with high, medium and low levels of peat contamination (left to right)

Misshaped mushrooms: Misshapen caps are caused by inadequate space surrounding the mushroom during growing to allow it expand unrestricted.

Control measures: Misshaped mushrooms that occur prior to start of the pick can be a growing issue. When picking commences at the start of the crop, the crop should be separated on time to avoid misshapen mushrooms.

Figure 19. Misshapen mushrooms

Stem rot: Stem rot is mainly associated with flats but can occur at all development stages of a mushroom.

Figure 20. Stem rot in mushrooms

Cuppiness: Cuppiness refers to the shape of the flat mushroom. The shape and cuppiness will vary in flats; this is caused by age and growing techniques. The presence of inverted flats or lack of cup shape is due to the flats not being harvested at their optimum growth stage.

Figure 21. Open mushrooms with acceptable and unacceptable levels of cuppiness.

3 AUTOMATED PICKING SYSTEMS

The idea of the robotic harvesting of mushrooms is not new and there has been steady development of technologies and systems that speed up the harvesting process and which can be adapted to fully robotic harvesters as and when they become available. The types of systems being developed include (a) systems that can be integrated into an existing farm with low level of investment, (b) systems that may require some modifications to existing farms and require moderate investment or (c) systems that are designed as a complete new build, with robotic-use firmly in focus, and requiring major capital investment. While new entrants to the sector may opt for custom designed facilities geared towards robotic use, many existing growers will be looking for systems that can integrate with their existing infrastructure. Some of the systems currently receiving attention in the mushroom growing world in Europe and North America are described briefly below.

3.1 TILTING SHELVES

The tilting shelf system is currently being developed by two engineering and construction companies who are both based in The Netherlands (1) Christiaens Group and (2) GTL Europe, with the aim to increase harvesting efficiency. It is based around a standard Dutch shelf that is divided into two sections that tilt towards the harvester at a 45 degree angle (Figure 22). This makes it much easier for the harvester to see the crop of mushrooms and harvest the correct mushroom. The tilting shelf eliminates the strain of reaching across the mushroom bed to harvest mushrooms, which in turn speeds up the picking process. The shelves are only tilted during harvesting and they return to the horizontal position once picking has ceased. A mushroom conveyor runs alongside the shelves, where the harvester places the mushroom into designated slots, and the conveyor transports these mushrooms out into the central corridor. Thus, the harvester can use both hands to harvest mushrooms, increasing the pick rate.

Figure 22. Tilting shelf system - the left side of the second shelf is tilted for harvesting while the other shelves remain flat until ready to harvest.

In the central corridor, mushrooms arriving on the conveyor have their stalks removed by a stalk cutter providing consistent optimum stalk length. The mushrooms are then either removed from the belt manually or by a robot, and then placed into a punnet. This punnet can then be transported to the packhouse if required. Installing a robot that can effectively place the mushroom into the punnet is a huge benefit as this eliminates the need for a harvester to do that job and the average pick rate on the farm will increase significantly. Modifications to the compost and casing filling machine would be required to accommodate filling a crop into the tilting shelves system, which is an additional cost that needs to be factored into the equation when considering investing in this system. The system may also lend itself to robotic harvesting in the future but there may be challenges with getting a robot to operate within the environmental conditions of a large growing room.

3.2 CHRISTIAENS GROUP DRAWER SYSTEM

The drawer system for efficient growing and harvesting is a new system also being developed by the Christiaens Group whereby a farm is designed so that crop shelves are winched across from one growing room to another during the harvest period. A picking station is located in the central corridor, so the harvesters are stationary and the crop passes in front of them (Figure 23). This is in comparison to the conventional picking system where the crop is stationary and the harvesters move through the crop within the tunnel. With the drawer system, the crop can be pulled across from one growing room to another several times a day to allow the harvester to easily graze pick and thus maximise mushroom size and yield. The harvested mushrooms are placed on a rotating disc which cuts the stem and they are then manually removed to be placed into the punnet or tray.

The two big advantages to this system are that the harvester only needs to focus on one area to pick mushrooms and it is visually much easier to identify and pick the correct mushroom as there is no crop directly above the shelf being picked. This system is designed to allow for robotic picking to be introduced in the future when it becomes available.

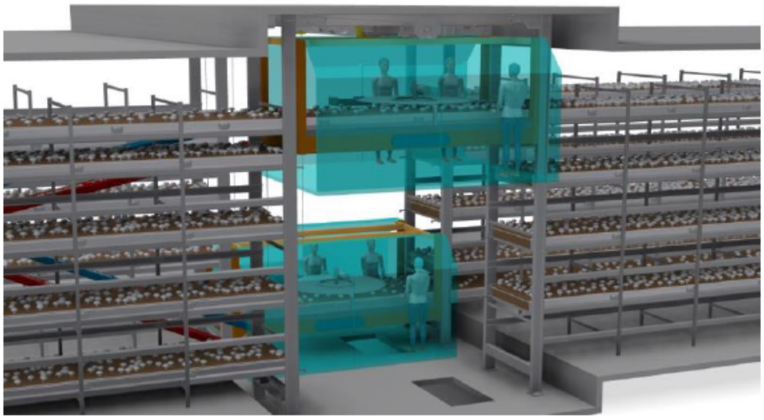

Figure 23. Drawer system with a central stationary picking platform.

3.3 VAN DEN TOP SINGLE LAYER SYSTEM WITH PICKING BRIDGE

A single layer system has been developed by Van den Top Mushroom Equipment, another Dutch company, which involves crops being grown in specific growing rooms on traditional Dutch shelving up until mushrooms are ready to be harvested. The shelves are then winched individually into the harvesting room, where the crop is brought down to a single layer which makes it easier for harvesters to pick. Harvesting is done in conjunction with a semi-automatic picking bridge. The system allows for two handed picking onto a conveyor with a specific mushroom holder. The mushrooms are transported, trimmed and then removed from the conveyor via a robot and placed in the punnet.

The advantage of this system is that the crop is much easier to pick at ground level compared to picking at the high levels associated with traditional picking trollies. Harvesters are much happier picking at ground level as the crop is easier to see as there is no shelf above it. Pick rates are much higher on this system. This system could not be implemented on an existing conventional farm so would require a new build and major investment. A major challenge for the single layer system is managing the growing environment in the picking room as air flow can be difficult to control which could result in quality issues. Another factor which needs to be considered is that a grower would need to acquire a larger site to construct this system in comparison to the traditional conventional system. The system lends itself to fully robotic harvesting in the future when this becomes available.

Figure 24. A single layer farm where the shelves of mushrooms are destacked and winched into a dedicated single layer picking room (left) and harvesting by hand is then done in conjunction with a semi-automatic picking bridge (right).

3.4 AXIS MUSHROOM PROCESSING UNIT AND CONVEYOR

A mushroom processing unit and conveyor system has been developed by Axis Technology, Northern Ireland, who are working in collaboration with a Canadian mushroom grower to enhance harvesting and picking efficiency (https://www.youtube.com/watch?v=T83I8WXviCY). This system involves a conveyor installed alongside existing Dutch shelving which transports mushrooms to the end of the shelf where the mushroom processing unit (MPU) is placed (Figure 25). This machine collects the mushrooms off the harvesting conveyor line, and the stalks are cut at the desired optimum length before placement into the correct punnet based on the mushroom size which the operator sets at the beginning of production. The processing machine is transferable between harvesting lines and tunnels so the farm would only need to invest in a number of these machines based on the number of tunnels harvesting at any given time. The conveyor would need to be installed in each stack of shelves in each tunnel.

This system will allow harvesters to pick mushrooms with both hands and will cut out tasks such as cutting the stalk, grading the mushrooms and weighing the punnet. Other secondary tasks such as emptying the stalk bucket, preparing harvesting equipment and obtaining packaging will also be eliminated. This system can be integrated into the existing Dutch shelving system and the existing picking trolleys can be utilised also. The system may also lend itself to robotic harvesting in the future, but there may be challenges with getting a robot to operate within the environmental conditions of a large growing room.

Figure 25. The Axis mushroom processing unit.

3.5 REEST GRIPPER SYSTEM

A recent introduction to the mushroom harvesting aid market is a suction gripper system developed by Reest in Ukraine. The system uses a vision system and suction device to identify and harvest mushrooms. Little is known about this system at the moment apart from what is available on YouTube (https://www.youtube.com/watch?v=mlsFbJvIqRk).

3.6 SUMMARY

All these systems are designed with one aim in mind - to increase harvesting pick rates which would allow a farm to reduce the harvesting workforce. All these systems achieve this target with average pick rates achieved of between 55 – 80 kg/hour which is a significant increase on the average 25 kg/hr reported above with a traditional system. An advantage is that fewer harvesters are required to pick the same amount of growing area which is a huge benefit. Harvester training costs are significantly reduced as the picking process is simplified and new pickers can achieve relatively high pick rates in a short period of time.

However, there are still significant challenges associated with any of these systems. Significant capital investment is required for growers to invest in any of these automated systems. Although these systems have been installed in farms in Europe and Canada, there is still no guarantee that they will be a success on Irish and UK farms who harvest a higher percentage of high quality mushrooms such as baby buttons and small closed cup mushrooms. A disadvantage is that most of these systems are unable to accommodate large flat mushrooms which need to be placed in punnets upside down to present the under surface to the customer. These small factors can have a major influence on productivity and the rate of the return on investment. Some automated systems cannot be integrated into existing units which means a new farm would need to be constructed which represents a major capital investment.

The quality and presentation of the mushrooms are also important factors to be considered when investing in automated technology. Some of these systems allow for or require double handling of the mushrooms: the first handling occurs when they are picked off the crop and placed on the conveyor and the second handling occurs when they are picked off the conveyor to be placed in the punnet. This results in mushrooms being bruised and marked. Mushrooms placed in punnets by robots can also be an issue as they are not presented attractively in comparison to a harvester's presentation. Currently, robots placing mushrooms into punnets are not able to grade poor quality mushrooms (e.g. with casing on, misshapes) and these mushrooms may end up in a high grade product which could lead to customer rejections.

4 FORCES CAUSING DAMAGE TO MUSHROOMS

Mushrooms are a fragile product that can be easily bruised and damaged by mishandling, resulting in brown discoloration that can lead to the product being rejected by retailers and consumers. Thus, the process of harvesting of mushrooms is a critical step to ensure that the maximum quality of the product is maintained. A **'one touch'** approach can achieve this - meaning that the mushrooms are handled only once between harvesting and placing in the final container destined for the consumer.

4.1 MECHANICAL AND PHYSICAL PROPERTIES OF MUSHROOMS

The mechanical and physical properties of mushrooms change as the mushroom develops. Seven mushroom growth stages have been categorised (Hammond and Nichols, 1975, 1976) (Figure 26) although in modern commercial mushroom production the sizes of each growth stages 2 – 7 can vary depending on crop and customer requirements. Mushrooms are firmer when smaller and become softer as they expand and grow (Figures 27). This correlates with an increase in the moisture content of the mushroom as it expands from pinhead stage to flat mushroom stage.

Bruising damage is one of the main factors causing quality loss in mushrooms. It takes place during mushroom harvesting, handling and transport. Bruising is usually caused by 'slip-shear' forces which combine a normal force on the mushroom surface with a shearing action, as might happen when harvesting a mushroom from the mushroom bed - fingers can slip across the mushroom surface, especially during the twisting action needed to uproot the mushroom – or when mushrooms roll around in a punnet, brushing and sliding against each other and the sides of the container. The firmer the force the greater the bruising.

Stage 1 Pinhead	Stage 2 Button	Stage 3 Closed Cup	Stage 4 Cup Veil breaking	Stage 5 Cup Veil torn, gills visible	Stage 6 Flat Gill surface concave	Stage 7 Flat Gill surface flat/convex
< 5 mm	20-30	30-40	30-40	30-50	40-60	50-70

Figure 26. Developmental stages of mushrooms – adapted from Hammond and Nichols (1975; 1976) and current commercial grades used in Ireland and the UK.

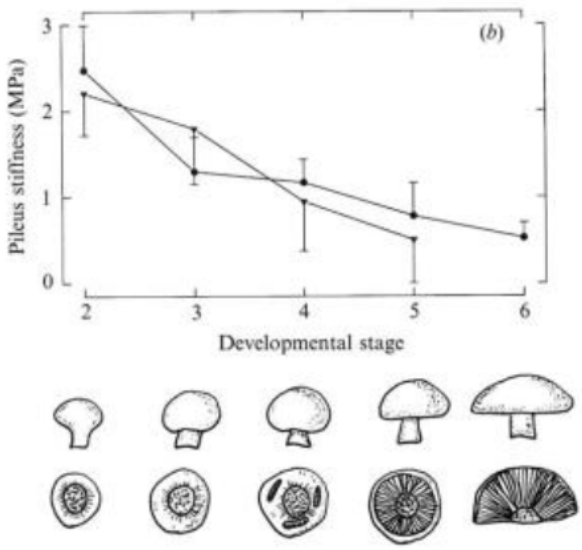

Figure 27. Effect of pre-harvest (●) and post-harvest (▼) development at 18°C on pileus (cap) stiffness. Bars indicate standard deviation (From McGarry & Burton 1998).

Mushroom bruisometer machines have been developed to apply a known force to a mushroom coupled with a shear action in order to quantify the bruising response. Burton & Rama (1999) and Burton 2000 developed and evaluated a bruisometer (Figure 28) over a series of experiments and identified a set of conditions that were suitable to measure the bruising response of mushrooms to a standard force. Mushrooms are held by a triangular arrangement of spikes on a pivot-bed. A variable force can be applied incrementally by means of block-masses of e.g. 15 g weight (0.147 N), with additional block-masses added up to a maximum of 195 g (1.92 N). The slip-shear force is applied by pivoting the mushroom over a range of 50 degrees. After incubation at 20°C for a period of time mushroom colour at the top of the mushroom is measured using a Minolta colour meter, which gives L, a and b readings. Degree of discoloration was determined using the formula [Log_{10} (100-L)]. It was decided that two passes of a 200 g (1.97 N) force gave the best data to discriminate bruising susceptibility after 2 hours (Figure 29) and these conditions were used in subsequent work (Burton 2002). Experiments with commercially grown mushrooms indicated that they bruised more easily (Figure 30).

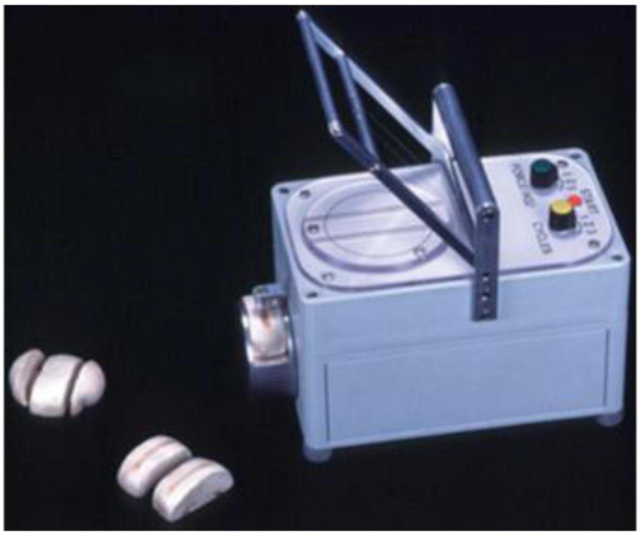

Figure 28. Mushroom bruisometer device developed following work by Burton & Rama (1999)
https://www.teagasc.ie/media/website/publications/2010/Kerry_Burton.pdf

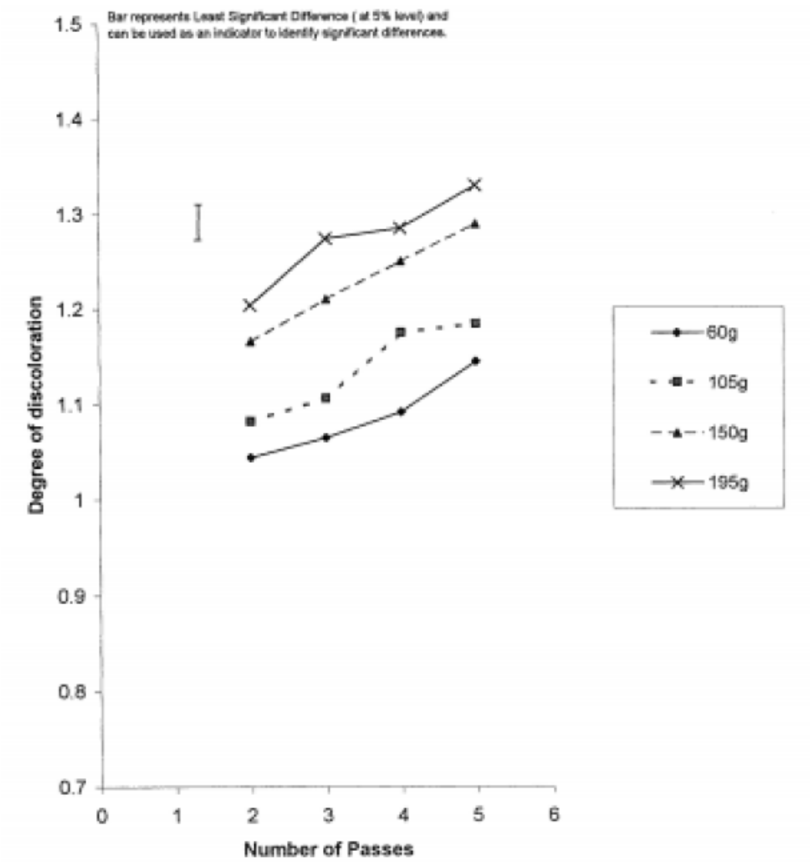

Figure 29. Data from Burton & Rama (Report M19a); An L value of 100 = pure white; a DoD score of 0.7 represents a very high-quality mushroom with an L value of 95; a score of 1 represents a moderate quality mushroom with an L value of 90; a score of 1.2 represents a bruised mushroom with an L value of 84.

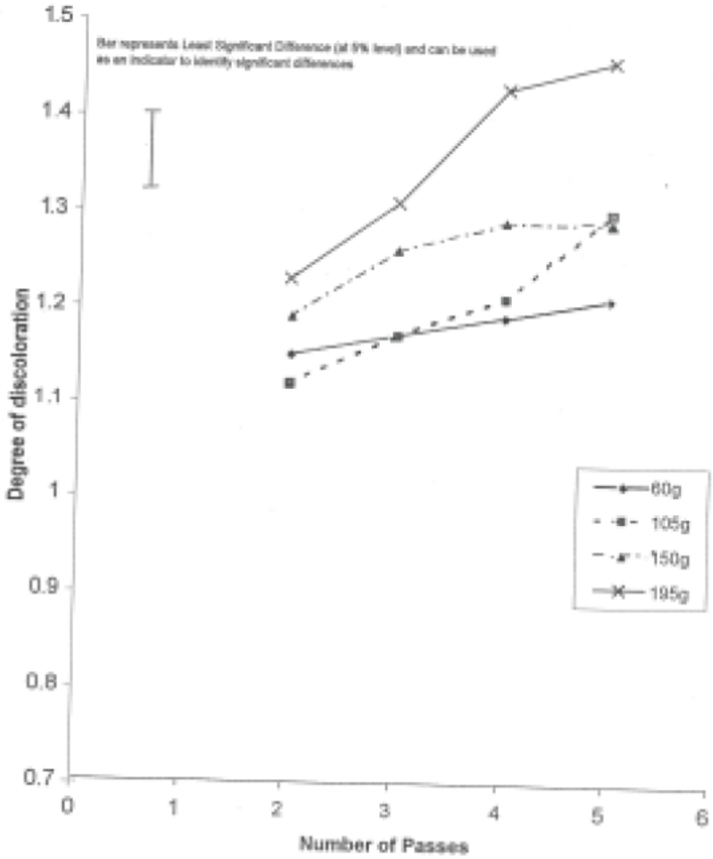

Figure 30. Data from Burton & Rama (1999) for commercially-grown mushrooms. An L value of 100 = pure white; a DoD score of 0.7 represents a very high-quality mushroom with an L value of 95; a score of 1 represents a moderate quality mushroom with an L value of 90; a score of 1.2 represents a bruised mushroom with an L value of 84; a score of 1.4 represents a bruised mushroom with an L value of 75.

A second bruisometer was developed by Weijn et al. (2012) where a 40 g weight was attached to a spatula and mushrooms were subjected to three passes of the spatula to cause bruising (Figure 31). Colour changes due to bruising treatments were measured by a computer imaging system combined with a software programme, which transformed the image data to equivalent CIE L*, a*, b* values. They calculated a 'Whiteness index' (WI) using the formula L-(3 x b*) and calculated a Whiteness Index difference as the difference between the WI of the control and the WI of the bruised sample (Figure 32).

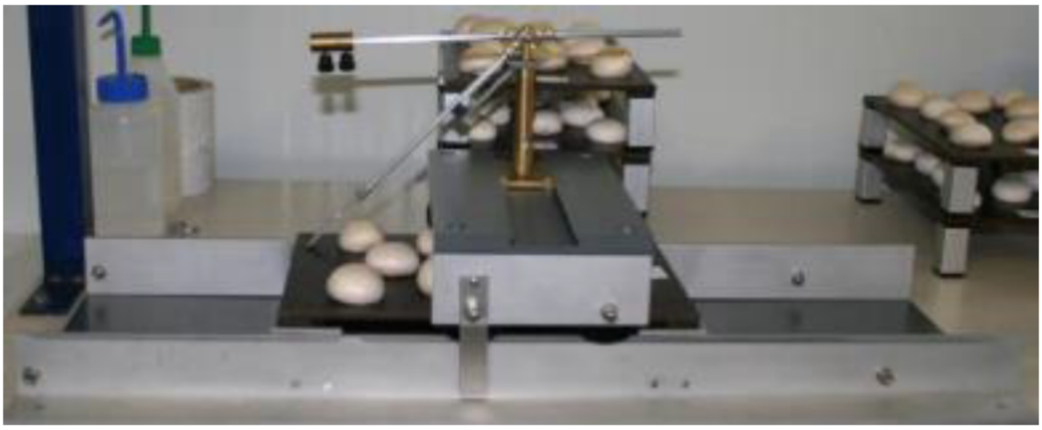

Figure 31. Bruising device from Weijn et al. (2012).

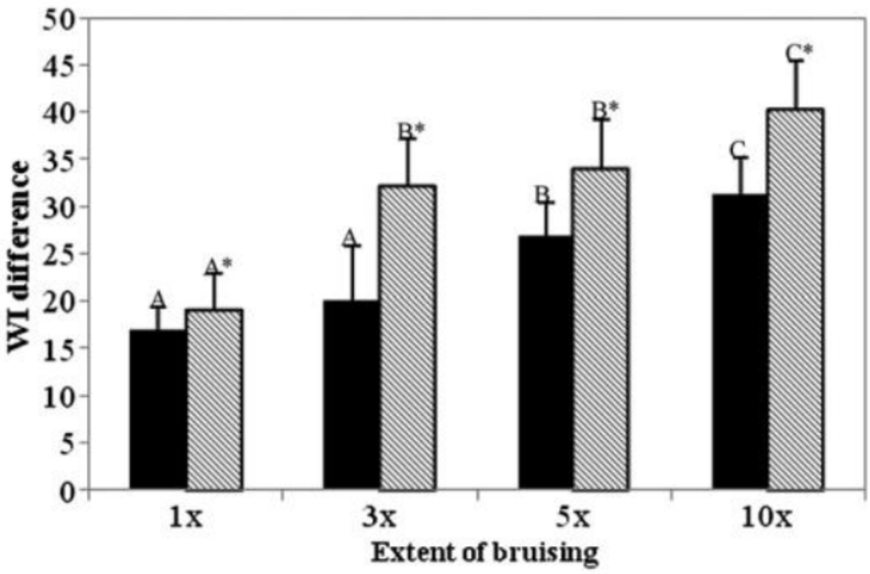

Figure 32. Data from Weijn et al (2012) on bruising of mushrooms. Original caption: [Bruising of mushrooms 1,3, 5 or10 times with the spatula. WI difference was determined for the60 min pictures for 2 different strains. The black bar is Le Lion X20 and the grey bar is Sinden A61. Error bars are from the standard deviation. Significance is indicated per strain, Le Lion X20 is normal letter, Sinden A61 is letter with asterisk. Values from the strain with the same letter are not significantly different at the 0.05 level].

4.2 MEASURING BRUISING DAMAGE IN SOFTGRIP

We anticipate evaluating bruising damage caused by the SoftGrip gripper device in a similar way to the work described above by conducting controlled bruising experiments. A range of gripper forces will be applied and the resulting bruising damage measured using a Minolta colour meter (Figure 33). Threshold forces that cause no or minimal bruising damage can be identified to inform the development of the gripper.

Figure 33. Measuring bruising damage post-harvest on mushrooms with a Minolta colour meter.

5 FOOD SAFETY ASPECTS OF MATERIALS

The materials used for the soft gripper and the robot parts will need to be 'food safe', meaning that they are approved for uses where they can come into contact with food. The materials must be manufactured in compliance with EU regulations, including good manufacturing practices, so that any potential transfer to foods does not raise safety concerns, change the composition of the food in an unacceptable way or have adverse effects on the taste and/or odour of foods. In the case of SoftGrip all materials involved in the external soft-gripper structures and their manufacturing practices will comply with the directives laid down in the Regulation EC 1935/2004 on materials and articles intended to come into contact with food. The Good Manufacturing Practice for materials and articles intended to come in contact with food as described in Regulation EC 2023/2006. Work will be undertaken to characterise any potential food-safety issues that need to be addressed before using a fully functioning SoftGrip system in a commercial setting. The European Food Safety Authority (Figure 34) will be the starting point for information concerning regulations and requirements for food contact materials.

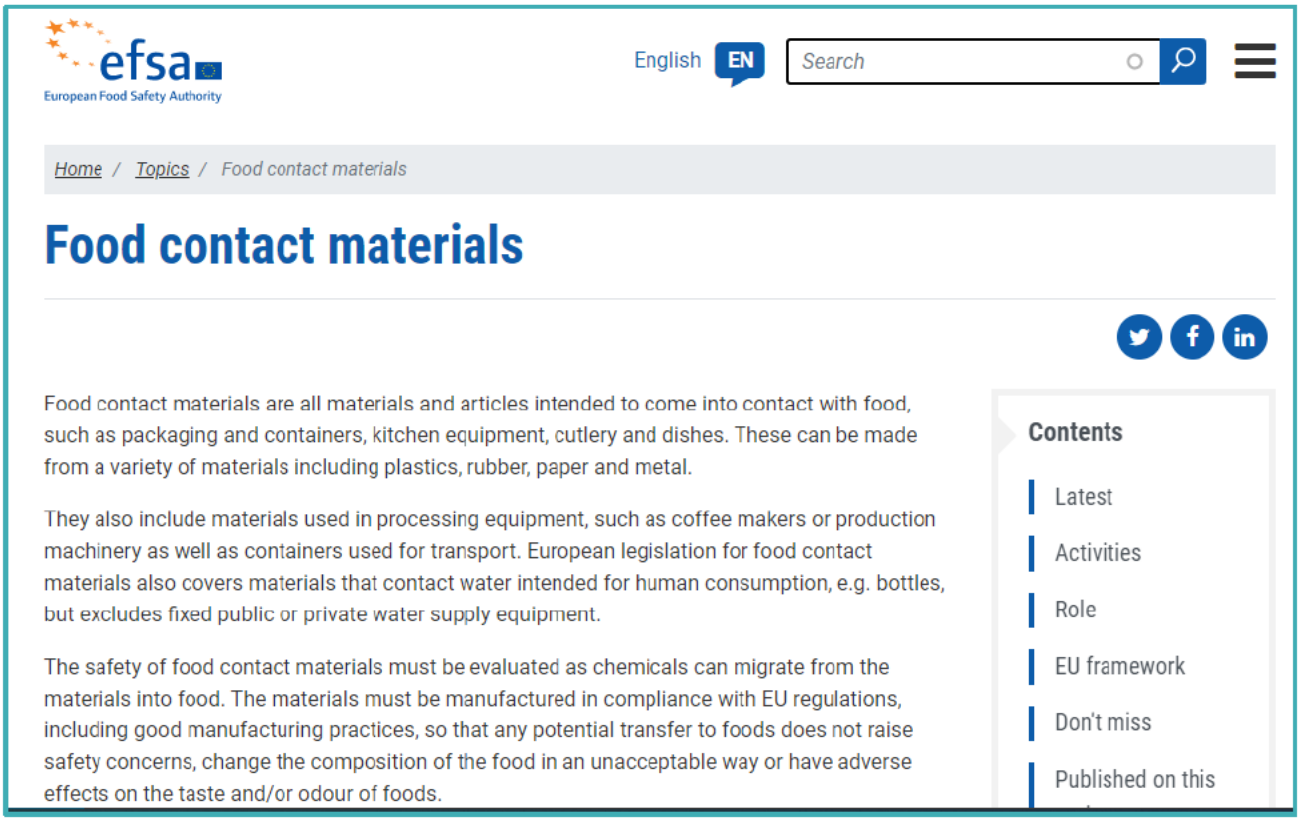

Figure 34. EFSA website for Food contact materials https://www.efsa.europa.eu/en/topics/topic/food-contact-materials

6 QUALITY FUNCTION DEPLOYMENT FOR THE SOFTGRIP SYSTEM

6.1 A BRIEF INTRODUCTION TO THE METHODOLOGY

Quality function deployment (QFD) is a method employed in the early phase of design to generate engineering specifications while systematically accounting for the requirements of all the stakeholders (Ullman 1992). This method is mostly employed in industry, nevertheless we believe that it will bring significant benefits also to a research project such as SoftGrip by providing a deeper understanding of the design process and by formally including the perspective of all its *customers*.

In brief, the application of the QFD method generates the House of Quality (HOQ) i.e., the schematic reported in Figure 35. The first step of the procedure consists in identifying the customers (WHO section). In the QFD the word ‘customers’ is meant in a broad sense i.e., not only the physical person purchasing the object of the design, but rather anyone, person or institution that is affected by it. In the second step, the different perspectives of customers will be collected in the form of well formulated requirements (WHAT) and the relationships between those requirements and the costumers who set them are reported in the WHO vs WHAT section of the table. Furthermore, the competitors (or state of the art) of the specific design are reported in the NOW section together with a rating on how well they perform on each requirement (NOW vs WHAT). Later, the requirements are converted into a set of engineering specifications (HOW section) which must be measurable and provide all the necessary constrains and information to the following design phase. The specifications that have been generated by a specific requirement are marked in the WHAT vs HOW section. For each specification, a limit and a target value are noted down in the HOW MUCH section. Finally, the relationships among specifications are included in the roof of the house of quality (HOW vs HOW section) to allow the identification and solution of possible trade-offs.

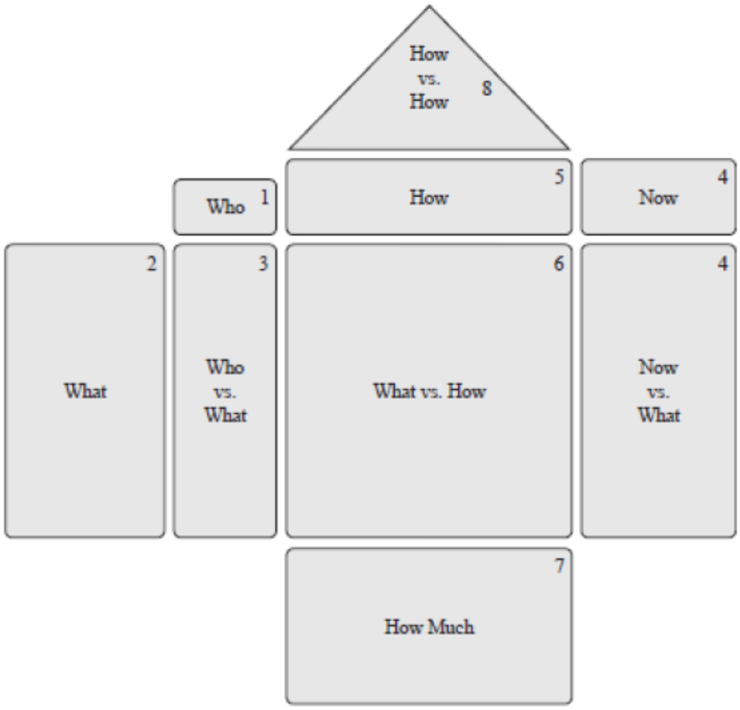

Figure 35. The house of quality (HOQ), also known as the quality function deployment (QFD) diagram.

6.2 HOUSE OF QUALITY FOR THE SOFTGRIP SYSTEM

In the present deliverable, we report on the development of the HOQ for the overall SoftGrip system. At the time of writing, with a reference to Figure 35, we have filled the WHO, WHAT, WHO vs WHAT, NOW, HOW and WHAT vs HOW sections of the schematics. At the present stage, in the sections WHO vs WHAT and WHAT vs HOW we applied a binary rating (relationship/no relationship). The HOQ will be completed by the end of WP1 (Technical & Functional Requirement Analysis), but the intention of the partners is to keep it as a living document for the whole duration of the project to account for any further information. We are planning to apply the QFD method also for the design of the end effector of the SoftGrip system i.e., the soft gripper. The HOQ for the SoftGrip system, at the current stage of development is reported in Figure 36.

In the remainder of this section, the accompanying document of QFD with a short description of all the engineering specifications derived so far is reported.

Harvesting rate: the number of mushrooms harvested by the system during non-stop operation over time. The target value for this specification is calculated based on standard operations in a grow room with human operators as follows. The worst-case scenario is considered, i.e. when there are more mushrooms to be picked (3rd or 4th day of first flush).

Q = Kg of mushroom ready to be picked per bed

N = number of beds at the same stage of crop and number of SoftGrip systems (assuming one per bed)

M = number of human harvesters

Average picking rate of human P_H=Q*N/M

Average picking rate of robot P_R=Q*N/N = Q

Measured in number of units per minute [n/min]. Higher harvesting rate is desired [↑].

Harvesting cycle time: time required for a full harvesting cycle from mushrooms selection to placing. Measured in seconds [s]. A lower time is desired [↓].

Ratio of damaged mushrooms on the total: the number of blemished/bruised mushroom over the total number of successfully harvested mushrooms in a given amount of time. Measured as the percentage [%] of blemished/total. A smaller number of blemished mushrooms is desired [↓].

% as Value Pack (lower price product): in the fresh mushroom industry, damaged products are sold in value packs. Measured as the percentage [%] of value packs/total. The lower the number of value packs, the better [↓].

Ratio of correct mushroom choices: at each cycle the system will choose the next mushroom to be harvested. This specification is measured as the percentage [%] of correct choices/total. A higher number of correct choices is desired [↑].

Harvesting successes over total attempts: Ratio between the number of non-damaged outrooted mushrooms over the total number of attempts. Measured as the percentage [%] of non-damaged outrooted mushrooms/total number of attempts. A higher rate of harvesting successes is desired [↑].

Torque to outroot: average twisting torque exerted by the system on the mushrooms to successfully outroot them without causing any damage. Measured in Newton-metre [Nm]. A smaller torque to outroot is desired [↓].

Max force to hold the cap: lowest shear force applied by the system to the mushroom cap in contact points without causing any damage. Measured in Newton [N]. A smaller max force to hold the cap is desired [↓].

x 1 [] 0		WHO						HOW																												NOW				
	WHAT	Owner of mushroom growing plant	Manager/Supervisor of mushroom growing plant	Harvester (working alongside robots)	Quality Contrller of Packhouse	Regulatory agencies	Retailer / Consumer of mushrooms	Harvesting rate	Harvesting cycle time	Ratio of damaged mushrooms on the total	% as Value Pack (lower price product)	Ratio of correct mushroom choices	Harvesting success over total attempts	Torque to outroot	Max force to hold the cap	Min force to hold the cap	Positioning error	Payload capacity	Resolution of the cameras	Amount of harvestable mushrooms detected	Range of cap sizes	Volume of the system	Noise emitted by the system	Grasping cycles before failure	Degradation time of construction materials in working environmental conditions	IP protection	Mass of the system	Number of steps for installation/deinstallation	Number of steps to alt/restart the system	Number of steps to re-program the system tasks	Maintenance costs	Power consumption	Production costs	Amount of recyclable material	Number of grasping cycles before food safety grade is compromised	Number of mushroom particles attached to the gripper per cycle	Food safety grade of construction materials	1 very bad 5 very good			☖ Reest Δ Human operator	
								↑	↓	↓	↓	↑	↑	↓	↓	↑	↓	↑	↑	↑	<>	↓	↓	↑	↑	↑	↓	↓	↓	↓	↓	↓	↓	↑	↑	↓	↓					
								n/min kg/hour	s	%	%	%	%	Nm	N	N	mm	Kg	MP	%	mm	m³	dB	n	h	[]	Kg	n	n	n	€	W	€	%	n	n	mg/L	1	2	3	4	5
Mushroom picking performance	Fast collection	x	x	x				o	o	o	o	o	o																													
	Do not damage mushrooms	x	x	x	x	x	x	o		o	o		o	o	o	o	o	o																								
	Mushroom deterioration detection	x	x	x															o																							
	Select correct mushrooms	x	x	x								o								o																						
Working environment	Fits in the allocated space	x	x	x																		o																				
	Ability to harvest multiple size	x	x	x																	o																					
	Ability to place mushroom on a conveyor	x	x	x													o	o																								
	Silent		x	x																			o																			
	Resistant to environmental conditions	x	x	x																				o	o	o																
	Transportable between tunnels and shelves	x	x	x																		o					o	o														
	User friendly (simplicity of human intervention and monitoring)		x	x																									o	o												
	Safety of human operators		x	x																							o		o													
Manufacturing and integration	Durability of the system	x	x	x																				o	o	o																
	Simplicity of installation/deinstallation		x	x																								o														
	Low cost	x																						o							o	o	o									
	Environmentally friendly	x				x																		o								o		o								
	Safe food interaction (protection from chemical damage)				x	x																			o										o	o						
	Simplicity of maintenance	x	x	x																				o				o	o	o							o					
		Lowest threshold																																								
		Target																																								

Figure 36. Draft HOQ for the SoftGrip system.

Min force to hold the cap: lowest shear force applied by the system to the mushroom cap in contact points to hold it firmly. Measured in Newton [N]. A smaller min force to hold the cap is desired [↓].

Position error: difference between reached and commanded end effector position. Measured in millimetres [mm]. A lower positioning error is desired [↓].

Payload capacity: Maximum weight of mushroom that the robot can handle. Measured in kilograms [Kg]. A higher payload capacity is desired [↑].

Resolution of the cameras: This specification impacts on the ability to select the mushrooms to be picked. Measured in megapixel [MP]. A higher resolution is desired [↑].

Amount of harvestable mushrooms detected: Ratio of harvestable mushrooms detected by the system over total of harvestable mushrooms identified by a skilled human harvester. Measured as a percentage [%]. A higher ration is desired [↑].

Range of cap sizes: Range of mushrooms' cap sizes that can be harvested. Measured in millimetres [mm]. The system must be able to harvest all sizes within the range [<>].

Volume of the system: Volume of the smallest bounding box of the overall system. Measured in cubic meters [m^3]. A smaller volume of the system is desired [↓].

Noise emitted by the system: Ratio between the energy of the noise emitted by the SoftGrip system in standard operative conditions (N_1) over the background noise in the plant measured when the SoftGrip system is off (N_0). Measured as $10\log_{10}(N_1/N_0)$ [dB]. A lower noise is desired [↓].

Grasping cycles before failure: Average number of mushrooms grasping attempts (successful or not) before any component of the SoftGrip system fails. Measured in number of attempts [n]. A higher number of grasping cycles before failure is desired [↑].

Degradation time of construction materials in working environmental conditions: Amount of time before construction materials, exposed to the environmental conditions of mushrooms growing room, begin to lose their functional properties. Measured in hours [h]. A longer degradation time is desired [↑].

IP protection: international standard to rate the degree of protection provided by mechanical casings and electrical enclosures against intrusion, dust, accidental contact, and water. No unit []. A higher protection is desired [↑].

Mass of the system: Mass of the overall system. Measured in kilograms [Kg]. A smaller mass of the system is desired [↓].

Number of steps for installation/deinstallation: Number of elementary steps (e.g. screw/unscrew a screw, connect/disconnect a pipe, etc…) to install/deinstall the SoftGrip system. Measured in number of steps [n]. A smaller number of steps for installation/deinstallation is desired [↓].

Number of steps to alt/restart the system: Number of elementary steps required by a human supervisor to alt and/or restart the system in case of emergency or need for maintenance. Measured in number of elementary steps (e.g. press the emergency button, unlock the protective barrier, etc…). A lower number of steps is desired [↓].

Number of steps to re-program the system tasks: Number of elementary steps required by a human supervisor to set the SoftGrip system tasks. Measured in number of elementary steps (e.g. pause the system, open the user interface panel, select a pre-programmed task, etc…). A lower number of steps is desired [↓].

Maintenance costs: Average costs to maintain the SoftGrip system (e.g. cleaning, substitution of components, supervising personnel, etc). Measured in euro [€]. Lower maintenance costs are desired [↓].

Power consumption: Average power consumption of the overall system during typical operations. Measured in watts [W]. A smaller power consumption is desired [↓].

Production costs: Total costs to produce the SoftGrip system. Measured in euro [€]. Smaller production costs are desired [↓].

Amount of recyclable material: Ratio between the mass of recyclable materials in the construction of the SoftGrip system over the total mass of the system. Measured as the percentage [%] of recyclable mass/total mass. A greater amount of recyclable material is desirable [↑].

Number of grasping cycles before food safety is compromised: The number of grasping attempts before the SoftGrip system, especially the part directly in contact with the mushroom, loses the food safety required grade. Measured in number of cycles [n]. A higher number of grasping cycles before food safety is compromised is desired [↓].

Number of mushroom particles attached to the gripper per cycle: The mushroom particles that stay attached to gripper may compromise the safety in handling food by transporting bacteria or posing hygiene issues. Measured as number of particles [n]. A lower number of particles attached is desired [↓].

Food safety grade of construction materials: Amount of construction materials of the SoftGrip system found in alcohol after performing standard food grade test. Measured in milligrams per litre [mg/L]. A smaller amount of construction materials found in alcohol indicates a higher food safety grade [↓].

7 CONCLUSION

To conclude, this document provides a detailed description of the mushroom growing system, it gives a general overview on existing automated picking systems and lays out the specifications and requirements needed to harvest mushrooms successfully, identifying the factors that need to be taken into consideration when developing a robotic soft gripper to complete this task. By the end of WP1 (M6), the information contained in this deliverable, will be elaborated and complemented resorting to the Quality Function Deployment methodology to generate a richer and better refined set of engineering specifications for the upcoming technical working packages.

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