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Comparison between Selective and Non-selective Kiwifruit Harvesters for Economic Viability

A thesis

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Abstract

Robotic harvesting of kiwifruit can help solve the labour shortage of the growing New Zealand kiwifruit industry. The objective of this thesis was to compare the performance of the improved state-of-the-art selective kiwifruit harvester and a new non-selective harvester in terms of economic viability. The harvesters were tested on commercial kiwifruit orchards. Both kiwifruit harvesters were not economically viable at the current state. The greatest barrier to economic viability was the high breakeven performance requirement of at least 95% success-picked-detached for green fruit and 97% for gold fruit. The high-performance requirement was forced by the high fruit value ratio of 16 for green fruit and 30 for gold fruit. Despite the high harvesting rate potential of a non-selective harvester, fruit handling and stemless detachment were the main barriers. The state-of-the-art kiwifruit harvester had high performance relative to other harvesters but required more development on fruit loss reduction and the robotic configuration for better workload sharing. To achieve economic viability, the primary focus for all kiwifruit harvesters should be on raising the success-detached ratio. The secondary focus should be on improving the performance-to-cost ratio. With further development, the selective harvester could reach economically viable performance.

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Table of Contents

Abstract	i
Acknowledgements	ii
List of Equations	vi
List of Tables.....	vi
List of Figures	vii
Chapter 1: Introduction	1
1.1 Background	1
1.2 Motivation	2
1.3 Objectives & Scope	2
1.4 Contributions	3
1.5 Innovation.....	3
1.6 Thesis Statement.....	3
Chapter 2: Literature Review	4
2.1 Introduction	4
2.2 Selective Harvester End-effector.....	4
2.2.1 Introduction	4
2.2.2 Harvest by Stem Cutting	5
2.2.3 Harvest by Motion	7
2.2.4 Kiwifruit End-effectors	8
2.2.5 Conclusion	9
2.3 Non-selective Harvester	9
2.3.1 Introduction	9
2.3.2 Indirect Contact.....	10
2.3.3 Direct Contact	13
2.3.4 Conclusion	14
Chapter 3: Selective Harvester.....	15
3.1 Introduction	15
3.1.1 Background	15
3.1.2 Objectives.....	16
3.1.3 End-Effector Grippers	17
3.2 Methodology	21
3.2.1 Gripper	21
3.2.2 Harvester	28
3.3 Results	30
3.3.1 Gripper	30

3.3.2	Harvester.....	38
3.4	Discussion.....	41
3.4.1	Gripper.....	41
3.4.2	Harvester.....	46
3.5	Conclusion.....	48
Chapter 4:	Non-selective Harvester	50
4.1	Introduction.....	50
4.1.1	Background.....	50
4.1.2	Objectives	50
4.1.3	Development.....	50
4.2	Methodology.....	56
4.2.1	Lab Testing.....	56
4.2.2	Preliminary Orchard Testing	57
4.2.3	Orchard Testing	57
4.2.4	Combing Test	58
4.2.5	Fruit Damage Test	60
4.3	Results.....	61
4.3.1	Lab Testing.....	61
4.3.2	Preliminary Orchard Testing	61
4.3.3	Orchard Testing	62
4.3.4	Combing Test	64
4.3.5	Fruit Damage Test	64
4.4	Discussion.....	65
4.4.1	Lab Testing.....	65
4.4.2	Preliminary Orchard Testing	67
4.4.3	Gold Fruit Test	69
4.4.4	Hayward Test.....	70
4.4.5	Combing Test	71
4.4.6	Fruit Damage Test	71
4.5	Conclusion.....	72
Chapter 5:	Comparison for Economic Viability	74
5.1	Introduction.....	74
5.2	Methodology.....	74
5.2.1	Human Pickers.....	74
5.2.2	Harvester Breakeven Requirements	79
5.2.3	Performance Comparison	80
5.3	Results.....	82

5.3.1	Human Pickers	82
5.3.2	Harvester Breakeven Requirements	86
5.3.3	Performance Comparison	92
5.4	Discussion	96
5.4.1	Human Pickers	96
5.4.2	Harvester Breakeven Requirements	99
5.4.3	Performance Comparison	102
5.5	Conclusion	106
Chapter 6:	Future Kiwifruit Harvesters	108
6.1	Introduction	108
6.2	Barriers to Economic Viability	108
6.2.1	Fruit Value Ratio	108
6.2.2	Reachability	109
6.2.3	Harvesting Speed	109
6.2.4	Cost	110
6.3	Assistance Factors to Economic Viability	111
6.4	Robotic Configurations	111
6.5	Conclusions	114
Chapter 7:	Conclusion	115
7.1	Selective Harvester	115
7.2	Non-selective Harvester	115
7.3	Comparison for Economic Viability	116
7.4	Future Kiwifruit Harvesters	116
7.5	Recommendations	117
References	119
Appendices	128
Appendix A – Individual Dataset Gripper Fruit Handling Results	128

List of Equations

Equation 1: Fruit per kiwifruit bin.....	76
Equation 2: Human kiwifruit picking rate.....	77
Equation 3: Total number of hours.....	77
Equation 4: Total kiwifruit harvesting cost.....	78
Equation 5: Kiwifruit breakeven.....	79
Equation 6: Cost performance ratio.....	81

List of Tables

Table 1: Orchard testing performance metrics.....	26
Table 2: Lab testing picking success.....	30
Table 3: Lab testing harvesting cycle time.....	30
Table 4: Gripper orchard testing performance.....	32
Table 5: Gripper orchard testing failure breakdown by fruit.....	33
Table 6: Gripper orchard testing failure breakdown by percentage of attempts ...	34
Table 7: 2018 AKH full system orchard testing results.....	38
Table 8: 2018 AKH cycle time calculation.....	40
Table 9: Non-selective harvester orchard test results.....	62
Table 10: Total harvesting cost calculation inputs.....	78
Table 11: Human picker harvesting cost.....	83
Table 12: Effect of fruit mass and picker wages on harvesting cost.....	85
Table 13: Performance of the kiwifruit harvesters.....	92
Table 14: Cost-performance calculation inputs.....	95
Table 15: Cost-performance results.....	95
Table 16: Gripper fruit handling detailed results.....	128

List of Figures

Figure 1: Robotics Plus Autonomous Kiwifruit Harvester	15
Figure 2: Robotics Plus kiwifruit harvesting end-effector	16
Figure 3: Robotics Plus M4 gripper	19
Figure 4: Robotics Plus M5 gripper	19
Figure 5: Robotics Plus M6 gripper	20
Figure 6: Robotics Plus Flexi gripper	20
Figure 7: Laboratory testing with silicone kiwifruit models.....	22
Figure 8: Lab testing isolated fruit setup	23
Figure 9: Lab testing 2-fruit cluster setup	24
Figure 10: Lab testing 3-fruit cluster setup	24
Figure 11: Lab testing 7-fruit cluster setup	24
Figure 12: Orchard testing of the grippers	25
Figure 13: Cutting along the fruit longitudinal axis for damage evaluation	28
Figure 14: Cutting normal to the kiwifruit longitudinal axis for damage evaluation	28
Figure 15: Robotics Plus Autonomous Mobile Modular Platform with Autonomous Kiwifruit Harvester	29
Figure 16: Lab picked success percentage	31
Figure 17: Lab harvesting cycle time.....	31
Figure 18: Gripper orchard testing success.....	32
Figure 19: Gripper orchard testing harvesting cycle.....	33
Figure 20: Gripper orchard harvesting attempts breakdown by gripper	34
Figure 21: Gripper orchard harvesting attempts breakdown by result.....	35
Figure 22: Kiwifruit firmness on the vine during harvesting season	36
Figure 23: Relationship between pneumatic cylinder actuator pressure and gripper compression force	36
Figure 24: Overall averaged gripper fruit handling performance	37
Figure 25: M5 and M6 gripper fruit handling performance.....	37
Figure 26: M4 gripper fruit handling performance	38
Figure 27: Comparison between 2017 and 2018 AKH reachability performance	39

Figure 28: Comparison between 2017 and 2018 AKH picked-detached performance	39
Figure 29: Comparison between 2017 and 2018 AKH cycle time performance ..	40
Figure 30: Stem-shear non-selective harvester concept	52
Figure 31: Top view of stem-shear detachment method	52
Figure 32: Side view of stem-shear detachment method.....	53
Figure 33: Proof-of-concept prototype closeup.....	53
Figure 34: Stem-shear detachment method as seen from below	54
Figure 35: Stem-shear non-selective harvester proof-of-concept prototype	55
Figure 36: Non-selective harvester lab testing with silicone kiwifruit models	56
Figure 37: Non-selective harvester preliminary orchard testing	57
Figure 38: Non-selective harvester orchard testing	58
Figure 39: Non-selective harvester combing orchard testing	59
Figure 40: Combing detachment method closeup view	59
Figure 41: Non-selective harvester fruit detachment performance	62
Figure 42: Non-selective harvester stem detachment performance.....	63
Figure 43: Stem-shear detachment performance breakdown	63
Figure 44: Combing detachment performance breakdown	64
Figure 45: Stem-shear fruit handling performance.....	64
Figure 46: Combing fruit handling performance based on obvious damage	65
Figure 47: Stem-shear fruit handling fruit with wrinkles	65
Figure 48: Target fruit position required for successful stem-shear detachment ..	66
Figure 49: Squished fruit that were positioned too high	66
Figure 50: Drooping fruit offshoots.....	67
Figure 51: Cane deflector fruit entry fruit reachability	67
Figure 52: Side view of reachable fruit in the canopy by the non-selective harvester	68
Figure 53: Fruit left on the canopy by the non-selective harvester	68
Figure 54: Unreachable fruit near leaders	68
Figure 55: Effect of fruit mass on fruit value	82
Figure 56: Effect of average fruit mass on fruit per hectare yield.....	82
Figure 57: Human picker harvesting rate	83
Figure 58: Harvesting Cost breakdown	84
Figure 59: Effect of robot reachability on human clean-up picker efficiency loss	86

Figure 60: Effect of robot reachability on harvesting cost.....	86
Figure 61: Breakeven success-detached performance for 130 g mean mass green fruit at \$21/h wage and \$53,555 OGR	87
Figure 62: Breakeven success-detached performance for 130 g mean mass gold fruit at \$21/h wage and \$98,838 OGR	88
Figure 63: Breakeven success-detached performance for 130 g mean mass green fruit at \$21/h wage and \$53,555 OGR	89
Figure 64: Breakeven success-detached performance for 130 g mean mass gold fruit at \$21/h wage and \$89,838 OGR	89
Figure 65: Breakeven success-detached performance for 130 g mean mass green fruit at \$30/h wage and \$53,555 OGR	90
Figure 66: Breakeven success-detached performance for 130 g mean mass gold fruit at \$30/h wage and \$89,838 OGR	90
Figure 67: Breakeven success-detached performance for 100 g mean mass green fruit at \$30/h wage and \$53,555 OGR	91
Figure 68: Breakeven success-detached performance for 100 g mean mass gold fruit at \$30/h wage and \$89,838 OGR	91
Figure 69: Kiwifruit harvester reachability comparison	92
Figure 70: Kiwifruit harvester picked-detached comparison.....	93
Figure 71: Kiwifruit harvester harvesting rate comparison	93
Figure 72: Kiwifruit harvester cycle time comparison	94
Figure 73: Kiwifruit harvester fruit handling comparison	94
Figure 74: Cost-performance comparison.....	96
Figure 75: Kiwifruit harvester 72-manipulator configuration	114

Chapter 1: Introduction

1.1 Background

The growing New Zealand kiwifruit industry achieved export sales of \$2.26 billion NZD during the 2016/17 season and has a goal to double to \$4.5 billion NZD by 2025 (Zespri, 2017). With this rapid growth, kiwifruit growers are experiencing challenges associated with labour shortages and rising labour costs.

The greatest problem is labour availability with the New Zealand Ministry of Social Development declaring an official seasonal labour shortage of 1,200 people for six weeks during the 2018 harvesting season (NZ MSD, 2018). This shortage is likely to worsen with a projected 7,000 more seasonal workers required for the kiwifruit industry by 2027 (NZKGI, 2018).

The second problem is rising labour costs. Pruning, thinning, and picking wages make up approximately half of the total orchard working expenses based on a 2011/12 orchard model. Of the 2011/12 labour expenses, pruning wages were the greatest at \$9,700 NZD/ha, followed by picking wages at \$3,922 NZD/ha (NZ MPI, 2012). Since 2012, the New Zealand minimum wage has significantly increased by 22% from \$13.50 NZD/h to \$16.50 NZD/h in 2018. The New Zealand Government has planned a minimum wage of \$20 NZD/h by 2021 (Statistics New Zealand, 2018), which is an increase of 48% from the 2012 minimum wage.

Robotics and automation in agriculture can play a key role in the long-term solution to both the labour shortage and rising labour cost. Scarfe, Flemmer, Bakker, & Flemmer (2000) and Scarfe (2012) developed the world's first autonomous kiwifruit harvester (AKH). It had high performance relative to harvesters for other crops (Bac, van Henten, Hemming, & Edan, 2014). Testing during 2017 revealed that the AKH end-effector grippers required improvement to reduce fruit loss from fruit drops and knock-offs (Seabright et al., 2017).

1.2 Motivation

A recommendation based on the 2017 AKH performance was to investigate a non-selective kiwifruit harvesting method. A non-selective harvester is a mass or bulk harvester that harvests many fruits at once, rather than one fruit at a time. The main advantage of a non-selective harvester was the much higher harvesting rate potential. It was desirable to determine the relative performance of a selective and non-selective kiwifruit harvester.

1.3 Objectives & Scope

The thesis objective was to compare the performance of an improved selective kiwifruit harvester with a non-selective kiwifruit harvester and investigate the economic viability relative to human pickers.

For the selective harvester, the objective was to improve and quantify the performance of the AKH. The performance improvement required was a reduction in fruit loss due to fruit drops and knockoffs. The scope of the development of the AKH was limited to the harvesting end-effector grippers because it was the main cause of fruit loss.

For the non-selective harvester, the objective was to investigate the viability and the potential of a non-selective kiwifruit harvester. The scope of the non-selective harvester was limited to the detachment method because this was the key feature of the harvester.

The final objective was to provide recommendations on the future direction of robotic kiwifruit harvesting based on the barriers and assistance factors for economic viability.

1.4 Contributions

- A. End-effector grippers
 - a. Development of new and improved kiwifruit end-effector grippers compatible with kiwifruit clusters
 - b. Comprehensive laboratory and orchard evaluation of the grippers and improved harvester
- B. Analyses
 - a. First comparison between selective and non-selective kiwifruit harvesters
 - b. Defined metrics for comparison between kiwifruit harvesters
 - c. Determination of the break-even performance based on the total picking cost, as seen from a grower's perspective
 - d. Provided future research directions based on barriers and assistance factors for economic viability
 - e. Investigation into alternative robotic configurations

1.5 Innovation

- A. Non-selective kiwifruit harvester
 - a. Development and comprehensive evaluation of the first non-selective kiwifruit harvester

1.6 Thesis Statement

“Kiwifruit harvesters have difficulty reaching economically viable performance due to the high value of the fruit relative to the harvesting cost. Non-selective harvesters have high harvesting rates at the expense of fruit handling whereas selective harvesters have good fruit handling at the expense of speed and high cost.”

Chapter 2: Literature Review

2.1 Introduction

The objective of this chapter was to complete literature reviews on selective and non-selective harvesters to summarise past key developments. The relevance to kiwifruit harvesting was discussed. Both selective and non-selective harvester literature reviews included harvesters for other crops because there was limited literature relating specifically to kiwifruit harvesting. Where possible, peer-reviewed literature were used. However, in some cases, non-peer-reviewed literature were used due to their value and scarcity. Non-English literature were also included because there has been significant development on robotic harvesting in many non-English speaking countries.

2.2 Selective Harvester End-effector

2.2.1 Introduction

This literature review presents the current state-of-the art end-effectors for various crops. There have been many end-effectors developed to harvest a wide variety of fruit and vegetables over the past four decades (Bac et al., 2014). The underlying harvesting methods were compared and discussed. Several key end-effector developments were selected to explain past and current approaches for harvesting various fruit. The end-effectors were separated into harvest by stem cutting, harvest by motion and kiwifruit end-effectors.

The scope of the selective harvesting literature review was on the harvesting end-effector because it is the part of the robot that directly interacts with the crop and growing environment. The three key requirements of any harvesting end-effector are effectiveness, speed, and fruit handling. Often, a trade-off was made between these key requirements which resulted in poor overall performance. Past end-effectors were developed with a proof-of-concept approach where the primary goal was to prove that harvesting a specific crop was possible. As a result, many developments did not consider the practicality of their designs. The main problems with previous designs included slow speed, high cost, high complexity, poor

practicality, and incompatibility with the growing environment. Recent developments have focused on simplifying the task and the use of more effective and robust fruit detachment methods.

2.2.2 Harvest by Stem Cutting

Harvest by stem cutting was a common approach because many human harvesters used cutters to cut the stem.

2.2.2.1 Rotating Jaw/lip

A common method used was a rotating jaw or lip that moved around a fruit to cut the stem. Various methods of achieving this have been used in the past as early as 1985 by Harrell, Adsit, & Slaughter (1985). Other similar harvesters which did not grasp fruit, but enclosed fruit first included the citrus harvester by Muscato, Prestifilippo, Abbate, & Rizzuto (2005) and the recent Panasonic tomato harvesting end-effector (Panasonic, 2018). The Panasonic tomato end-effector used a guiding part that wrapped around the fruit to guide it into the harvesting zone, where a stem shearer pulled against the fruit-stem connection. The innovation was the guiding part which made the harvesting action more robust. The fruit was dropped into a cup and that could hold multiple fruit, so the placing operation component of the cycle time was spread across the fruit in the cup, reducing the overall cycle time per fruit.

Some end-effectors used vacuum pads for the initial grasping to position the fruit such as the Kubota (Hayashi & Ueda, 1991, as cited in Sarig, 1993), the OlinScope (Boutelle, Greeley, Kavett, McClure, & Yarak, 2009), and more recently, the EU CROPS project lip-type end-effector (Bac et al., 2017). Instead of combining the grasping and cutting mechanisms, the QUT Harvey sweet pepper harvester separated the vacuum grasper and stem cutter by using a detachable vacuum cup (Lehnert, McCool, & Perez, 2017). The innovation was the grasping and cutting mechanisms that could be positioned independently which allowed greater reachability.

2.2.2.2 Simultaneous Grip-cut

A commonly used approach was a simultaneous grip-cut stem detachment method which reduced the cycle time. The advantage of this method was fruit handling

because there was no contact with the fruit surface. Therefore, this method was suitable for delicate fruit like strawberries and tomatoes. Cui et al. (2007) used a grip-cut method for strawberries which was subsequently used by others (Feng, Qixin, & Masateru, 2008; Han et al., 2012; Hayashi et al., 2010; Ji, Zhang, Yuan, & Li, 2014). A recently developed Agrobot strawberry harvester used the same grip-cut concept (US20180153103A1, 2018).

Newer developments have applied the grip-cut method one-step further by harvesting clusters of tomatoes (Kondo et al., 2010; MetoMotion, 2018). Harvesting clusters of fruit allows the detection, localisation, manipulator movement and placing operation times to be spread across the fruit in the cluster, which decreases the overall cycle time per fruit. The MetoMotion end-effector used a unique parallelogram grip-cut end-effector which approached fruit clusters from below. It moved upwards while enclosing the cluster before cutting the cluster from the main plant. The advantage of this method over a traditional grip-cut method was that it required less precise positioning.

2.2.2.3 Cut-catch

An older version of the Agrobot (US20110252760A1, 2011) used a simple basket with two counter-rotating blades to cut the stem upon approach to avoid grasping the fruit. The key innovation was that the approach motion was the cutting action itself. The strawberry growing environment where fruit hanged off the side allowed easy approach from below.

The SWEEPER sweet pepper harvester project end-effector (SWEEPER, 2018) was an improvement over the CROPS project end-effectors (Hemming et al., 2014) because it was more compatible with the growing environment and simplified the task. Instead of using the grasp and cut approach, the harvesting action was simplified. Approaching the fruit in the direction where the fruit stem was facing allows the cutter to target the stem from the top. Furthermore, using the vertical plant as a guide greatly reduced the complexity of the task.

An innovative method used by Aloisio, Mishra, Chang, & English (2012) was the use of many simple, low cost actuators which targeted the fruit-stem connection of citrus fruit. This method was of interest because the low cost allowed many more actuators to be placed in an array. The collective harvesting rate could be many

times greater than a more complex, single actuator. Despite the fruit not being touched directly, there was a possibility of fruit damage if the detaching part impacted another fruit.

2.2.3 Harvest by Motion

2.2.3.1 Vacuum

Vacuum end-effectors were used as early as 1987 on the Magali apple harvester where a vacuum cup was used to pick apples (Grand d' Eson, Rabatel, Pellenc, Journeau, & Aldon, 1987). The same concept was subsequently used by the Belgium AFPM apple picker (Baeten, Donné, Boedrij, Beckers, & Claesen, 2007). The advantage with vacuum grippers was fruit handling because spherical fruit could be picked with no damage. Abundant Robotics took this concept further but instead of using vacuum for grasping, fruit were picked using vacuum alone (Salisbury & Mahoney, 2015; Salisbury & Steere, 2016). A fruit decelerator was used to slow the fruit down that had been picked. The key advantage of this was that a placing operation was not required which halved the cycle time compared to a pick and place operation (Davidson, Hohimer, Mo, & Karkee, 2017). Arikapudi, Durand-Petiteville, & Vougioukas (2014) found that 40-65% of the time in a pick-and-place operation was used for the placing operation.

2.2.3.2 Grippers

Standard off-the-shelf industrial grippers were unsuitable for fruit harvesting due to fruit damage. Intelligent control or gripper design could be used to prevent fruit damage by grippers. Grippers were first used by Kawamura, Namikawa, Fujiura, & Ura (1984) on a two-finger tomato harvester. Newer soft robotic gripper designs have much better fruit handling such as the commercialised Soft Robotics food and beverage grippers (Soft Robotics Inc., 2018). The EU CROPS project sweet-pepper harvesting project used the innovative Festo Fin-ray gripper which could adapt to the shape of round objects (Festo, 2009; Hemming, Tuijl, Gauchel, & Wais, 2016).

The Octinion strawberry end-effector used a similar harvesting action as the AKH by rotating the fruit about the stem (Octinion, 2018). The key innovation with the Octinion end-effector was the additive manufactured soft lattice structure which could adapt to the fruit. The WSU apple picking end-effector was low-cost, additive

manufactured, and under-sensed (Davidson & Mo, 2015). The gripper could deal with variation due to the design of the finger structure. The Pitzer wheel by Harvest CROO used soft grippers to pick strawberries (US20160161238A1, 2016). The key innovation was the patented Pitzer wheel end-effector with multiple grippers on a rotating wheel. With each rotation, the end-effector was able to reset, which effectively removed the placing operation time.

2.2.4 Kiwifruit End-effectors

2.2.4.1 AKH End-effectors

The end-effector designed by Scarfe (2012) was the first kiwifruit harvesting end-effector that rotated fruit about the fruit-stem connection. The M1 (Mark 1) gripper used silicone tubing as the contact surface to conform to the fruit surface. Subsequent development simplified the grasping and rotating actions such that only one actuator was required. Newer grippers were developed to improve the performance. The M4 (Mark 4) gripper used a soft silicone structure that was able to conform to the fruit surface, and deal with position variation. However, 2017 testing revealed high fruit loss (Seabright et al., 2017).

There were several reasons why the AKH end-effector had high performance relative to other harvesters. The harvesting action and control were simple and effective with no special path planning required. The robot simply advanced to a fruit position and actuated. The industry standard planar growing structure was compatible because it allowed easy access to fruit from below. This simplified the task greatly and minimised obstructions. The harvesting mechanism did not require a placing operation which reduced the cycle time. Kiwifruit had lower susceptibility to bruising compared to more delicate fruit such as strawberries or tomatoes.

2.2.4.2 Other Developments

J. Chen et al. (2012) designed a large kiwifruit harvesting end-effector which approached kiwifruit from the side and rotated the fruit with a cycle time of 9 s. Hanhui, Ken, HuaZhou, & Zhaofeng (2015) used an off the shelf gripper to grasp fruit but it was obvious that the fruit would likely be damaged due to the small contact area. Kahya (2012) used a scissor cutter end-effector to cut the kiwifruit stem. Graham, Zong, Feng, & Tang (2017) also developed a kiwifruit stem cutter which

used a solenoid to actuate a cutter. Kiwifruit stem cutter end-effectors were not very useful as kiwifruit need to be harvested without the stem. Kiwifruit with stems attached in the kiwifruit bin could puncture other fruit, leading to decreased quality and post-harvest losses. The key innovation by Graham et al. (2017) was that the cutter was hidden and only the stem could enter the cutting zone. Fu et al. (2015) and Mu et al. (2017) used a cam follower mechanism to achieve a similar harvesting action as Scarfe which rotated fruit about the stem.

2.2.5 Conclusion

Many different end-effectors have been developed for harvesting various crops. Past developments often had poor performance or were impractical. However, recent developments used innovative methods to simplify the task, reduce the harvesting cycle time, and improve robustness. Simultaneous grip-cut methods combined with cluster harvesting could reduce the cycle time significantly. Harvesting by motion methods focused on fruit handling. Compared to all the other end-effectors, the AKH end-effector had high performance due to the simple yet effective design and control, combined with compatibility with the growing environment.

2.3 Non-selective Harvester

2.3.1 Introduction

The objective of the non-selective harvesting literature review was to summarise the key developments and to discuss their potential application for kiwifruit.

Non-selective harvesters specifically for kiwifruit were not found in literature. However, there were some comments relating to them found in the past. Warrington, Weston, & New Zealand Society for Horticultural Science (1990) stated that “the possibilities of mechanised harvesting are at present being investigated, but it may be some time before this procedure becomes a commercial reality on existing orchards”. Thompson (1982, as cited in Pandey & Joshi, 1997) stated that “mechanical harvesting is also not advocated as the fruits bruise easily”. Therefore, non-selective harvesters for other crops were reviewed. The same underlying detachment concepts could be applied to kiwifruit harvesting. The scope

of the non-selective harvester was limited to the detachment method because it was the most important part of the harvester. The scope was also limited to non-selective harvesters specifically for the fresh fruit market because most kiwifruit are harvested for the fresh fruit market. Some process fruit market harvesters were discussed due to the similar harvesting methods used as fresh fruit market harvesters.

There were two main types of harvesters: Indirect contact and direct contact. Direct contact harvesters used a combing, pushing, hooking, or rotating actions to directly contact and detach fruit. Indirect contact method was the shake-and-catch method which shook fruit off on to a catching surface.

2.3.2 Indirect Contact

2.3.2.1 Shake-and-catch

The shake-and-catch method was a popular method of non-selectively harvesting fruit. It involved shaking the fruit off at a certain frequency and amplitude. The shaking frequency could be chosen to cause detachment at the plant-stem connection or the fruit-stem connection (Crooke & Rand, 1969). The main advantage of the shake-and-catch method was the high harvesting rate potential of at least an order of magnitude faster than hand or selective harvesting. However, the challenge was fruit damage which is why most current commercial shake-and-catch systems are used for the process fruit market rather than the fresh fruit market.

Brown (2005) described citrus shake-and-catch systems for the process fruit market which revealed productivity increases and labour cost savings. Shake-and-catch systems were suitable for the process industry because it has lower standards for fruit handling. Brown & Schertz (1967) found that the growing structure for oranges must change to reduce the fruit loss for the fresh-fruit market. Zhang, Heinemann, Liu, Baugher, & Schupp (2016) reviewed various mechanical apple harvesters which were mostly shakers for the process fruit market.

There have been many attempts at a shake-and-catch harvester for fresh market apples. Apple fruit handling was often reported as the percentage of fruit graded as Extra Fancy or Fancy. Berlage & Langmo (1979) tested an apple shake-and-catch harvester with an average of 61% graded as Extra Fancy or Fancy. Peterson &

Miller (1989) reported that for an over-the-row continuously moving shake-and-catch apple harvester, the results were 31.5-68.4% Extra Fancy, 20.3-44.5% Fancy, 4.1-11.8% bruised, and 3.8-29.1% cuts or punctures. An early shake-and-catch prototype developed by Peterson, Bennedsen, Anger, & Wolford (1999) showed high potential with a 99.6% Extra Fancy grading. However, further development and more extensive testing on multiple apple cultivars resulted in 59.1-84.0% Extra Fancy, 2.8-7.8% Fancy, 1.6-7.6% bruised and 6.8-27.2% cuts or punctures gradings (Peterson & Wolford, 2003).

In some cases, the shake-and-catch method had fruit handling performance comparable to hand-harvesting. Peterson & Wolford (2001) developed a cherry harvester which had 2-6% more damage than hand harvested cherries. The lower fruit damage was largely attributed to the use of a chemical Ethrel, which reduced the fruit retention force. This decreased the shaking required to detach fruit, and hence, improved fruit handling. Commercial shake-and-catch systems are currently being used for smaller fresh fruit market crops such as blueberries, raspberries, and cherries. Compared to larger fruit, smaller fruit are more suitable for shake-and-catch harvesting because the fruit mass is lower. Therefore, the kinetic energy prior to impact is lower so there is less chance of fruit damage.

Shake-and-catch harvesters for apple planar growing structures were of high interest because they were very similar to the kiwifruit T-bar and Pergola support structures. Dunn & Stolp (1981) trained apples on a Lincoln canopy system which was like the kiwifruit T-bar support structure. The apple tree was trained to have leaders and lateral canes like kiwifruit. A simple 50 mm square section wooden beam with a length of 1.4 m was used to lift the laterals at 1 Hz every 150 mm between impacts to detach fruit (Dunn & Stolp, 1981). Dunn & Stolp (1986, as cited in Lang, 1989) stated that subsequent testing on older and higher yielding canopies resulted in less fruit detachment due to less effective impacts. The fruit handling performance of the system was 14.9-16.6% bruising, 0.6-1.9% punctures, and 42-61.1% stem pulls (Dunn & Stolp, 1981). Hao (1974, as cited in Lang, 1989), detached fruit by applying three shocks to the laterals from above with a 60-70% fruit removal. Domigan et al. (1988) tested a support wire impactor from below with 84-99% Extra Fancy and Fancy grading for Golden Delicious and Red Delicious apple varieties. The good fruit handling was attributed to the short drop

heights and gentle transfer to the bin. The hand harvesting results were surprisingly poor with a range of 65-98% Extra Fancy and Fancy. In comparison, Lang (1989) reported no hand harvesting bruising for six apple varieties grown with the same growing structure. Furthermore, he developed a continuous apple shake-and-catch harvester specifically for a T-bar canopy which shook each lateral limb with an amplitude of 26 mm and frequency of 10 Hz. The shaker heads consisted of two shafts, each with three disks. Each disk had rubber teeth used to prevent damage to the fruit or lateral limbs. The key innovation was the selective horizontal limb shaking. His results were quite impressive with 89-97% removed. For three varieties (Golden Delicious, Gala, Sturmer), the bruised percentage was 15-31%. However, the other three varieties (Cox's Orange, Red Delicious, Braeburn) had very low bruising of between 3-5%. Furthermore, "The rubber teeth helped detach apples growing on the top of the branches by direct contact" (Lang, 1989). More recent attempts by He, Fu, Sun, Karkee, & Zhang (2017) revealed similar results.

Peterson (2005) stated that for mass removal methods, fruit damage during detachment, falling interaction, and catching caused excessive fruit damage. Peterson, Miller, & Whitney (1994) stated that "fruit with an unobstructed path to the catching surface removed with very low energy level has the best chance of being harvested without damage". For kiwifruit, the main concern is the damage during shaking because fruit could contact other fruit, offshoots, canes, or the growing structure. Contact with other fruit could cause bruising whereas contact with the growing or support structure could lead to cuts and punctures. The horizontal kiwifruit canopy structure limits the effect of falling damage unless the fruit is above the canopy. Due to the planar kiwifruit canopy, a soft catching surface positioned as close to the canopy as possible should be used to minimise the drop height.

2.3.2.2 Air Blast

An oscillating air blast machine was used to detach 40-95.6% of fruit but "fruit damage was sufficient to render this method unfit for fresh fruit harvesting" (Jutras, Coppock, & Patterson, 1962). The same harvester was tested by Whitney (1968) and resulted in an overall average removal of 67% and average reductions in yield of 5% and 12% for grapefruit and oranges, respectively. Reductions in yield should

be investigated for non-selective harvesters because it is future fruit loss and may drastically change economic viability.

2.3.3 Direct Contact

2.3.3.1 Combing

An apple combing harvester developed by Child & LeFlufy (1980) used two continuously rotating conveyers each with 200 picking fingers. The conveyers were positioned at a 30° angle and each finger was padded. The conveyer speed and machine speed were synchronised such that each finger travelled vertically as described by Flufy (1982). The results revealed 43-64% fruit damage of the caught fruit and 20-29% drop rate of the total fruit (Le Flufy, 1983). A combing method could be used with the planar kiwifruit canopy to comb fruit off on to a catching surface close to the canopy.

2.3.3.2 Array Type

An array of rods has been used to detach apples for the fresh fruit market by pushing the array against the apple canopy. The rods used had a soft tip and were spaced 50 mm apart. Each rod had a release mechanism to prevent damage to the plant or support trellis. The problem was fruit damage with calculated average damage percentages of near 18% in one study by Peterson (1982) and 9.9-45.7% in a second study Peterson & Kornecki (1987). The damage percentage included fruit that were not graded as Extra Fancy or Fancy. Fruit damage was caused mostly by cuts or punctures (Peterson & Miller, 1989).

Coppock (1961) used an auger array to harvest citrus fruit. Sanders (2005) used a conical picking head array to pick citrus. As the array was pushed against the canopy, the rotating picking heads deformed and picked fruit by twisting them. Qualitative fruit damage results were not presented but both stated that the main cause of damage was when a branch or limb was caught between the fruit and the picking heads. Puncture or cuts of the fruit surface would have been the likely outcome. A subsequent study by Lenker (1970) on the auger array found that the fruit damage was twice that of hand-picked fruit based on fruit decay in storage.

P. Chen (1973) used a finger hook array to harvest citrus fruit. Each finger had several flexible retractable hooks that were used to pick fruit off once the array was

positioned in the tree. Subsequent development revealed that an average of 27% of fruit were damaged (P. Chen, Mehlschau, & Ortiz-Canavate, 1982).

Array type non-selective harvesters could potentially be used for kiwifruit. A rod-press type would have to approach the canopy from the top whereas the auger or cone array and the finger hook array would have to reach the fruit from the bottom.

2.3.4 Conclusion

Direct and indirect harvesters were reviewed. Indirect harvesters were shake-and-catch harvesters which either shook part of the growing structure or used an air blast. Direct contact methods included rod pushes, cone or augers, or a hook array. Despite no literature on kiwifruit specific non-selective harvesters, literature on non-selective harvesting of apples grown in planar growing structures were directly transferrable to kiwifruit harvesting. Similar methods used on apples should be tested on kiwifruit with a focus on fruit handling. Compared to selective harvesters, non-selective harvesting had a much higher harvesting rate, but this came at the cost of lower fruit quality due to fruit damage, and damage to the plant. It would be valuable to test the reviewed literature detachment methods with kiwifruit.

Chapter 3: Selective Harvester

3.1 Introduction

The objective of this chapter was quantifying the performance of an improved AKH (Figure 1). The AKH platform consists of four robotic arms, each with a harvesting end-effector and a pair of grippers. Past performance from 2017 orchard tests reported high fruit loss due to fruit drops and knock-offs (Seabright et al., 2017). The scope of the AKH development was limited to the harvesting end-effector grippers because it was the main cause of fruit loss.

New end-effector grippers were developed to improve the performance. They were tested in the lab and orchard to determine the best performing gripper. The improved AKH was tested with new grippers on orchard to determine the performance of the overall harvester.

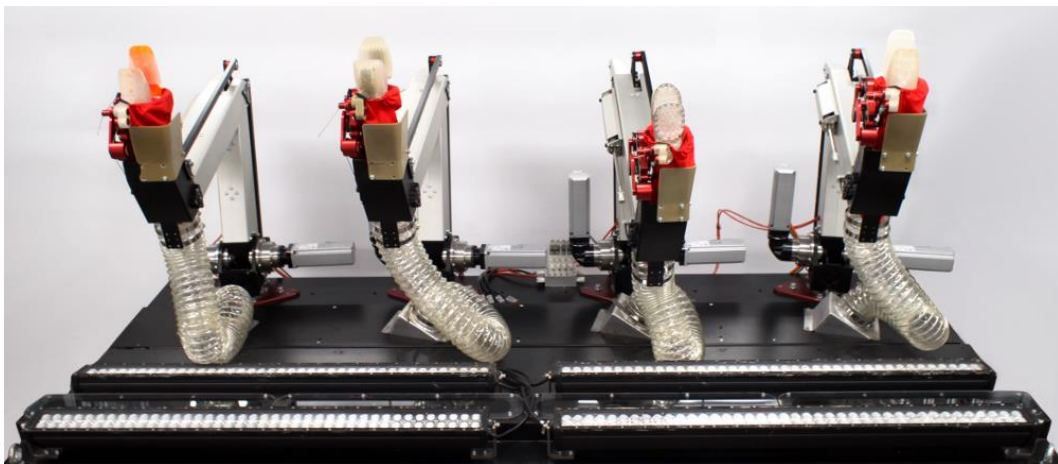


Figure 1: Robotics Plus Autonomous Kiwifruit Harvester

3.1.1 Background

During picking, human workers wear soft cotton gloves to prevent damage to the fruit skin. Kiwifruit are harvested manually by rotating the fruit about its fruit-stem connection and pulling down. The kiwifruit harvesting end-effector used the same picking method with a pair of grippers attached to a double four-bar mechanism (Figure 2). The gripper must have good fruit handling to prevent fruit damage. The double four-bar linkage had an elegant design where one actuator actuated both the grasping and rotating harvesting actions simultaneously. A pneumatic cylinder

attached to a cable was used to actuate the mechanism. After grasping, the mechanism was reset, which allowed fruit to drop down a fruit tube. A harvesting sock was used with a guard to reduce fruit drops.

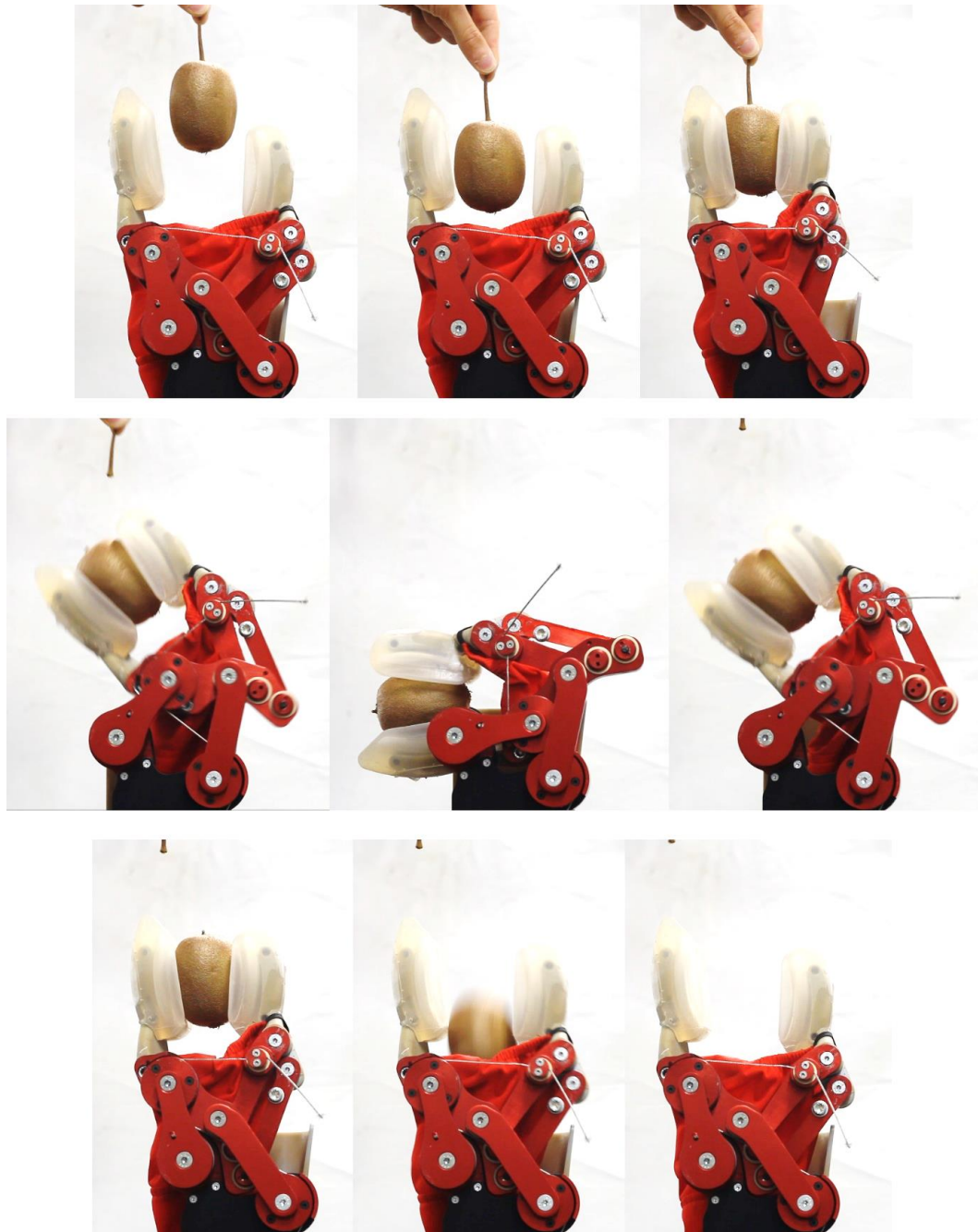


Figure 2: Robotics Plus kiwifruit harvesting end-effector

3.1.2 Objectives

1. Develop kiwifruit grippers that meets the requirements for kiwifruit harvesting
2. Evaluate and compare the performance of the new grippers

3. Obtain quantitative performance data on an improved harvester with the chosen new grippers

3.1.3 End-Effector Grippers

Three new distinct kiwifruit grippers designs were developed, prototyped, and tested in the laboratory and kiwifruit orchard. The greatest challenge during development of kiwifruit grippers was increasing the performance of multiple aspects of the gripper simultaneously while minimising any decrease in another aspect. The development of the M4 (Mark 4) gripper was included to show the underlying cause of fruit loss during 2017 testing. Prior to development, the gripper design requirements were defined:

1. Good fruit handling (does not damage fruit)
2. Grasp and harvest fruit
3. Tolerance to error and variation
4. Able to approach clusters of fruit with minimal canopy disturbance
5. Mechanically strong
6. Durable to withstand orchard environment
7. Food-safe materials
8. Low cost
9. Easy to manufacture and assemble

3.1.3.1 M4

Designed in 2016, the M4 gripper development focus was fruit handling. The gripper used a soft silicone air channel structure to conform to the fruit shape and maximise contact area (Figure 3). The structure was a mechanical metamaterial that obtained part of its properties from the structure of the material. The silicone air channel support buckled upon load to conform to the fruit. The effective stiffness of the structure could be altered by changing the structure geometry or the material. A design feature of the air channel structure was the ability to deal with fruit shape, size, pose, and position variation through shearing of the supporting channels. This feature allowed the gripper to consistently and reliably grasp fruit. Despite the advantages of the design, the gripper had high fruit loss based on 2016 orchard testing. The fruit loss was due to poor entry into fruit clusters. Upon approach, fruit

were regularly knocked off because of the high friction silicone top surface and the thickness of the gripper when entering clusters.

3.1.3.2 M5

The M5 gripper was designed by Robotics Plus near the end of the 2017 harvesting season to fix the design flaws of the M4 gripper. The thickness of the gripper was decreased significantly, and the back was tapered with a smooth surface (Figure 4). The top radius was reduced to 2 mm. These changes allowed the gripper to retain most of the M4 gripper design features while addressing the problems from past testing. The design however, added pressure concentrations to the side of the grippers. Contributions made to the gripper included pressure concentrations and gripper thickness reductions. The moulds for the silicone gripper were also improved. Furthermore, a low-cost additive manufactured version was created.

3.1.3.3 M6

The M6 gripper was designed based on a first principles design approach (Figure 5). The design goals were to minimise gripper thickness and maximise contact area. A racket-style design was used to minimise gripper thickness. This also allowed the contact surface to conform to the shape of the fruit, maximising the contact area. To slide between fruit in large kiwifruit clusters from below with minimal disturbance, a thin gripper with an arc shape cross-section was ideal.

Due to the arc shape and cylindrical contact surface, a metal tube was chosen as the starting gripper stock material form. Rotary laser-cutting of the tube allowed low-cost, high strength parts. Several deformable configurations of silicone were prototyped for the contact surface, but a weaved silicone food-grade mesh was chosen. The gripper was attached to the end-effector with an additive manufactured part.

3.1.3.4 Flexi

The Flexi gripper was designed to be resistant to impacts by elastic deformation and returning to the original shape (Figure 6). Quick prototyping was made possible with FDM (fused deposition method) additive manufacturing. Ninjaflex, a thermoplastic polyurethane (TPU), was used due to its flexibility and strength. Compared to silicone, TPU had greater strength, stiffness, and abrasion resistance. As the gripper structure itself was the cushioning, the gripper was able to be made

very thin. A small contact surface diameter of $\phi 60$ mm was used. A rigid version (Flexi V2) of the Flexi gripper with the same geometry was also developed due to orchard testing results.



Figure 3: Robotics Plus M4 gripper



Figure 4: Robotics Plus M5 gripper



Figure 5: Robotics Plus M6 gripper



Figure 6: Robotics Plus Flexi gripper

3.2 Methodology

The performance of the grippers was determined by a combination of lab and orchard testing. A set of the best performing grippers was made to determine the 2018 improved harvester performance. A past comparison by Hemming et al. (2016) on sweet pepper harvesting end-effectors broke down the cause of the harvesting failures. The same method was used but with more relevant harvesting failure categories for kiwifruit harvesting. The orchard tests for the grippers were used to determine the performance of the grippers and to break down the cause of the failures. The tests were designed with best practise for field tests in mind as described by Bac et al. (2014) on the tests by Hayashi et al. (2010) where many fruit were tested in different fruit positions.

3.2.1 Gripper

3.2.1.1 Lab Testing

The objective of the lab tests was to quantitatively determine the performance of the grippers in kiwifruit clusters. The focus of lab testing was on the ability of the gripper to enter and harvest fruit in various clusters configurations. The advantage of lab testing over orchard testing was that it could be easily repeated. Silicone kiwifruit models were set up in various configurations (Figure 7). Each test included video recording for subsequent analysis. Where possible, blocking through symmetry was used to reduce the number of test configurations required. The M5, M6, and Flexi grippers were tested with at least 2,000 fruit picks per gripper.

Cluster configuration variables included the number of fruit in a cluster, fruit Z position (high/low), fruit Z position overlap, and fruit cluster orientation relative to the gripper. Other than the single isolated fruit case, the number of fruits in clusters tested were 2, 3, and 7. The fruit Z position overlap was defined as no overlap (planar), 50% overlap, or 100% overlap, with a corresponding low (L), medium (M), or high (H) position. For example, an overlap of '50% L' meant that a fruit's Z position was below that of a planar fruit by 50% of the height of the fruit.



Figure 7: Lab testing with silicone kiwifruit models

3.2.1.1.1 Isolated Fruit

The purpose of isolated fruit testing was to determine if the grippers could harvest isolated fruit consistently. Silicone kiwifruit were placed in a 5 x 3 array of isolated fruit (Figure 8). The distance between each fruit was approximately 100 mm to avoid interference with neighbouring fruit. An array of fruit was used to increase the sample number and speed up the testing process. The number of fruit detected, knocked off, dropped, thrown, and picked were recorded. At least 20 repeats were done so total number of fruit picks exceeded 300 picks per gripper.

3.2.1.1.2 Two-fruit Clusters

Two-fruit cluster testing variables included the orientation of the cluster relative to the gripper, and the vertical Z position of the fruit (Figure 9). For the orientation, either both fruit were side-by-side, or one fruit was behind the other relative to the gripper. The fruit on the two-fruit cluster board was arranged such that all combinations of the orientation and vertical Z positions were covered. Blocking of certain 2-cluster configurations was possible due to the symmetry of fruit for the orientation when both fruit were visible to the gripper. Each data set consisted of 8 2-cluster configurations. At least 20 dataset repeats were done with the number of fruits picks exceeding 320 picks per gripper.

3.2.1.1.3 Three-fruit Clusters

Three-fruit cluster variables were the same as the two-fruit cluster, but 14 3-cluster configurations were required per data set to cover all the possible cases (Figure 10). Blocking due to symmetry was used to reduce the number of 3-cluster configurations. An additional 4 spare 3-fruit cluster spots were used to obtain additional data for the planar fruit case. At least 20 data set repeats were done with the number of fruit picked exceeding 1080 picks per gripper.

3.2.1.1.4 Seven-fruit Clusters

Due to the number of possible configurations increasing with the number of fruit, it was impractical to test every combination of a 7-fruit cluster. Each data set consisted of 3 7-fruit clusters where each cluster had 6 fruits surrounding one fruit (Figure 11). Three cluster Z position overall positions were tested including 0% (planar), 50%, and 100% height variation. The second and third cluster had two high, two low, and three medium fruit, positioned randomly in the cluster. Fruit orientation was not considered to reduce the number of tests. At least 20 data set repeats were done with the number of fruit picks exceeding 420 picks per gripper.

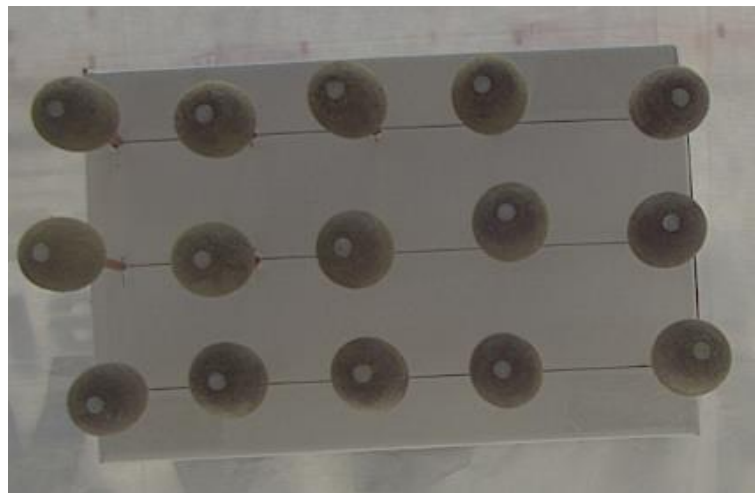


Figure 8: Lab testing isolated fruit setup

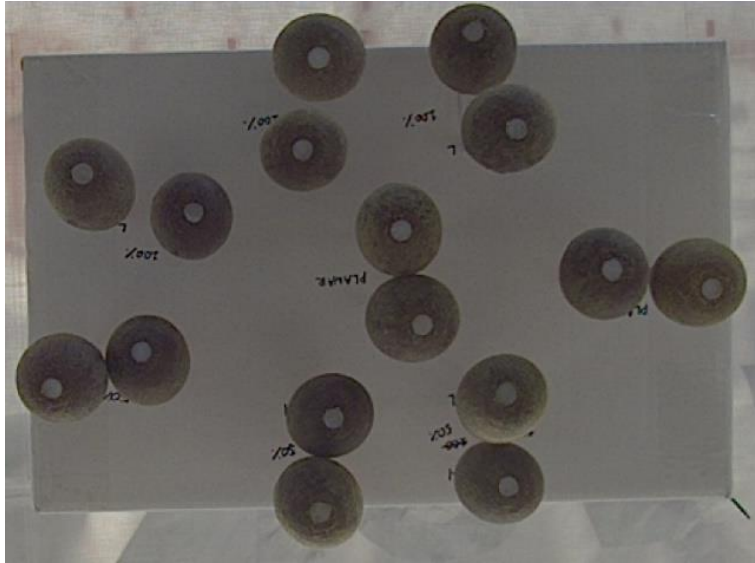


Figure 9: Lab testing 2-fruit cluster setup

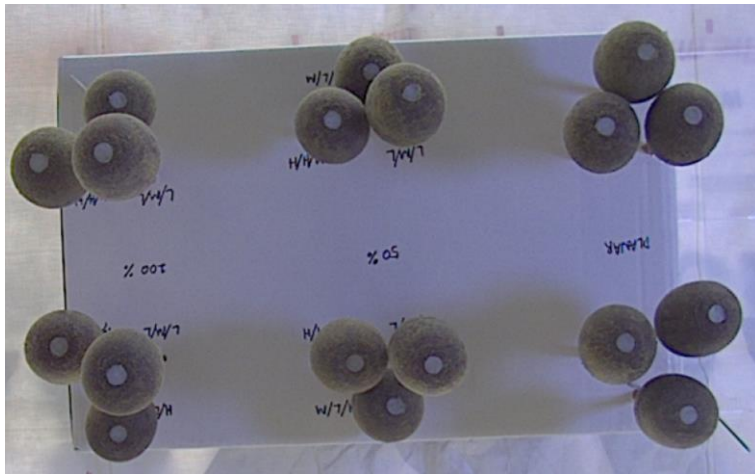


Figure 10: Lab testing 3-fruit cluster setup



Figure 11: Lab testing 7-fruit cluster setup

3.2.1.2 Orchard Testing

The objective of the orchard tests was to quantitatively determine the performance of the grippers in real kiwifruit orchards. The results were used to select grippers for the full system harvester test. The orchard test was also used to represent the one-arm performance of the harvester. Real-world orchard testing was much more valuable than lab testing because it revealed the actual performance.

Each gripper was attached to one arm and tested individually (Figure 12). The harvesting arm was positioned below kiwifruit clusters to pick all reachable fruit before moving the arm to another cluster of fruit. Each set of harvesting attempts were recorded on video. The duration, attempts, and number of fruit picked and lost were obtained from the video. Subsequent video analysis allowed detailed categorisation of the harvesting attempts. The M4, M5, M6, and Flexi grippers tested had 237, 990, 898, 1110 attempts for each gripper, respectively. The collective total number of attempts for all the grippers was 3,235.



Figure 12: Orchard testing of the grippers

The definitions for the categories below were used to categorise every harvesting attempt (Table 1). One harvesting attempt was categorised into only one category that was the main cause. This was done to simplify the data to a per-attempt basis. Air picked, obstacle, entry failure and grip failure were all attempts that did not detach the fruit. Grip failure, target knockoffs, throws, drops, and picked were all

attempts that detached fruit. The total number of harvesting attempts was the sum of all categories excluding the non-target knockoffs. The failed attempts which detached fruit were categorised into the reasons for failure so future improvements could be made.

The harvesting duration was the time between the first movement of the arm and the return of the arm to the starting position. The cycle time was calculated as the total picking duration divided by the number of fruit picked. This cycle time did not include the movement of the platform between clusters and hence was representative of what the harvesting rate a one-arm AKH could achieve.

Table 1: Orchard testing performance metrics

Performance Metric	Description
Air picked	Picked nothing but air
Obstacle	Any failure to pick due to obstacle
Entry Failure	Fruit does not enter between the grippers
Grip Failure	Fruit entered between the grippers, but slipped out
Target knock-offs	Target fruit that is knocked off the canopy
Fruit throws	Target fruit detached but is thrown from the gripper
Fruit drops	Target fruit detached but does not go down chute
Picked	Fruit detached and down chute
Non-target knockoffs	Non-target fruit that is knocked off the canopy

3.2.1.3 Fruit Handling

The objective of the fruit handling test was to determine the percentage of fruit damaged by each gripper. The fruit handling performance was tested by actuating the harvesting mechanism with real kiwifruit in the lab. Lab testing was done to isolate the effect of the grippers and for better tracking of the fruit tested. The fruit used were carefully hand harvested into padded boxes prior to testing. Fruit were placed by hand at the approximate designed calyx target position between the grippers. The grasping contact time was less than one second and fruit were caught immediately after. Pneumatic cylinder actuator pressures of 2.5, 3.0, 3.5, and 4.0 bar were used. Actuator pressures of 2 bar and lower were not used as these pressures were insufficient to actuate the rotation action of the mechanism. Pressures over 4.0 bar were not used to prevent damage to the grippers. After

testing, the fruit were placed back into the padded boxes. Control fruit were placed in the same box as the tested fruit. The fruit were held for 3 to 4 weeks at room temperature to let fruit damage develop. This reduced the chance of false negatives by making the damage obvious.

During evaluation, the testing parameters were not viewed to prevent confirmation bias. Damage was evaluated first by visual observation and tactile feeling of the fruit. If there was no obvious damage, the fruit was cut, and the fruit flesh was examined for signs of internal damage. Each fruit was cut along the fruit longitudinal axis with four cuts leading to 8 slices of kiwifruit and 16 fruit surfaces (Figure 13). Subsequent cuts along the normal plane relative to the fruit longitudinal axis allowed more of the interior flesh to be observed (Figure 14). Cutting stopped when fruit damage was found. The likelihood of an undetected bruise was low by using this method. The recorded results for each fruit was a binary response (damage or no-damage), but comments on the extent of the damage were recorded. The total number of fruit used in the tests were 250, 250, 100, for the M5, M6, and M4 grippers, respectively.

Several test repeats for the new grippers were done to find the effect of the grippers on softer fruit. The fruit firmness of each dataset was measured with a $\phi 7.9$ mm diameter by 8 mm high cylindrical penetrometer probe for kiwifruit, attached to a hand-held force sensor (Model: Starr FGD-500) with an error of ± 1 N . The kiwifruit skin at the measurement area was removed with a peeler prior to measurement. Two measurements were made per fruit at right angles relative to the longitudinal axis. At least ten random kiwifruit were used for the measurement.

The relationship between the pneumatic cylinder actuation force and the gripper compression force was determined by actuating the end-effector and measuring the force at different pneumatic cylinder pressures. As inspired by Odhner et al. (2014), a compression load cell (TE Connectivity FC22) with an additive manufactured kiwifruit shell was placed between the grippers to measure the peak force. Two FC22 sensors with limits of 10 lbf (44.4N) and 50 lbf (222 N) were used to cover the required grasping force range. The load cell error of the 44.4 N and 222 N sensors were ± 1 N and ± 5 N, respectively, based on the rated 2.25% of span (TE Connectivity, 2018). Prior to testing, the accuracy of the sensors was verified with

another force gauge. An Arduino microcontroller was used to record the grasping force.



Figure 13: Cutting along the fruit longitudinal axis for damage evaluation

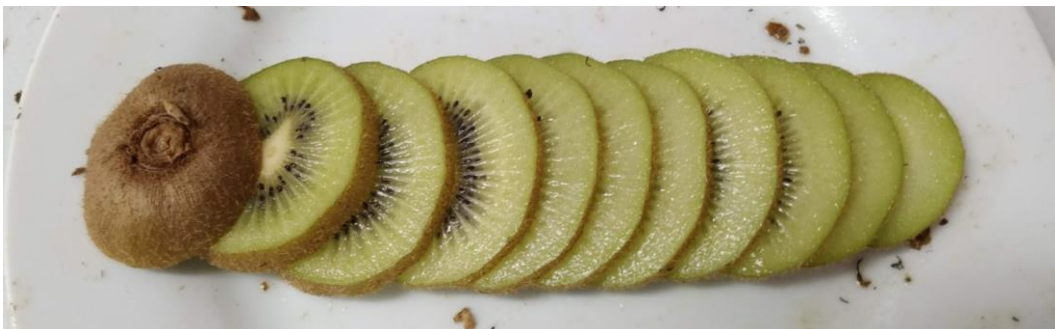


Figure 14: Cutting normal to the kiwifruit longitudinal axis for damage evaluation

3.2.2 Harvester

The objective was to determine the improved performance of the harvester with the chosen new grippers. Due to the orchard test results of the individual grippers, two full four-bay harvester tests were done. The performance increase was also partly due to improvement of the vision system by another researcher. Four bays of kiwifruit were harvested to determine the performance. The grippers were tested on commercial Hayward orchards. Four pairs of the chosen grippers were attached to the four arms of the harvesting unit. The AKH was placed on the Robotics Plus AMMP (Autonomous Multipurpose Mobile Platform) for orchard navigation (Figure 15). Harvesting started at the left side of each bay and moved forward

approximately 300 mm each time. For each half bay, about 16 300 mm harvesting zones were required. Hence, 32 zones on average were required to harvest a full bay. At each zone, the harvester was instructed to pick the fruit that were detected. At the end of harvesting a zone, fruit picks and fruit lost were counted to ensure accuracy of the results. After harvesting a full bay, the rest of the fruit left in the canopy were manually picked and counted. The reachability was measured as the percentage of fruit detached from the canopy because reachable fruit were attempted until they were either successfully harvested or lost. The reachability was dependent on the canopy itself and varied from orchard to orchard based on the vine structure and management. The performance metrics of interest were reachability, picked-detached, stemless, fruit handling, and cycle time.

Video recording of harvesting allowed more detailed analysis of the performance. Four randomly selected zones in a bay, of four bays were used to calculate the harvesting duration and hence the cycle time. The harvesting duration for a zone was defined as the time when the robot first starts picking to the time when the robot returns to the starting position.

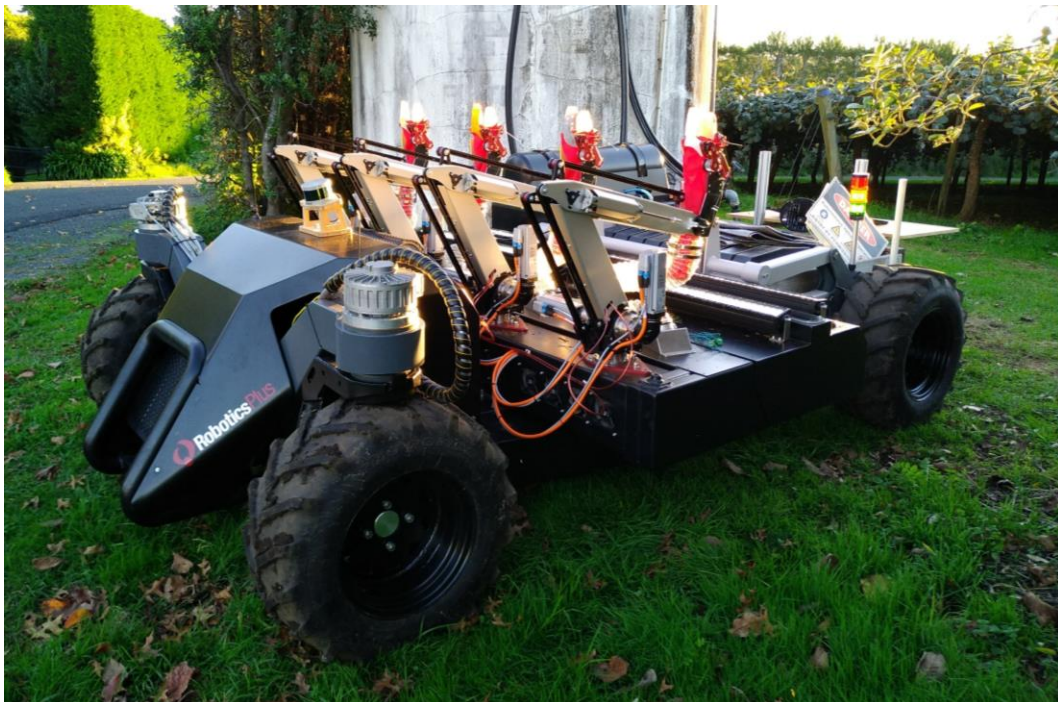


Figure 15: Robotics Plus Autonomous Mobile Modular Platform (AMMP) with Autonomous Kiwifruit Harvester (AKH)

3.3 Results

3.3.1 Gripper

3.3.1.1 Lab Testing

Table 2: Lab testing picking success

	Fruit Picked Success (%)			
	M5	M6	Flexi	Average
Isolated fruit	99.7	97.8	95.9	97.8
2-fruit cluster	82.1	81.4	83.8	82.4
3-fruit cluster	82.0	82.8	76.4	80.4
7-fruit cluster	67.0	64.7	70.7	67.5
Average	82.7	81.7	81.7	-

Table 3: Lab testing harvesting cycle time

	Harvesting Cycle Time (s/fruit)			
	M5	M6	Flexi	Average
Isolated fruit	1.81	1.81	1.91	1.84
2-fruit cluster	2.09	2.08	1.99	2.05
3-fruit cluster	2.61	3.10	2.27	2.66
7-fruit cluster	3.51	3.20	2.56	3.09
Average	2.51	2.55	2.18	-

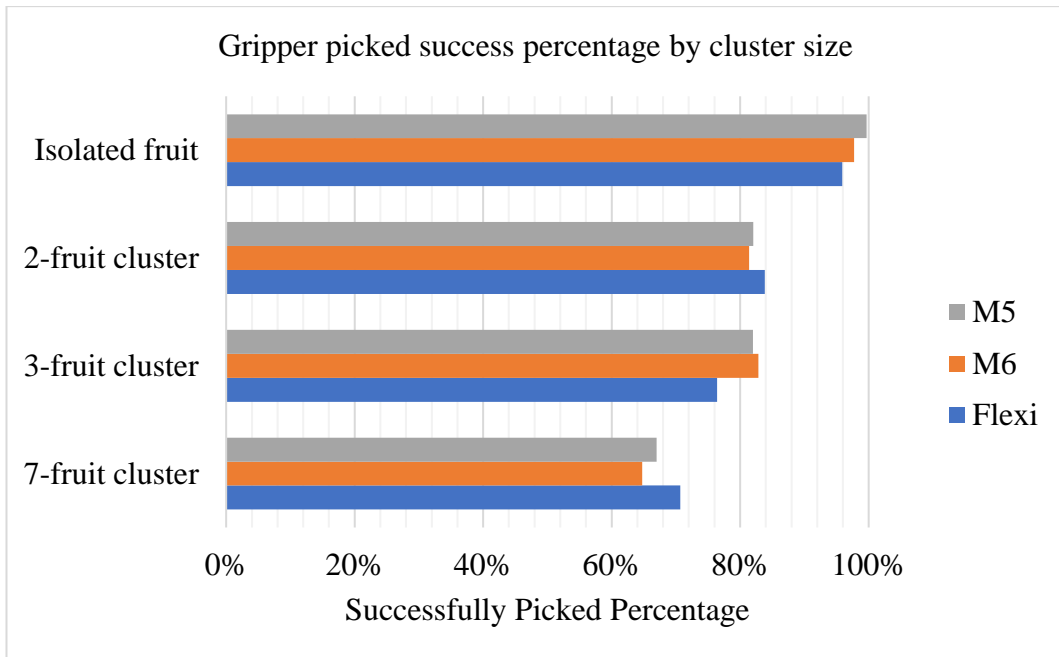


Figure 16: Lab picked success percentage

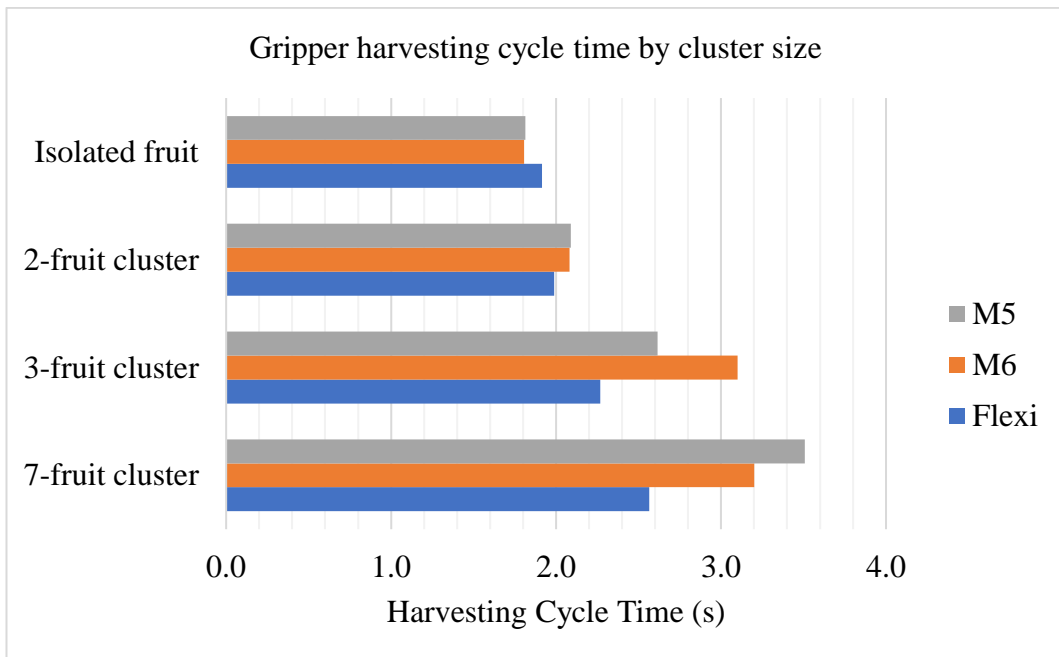


Figure 17: Lab harvesting cycle time

3.3.1.2 Orchard Testing

Table 4: Gripper orchard testing performance

Performance Metric	Gripper				
	M4	M5	M6	Flexi	Flexi V2
Picked Fruit	135	704	653	76	258
Fruit Lost	52	82	84	29	44
Detached Fruit	187	786	737	105	302
Harvesting Attempts	237	990	898	223	380
Total Harvesting Time (s)	667	2393	2163	509	941
Harvesting Rate (fruit/s)	0.20	0.29	0.30	0.15	0.27
Harvesting Cycle (s/fruit)	4.94	3.40	3.31	6.70	3.65
Picked/Detached (%)	72.2	89.6	88.6	72.4	85.4
Picked/Attempt (%)	57.0	71.1	72.7	34.1	67.9

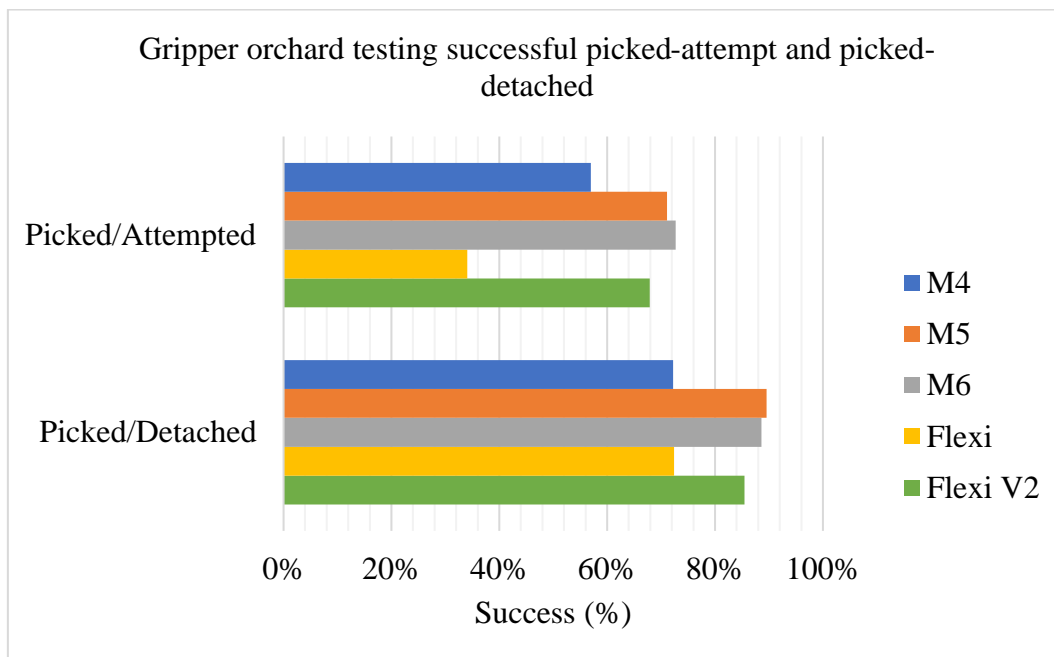


Figure 18: Gripper orchard testing success

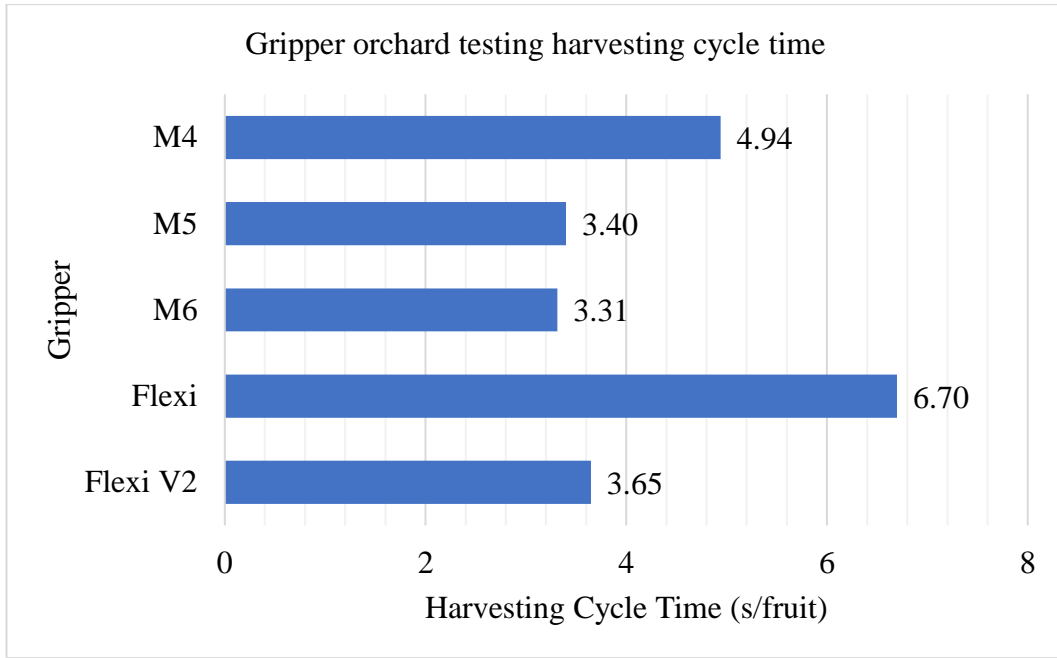


Figure 19: Gripper orchard testing harvesting cycle

Table 5: Gripper orchard testing failure breakdown by fruit

Gripper	Stem un-detached				Stem detached				Total Attempts	Non-target Knockoffs
	Air picked	Obstacle	Entry Failure	Grip Failure	Target Knock-offs	Fruit Throws	Fruit Drops	Picked		
M4	16	22	33	5	8	15	3	135	237	26
M5	38	36	120	27	25	26	14	704	990	17
M6	41	58	84	22	21	13	11	653	898	39
Flexi	18	5	33	67	13	2	9	76	223	5
FlexiV2	14	28	40	8	18	8	6	258	380	12
Total	127	149	310	129	85	64	43	1826	2728	99

Table 6: Gripper orchard testing failure breakdown by percentage of attempts

Gripper	Stem un-detached				Stem detached				Non-target Knockoffs (%)
	Air picked (%)	Obstacle (%)	Entry Failure (%)	Grip Failure (%)	Target Knock-offs (%)	Fruit Throws (%)	Fruit Drops (%)	Picked (%)	
M4	6.8	9.3	13.9	2.1	3.4	6.3	1.3	57.0	11.0
M5	3.8	3.6	12.1	2.7	2.5	2.6	1.4	71.1	1.7
M6	4.6	6.5	9.4	2.4	2.3	1.4	1.2	72.7	4.3
Flexi	8.1	2.2	14.8	30	5.8	0.9	4.0	34.1	2.2
Flexi V2	3.7	7.4	10.5	2.1	4.7	2.1	1.6	67.9	3.2
Average	4.7	5.5	11.4	4.7	3.1	2.3	1.6	66.9	3.6

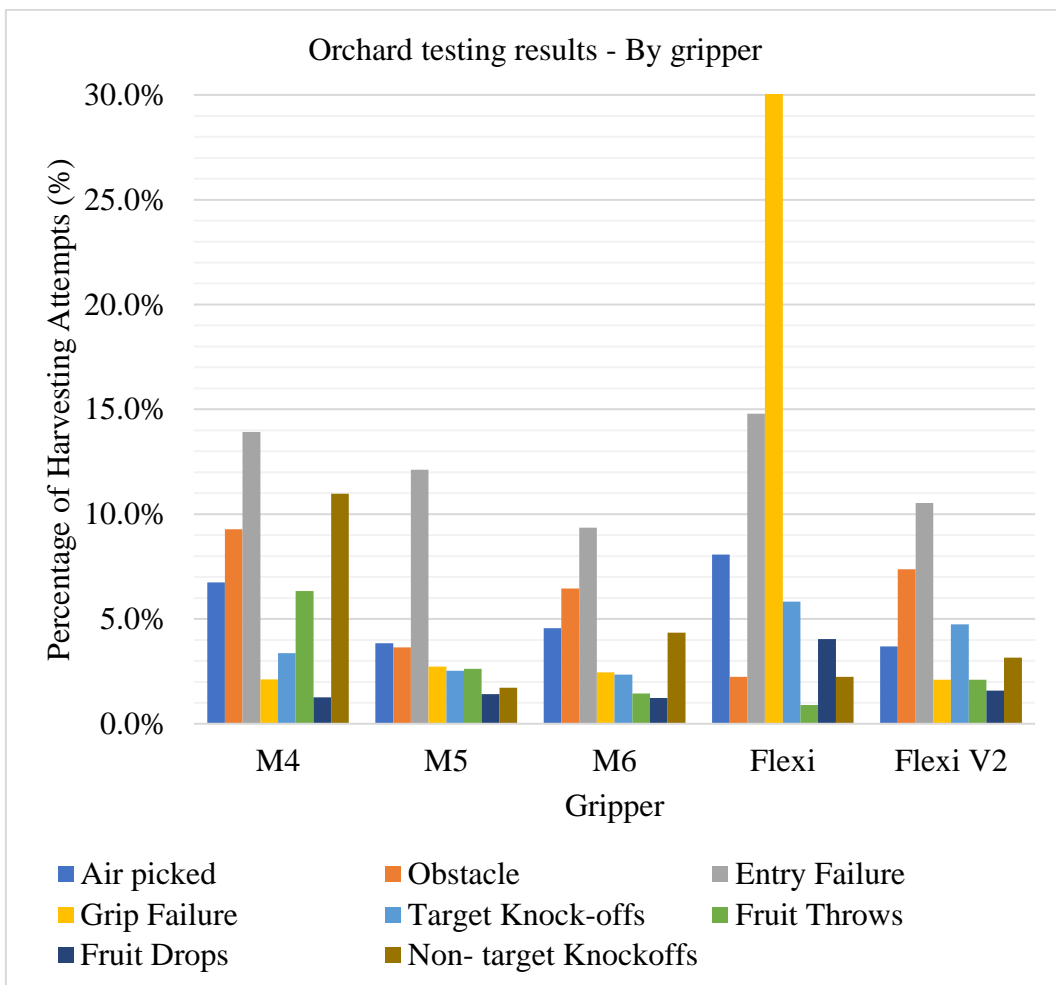


Figure 20: Gripper orchard harvesting attempts breakdown by gripper

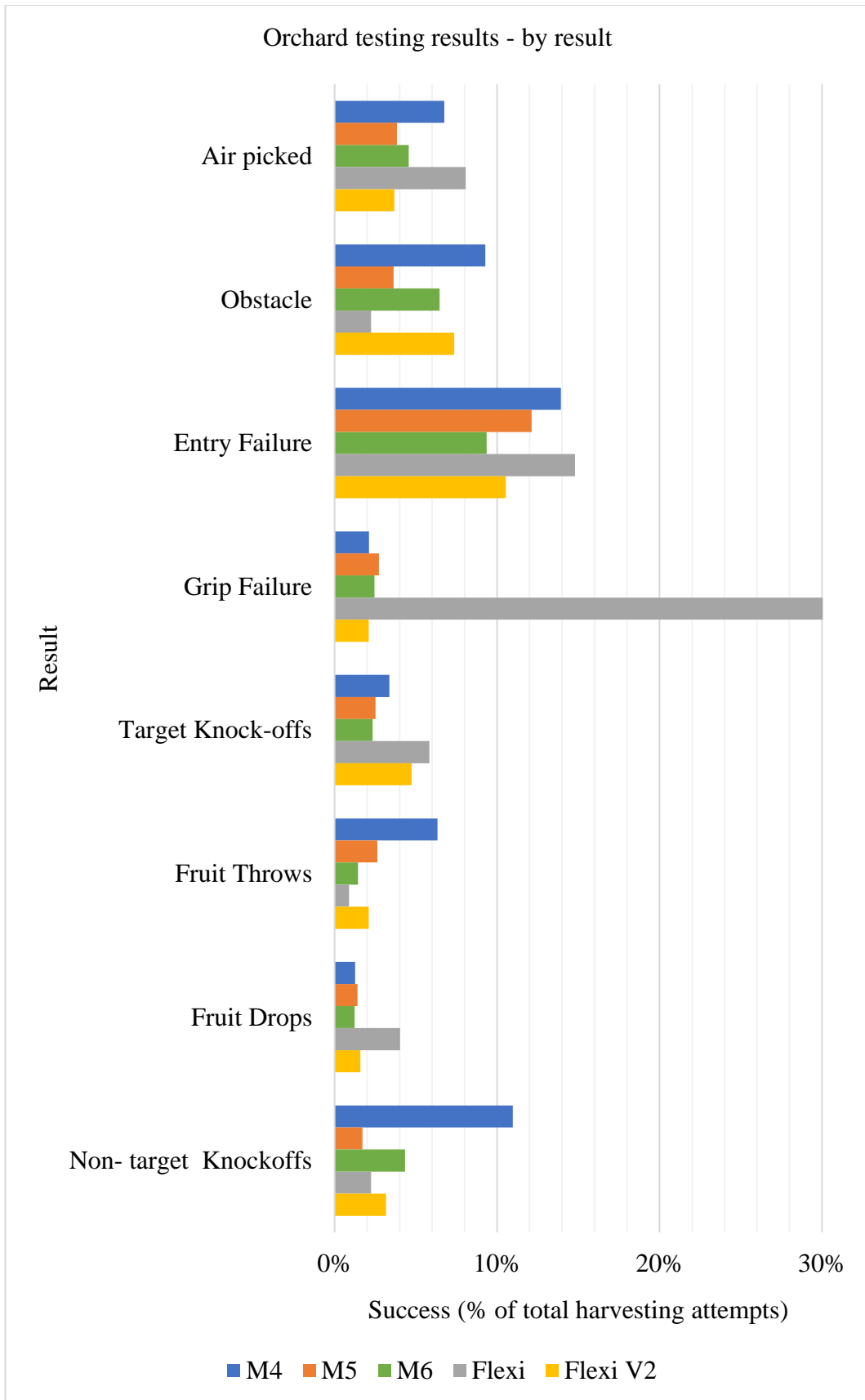


Figure 21: Gripper orchard harvesting attempts breakdown by result

3.3.1.3 Fruit Handling

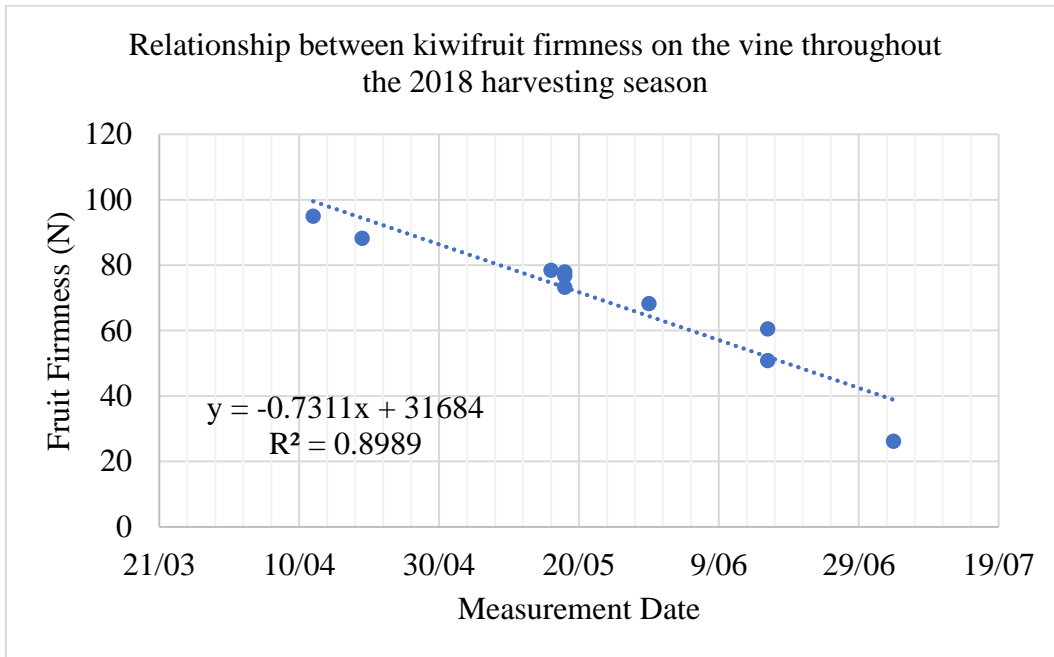


Figure 22: Kiwifruit firmness on the vine during harvesting season

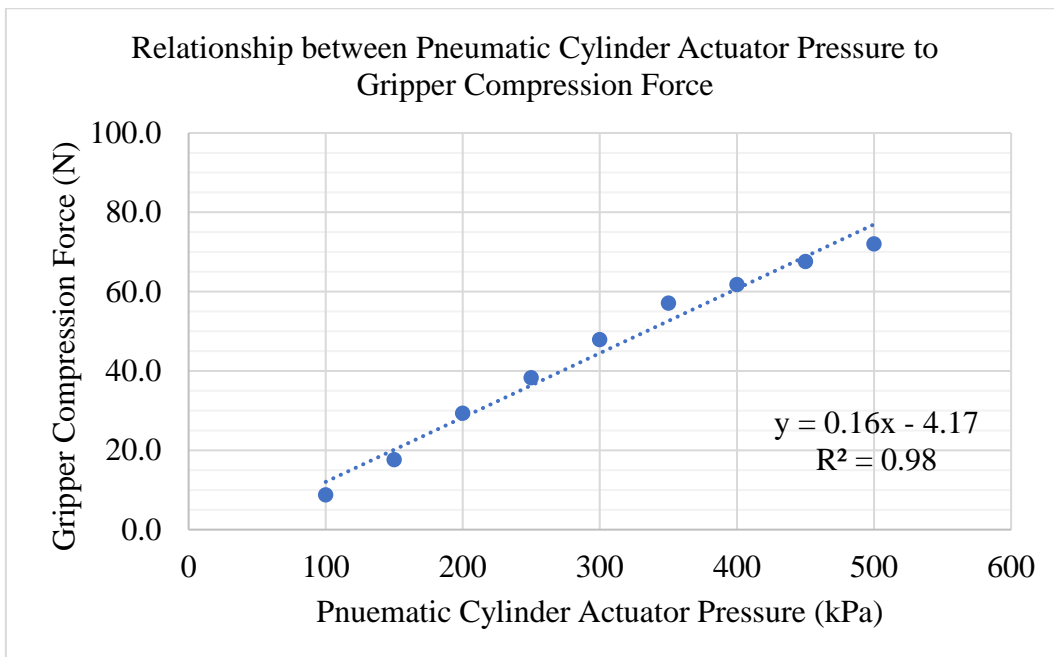


Figure 23: Relationship between pneumatic cylinder actuator pressure and gripper compression force

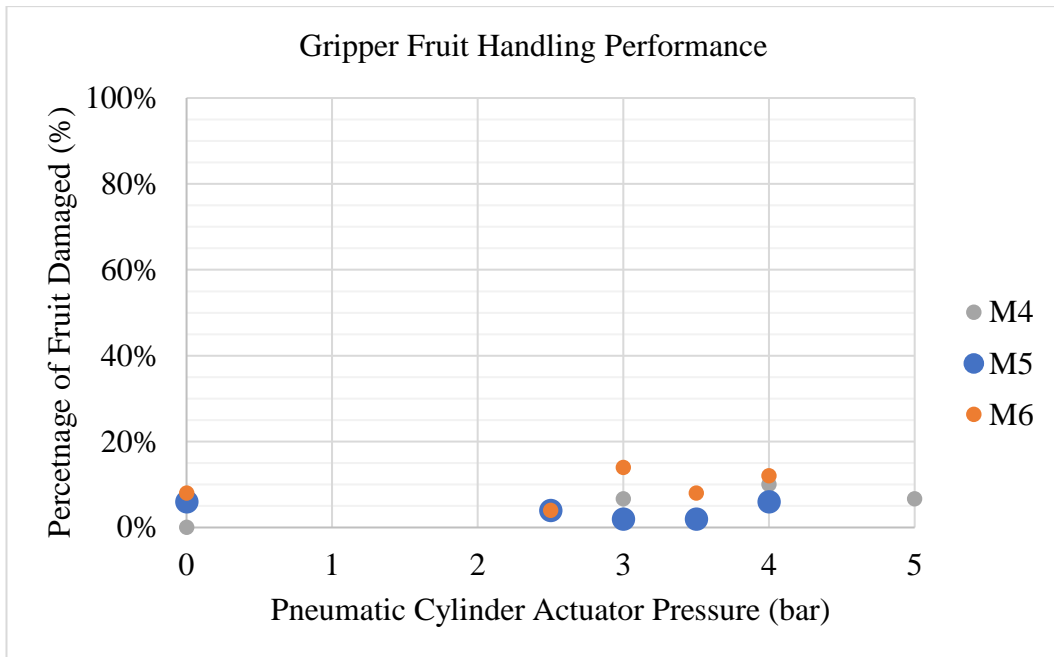


Figure 24: Overall averaged gripper fruit handling performance

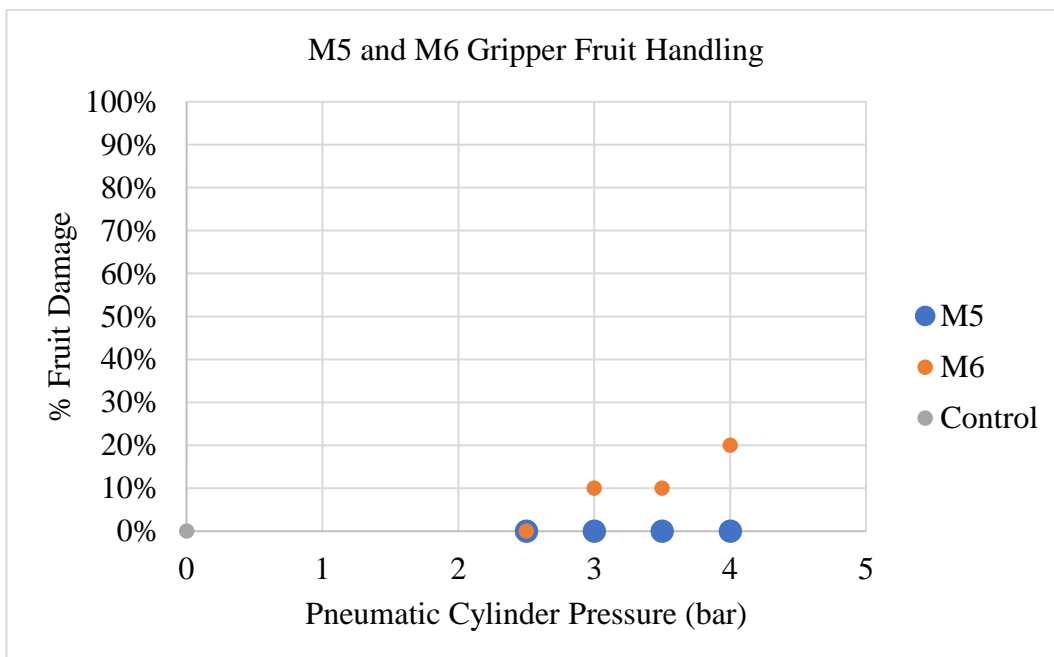


Figure 25: M5 and M6 gripper fruit handling performance

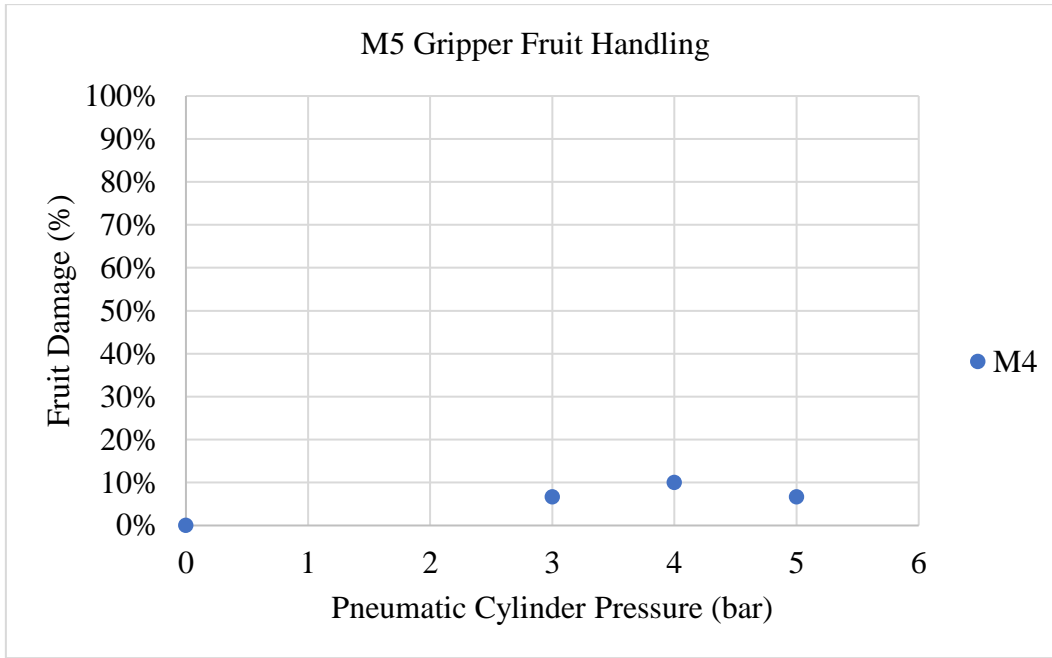


Figure 26: M4 gripper fruit handling performance

3.3.2 Harvester

Table 7: 2018 AKH full system orchard testing results

Gripper or Year	Kiwifruit Bays	Total Kiwifruit	Picked (%)	Dropped (%)	Left (%)	Detached (%)	Picked/Detached (%)	Stems/Picks (%)	Harvesting Rate (fruit/s)	Cycle Time (s/fruit)
M5	4	5327	55.0	10.7	34.3	65.7	83.8	-	0.35	2.83
M6	4	6727	56.5	6.8	36.7	63.3	89.2	6.2	0.37	2.73
2018	8	12054	55.8	8.7	35.5	64.5	86.4	6.2	0.36	2.78
2017	-	1456	50.8	24.6	24.6	75.4	67.4	-	0.19	5.37

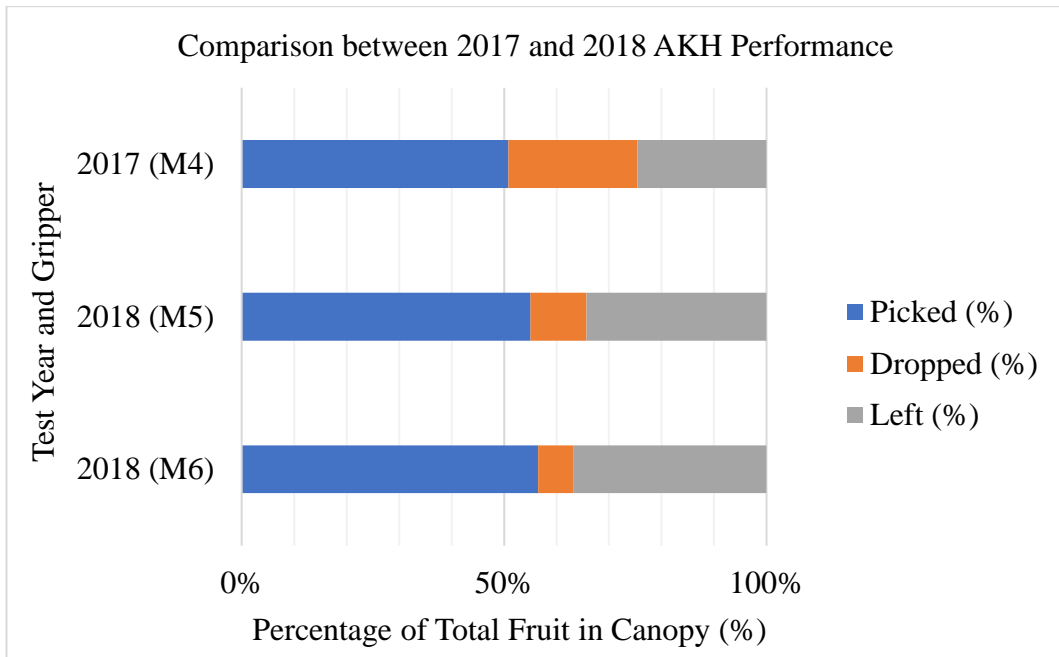


Figure 27: Comparison between 2017 and 2018 AKH reachability performance

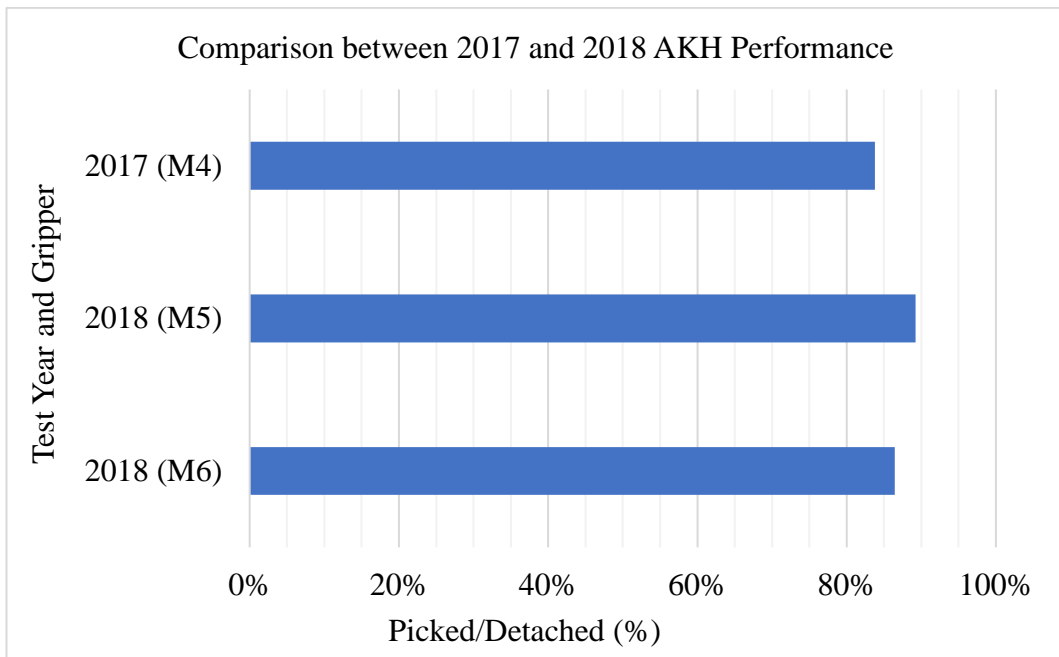


Figure 28: Comparison between 2017 and 2018 AKH picked-detached performance

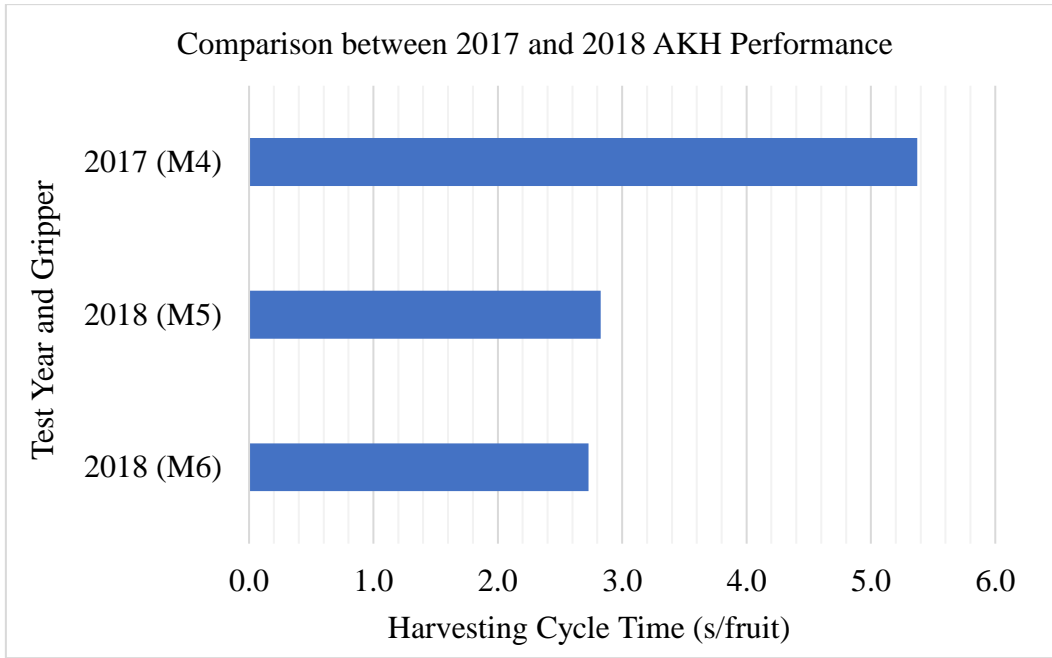


Figure 29: Comparison between 2017 and 2018 AKH cycle time performance

Table 8: 2018 AKH cycle time calculation

	M5	M6	Overall
Number (regions)	16	16	32
Picked (fruit)	446	505	951
Dropped (fruit)	89	70	159
Detached (fruit)	535	575	1110
Picking time (s)	1197	1315	2512
Region move time (s)	4	4	4
Total move time (s)	64	64	128
Total time (s)	1261	1379	2640
Harvesting rate (fruit/s)	0.35	0.37	0.36
Cycle time (s/fruit)	2.83	2.73	2.78

3.4 Discussion

3.4.1 Gripper

3.4.1.1 Lab Testing

3.4.1.1.1 Isolated Fruit

All grippers were able to successfully harvest isolated fruit with a success rate of 97.8%, 99.7%, and 95.9%, for the M5, M6, and Flexi grippers, respectively (Table 2). The M5 gripper picked 312 fruit and lost only one fruit by grasping too low which caused a fruit throw. The M6 gripper picked 312 fruit with 7 losses, 6 of which were due to drops or throws. The Flexi gripper picked 318 fruit with 14 fruit losses, of which 12 were due to drops or throws. The main cause of most fruit losses (drops and throws) was positioning error of the grippers relative to the fruit right before actuation. The positioning errors may be due to a variety of factors including localisation error, robot arm positioning error, and fruit position change. Provided that the gripper was positioned correctly relative to the fruit, isolated fruit could be grasped successfully near a 100% success rate. The M5 and M6 grippers had the same cycle time of 1.81 s/fruit (Table 3). The Flexi gripper cycle time was a tenth of a second higher at 1.91 s/fruit due to higher fruit loss. The isolated fruit cycles times were representative of what the harvester could achieve in the orchard in ideal conditions where fruit are evenly spread out, planar, and not in clusters.

3.4.1.1.2 Two-fruit Clusters

For two-fruit clusters, the success was about the same with success percentages of 82.1%, 81.4%, and 83.8%, for grippers M5, M6, and Flexi, respectively (Table 2). The Flexi gripper cycle time was fastest at 1.99 s/fruit, which was about a tenth of a second faster than both the M5 and M6 grippers. The influence of fruit clusters was obvious from the significant drop in harvesting success with an average of 82.4% compared to the 97.8% average for isolated fruit. The average cycle time also increased from 1.84 s/fruit for the isolated fruit case to 2.05 s/fruit for the two-fruit cluster case (Table 3).

Most fruit losses were knock-offs which caused 12.5% to 15.3% fruit loss. Drops and throws caused only 2.8% to 3.7% loss. The fruit losses were due to positioning errors and harvesting order. A low fruit grasp caused fruit throws. Positioning errors in the horizontal plane often caused an entry failure where fruit did not enter

between the grippers. This often caused the target or non-target fruit to be knocked off upon approach. Even if the target fruit entered between the grippers, poor positioning resulted in a poor grasp and a high chance of fruit drop.

Another cause of the knockoffs was the harvest order. Fruit harvested in the wrong order had a high chance of knock-offs. This was evident when higher fruit were picked before lower fruit. In this case, the harvesting action often knocked the bottom fruit off. Other fruit losses were due to canopy shaking, fruit getting stuck between the grippers, or less common causes such as one fruit hitting another. The two improvements required were the positioning of the gripper prior to the harvesting action, and the harvest scheduling order.

3.4.1.1.3 Three-fruit Clusters

The three-fruit cluster success percentages were 82.0%, 82.8%, and 76.4% for the M5, M6, and Flexi grippers, respectively (Table 2). The success percentages and cycle times were worse than the two-fruit cluster case except for the M6 gripper success percentage which surprisingly increased by 1.4%. The M5 gripper success percentage for the two-cluster and three-cluster case was about the same but the cycle time increased from 2.09 s/fruit to 2.61 s/fruit (Table 3). The two main causes of the loss were gripper positioning error and scheduling order.

3.4.1.1.4 Seven-fruit Clusters

The seven-fruit cluster success percentages were 67.0%, 64.7%, and 70.7% for the M5, M6, and Flexi grippers, respectively (Table 2). The cycle time increased further to 2.56-3.51 s/fruit for the three grippers (Table 3). In a large cluster, each fruit on average had more neighbouring fruit than a smaller cluster. Therefore, each disturbance was more likely to affect more neighbouring fruit which could increase the fruit loss. Any side fruit had three neighbouring fruit while the centre fruit had six neighbouring fruit. The Flexi gripper performed the best in the seven-fruit cluster with highest success percentage and the lowest cycle time. The Flexi gripper had the smallest cross-section compared to the other grippers and caused the least disturbance during entry into a cluster.

3.4.1.1.5 Summary

Fruit in larger clusters had more neighbouring fruit which could be affected by the two main causes of fruit loss which was positioning error and scheduling order. An

increase in the number of fruit in a cluster decreased the success. The average success dropped from 97.8% for single fruit to 82.4% for two-fruit clusters, 80.4% for three-fruit clusters, and 67.5% for seven-fruit clusters (Figure 16). The average cycle time increased from 1.84 s/fruit for isolated fruit to 2.05 s/fruit, 2.66 s/fruit, and 3.09 s/fruit, for the two-fruit, three-fruit, and seven-fruit clusters, respectively (Figure 17).

The Flexi gripper was the fastest because it had the lowest cycle time for every cluster scenario as well as the overall lowest cycle time. The M5 had the best isolated fruit cluster success. The Flexi had the best two-fruit and seven fruit cluster success. The M6 had the best three-fruit cluster success. The overall best gripper based on lab testing was the Flexi because it was the fastest and had the highest success in the two-cluster and seven-cluster tests. In real kiwifruit orchards, fruit were almost always in clusters, so the cluster performance was of high importance.

3.4.1.2 Orchard Testing

The Flexi gripper performance was the worse which was unexpected because it had the best performance during lab testing. Poor grasping required additional attempts which resulted in a high cycle time. The cause was fruit slipping because of the low coefficient of friction surface combined with insufficient rigidity which formed a V-shape grasp. During lab testing, the fruit were made of silicone with modelling flock to lower the friction, but real kiwifruit had much lower coefficients of friction. Therefore, the Flexi gripper was able to grasp silicone fruit but not real fruit without slipping out. The poor performance of the Flexi was addressed by creating the Flexi V2 (Version 2) gripper. The gripper was made rigid and a silicone layer was added while retaining the same geometry. It was tested on another robot arm.

Orchard testing of the single arm revealed the performance of the grippers in real orchard conditions (Table 4). The picked-detached performance was 72%, 90%, 89%, 72%, and 85% for the M4, M5, M6, Flexi, and Flexi V2 (Version 2) grippers, respectively. The cycle time was 4.94 s/fruit, 3.40 s/fruit, 3.31 s/fruit, 6.70 s/fruit, and 3.65 s/fruit for the M4, M5, M6, Flexi, and Flexi V2 grippers, respectively. The new grippers (M5, M6, Flexi V2) showed significant improvement relative to the M4 gripper in terms of picked-attempt, picked-detached, and cycle time performance (Figure 18, Figure 19). The performance difference between the new

grippers was quite small but the difference between the new grippers and the M4 was large. Therefore, three good gripper solutions were developed. The results showed that the performance of M6 was the best with the highest picked-detached percentage and the lowest cycle time. However, the M5 gripper performance was very close with 1% less pick-detached, and only a tenth of a second slower cycle time. Due to the small performance difference between the M5 and M6 grippers, it could not be said with confidence that one gripper was better than the other without a large dataset. As a result, both the M5 and M6 grippers were chosen for the full harvester test.

The results were broken down into a per-attempt basis to determine the cause of harvesting failures (Table 5, Table 6). The harvester performance breakdown showed that entry failures caused the greatest fruit losses (Figure 20, Figure 21). Improvement to the positioning of the gripper would reduce entry failures, grip failures, target and non-target knockoffs, fruit throws and drops. This could be done by adding three additional degree of freedoms to the end-effector. Additions of a gripper spacing, tilt, and twist degree of freedoms would allow improved dexterity during the approach to kiwifruit clusters. It may be better to avoid harvesting fruit near obstacles because of the extra time required and higher risk of fruit damage. Each harvester should also have a catching system to reduce fruit loss by catching fruit drops, throws, and knock-offs.

3.4.1.3 Fruit Handling

The fruit firmness on the kiwifruit vines followed a linear relationship during the harvesting season with a 0.90 r-squared value (Figure 22). Kiwifruit were typically harvested when the firmness was between 59-88 N (6-9 kg-force) based on literature (Warrington et al., 1990). Softer fruit were more susceptible to bruising. Therefore, if fruit were not damaged in a test on soft fruit, it can be inferred that fruit damage would not happen on firmer fruit under the same conditions.

The kiwifruit gripper compression force was found. There was a linear relationship between the pneumatic cylinder actuator and grasping compression force with a 0.98 r-squared value (Figure 23). The end-effector pressure used was 3 bar which corresponded to a harvesting force of 47.9 ± 4.2 N. The compression force was of interest because it could be compared with literature bruising pressure thresholds.

Overall, the average fruit damage for the M4, M5, and M6 grippers were 8%, 4%, and 10%, respectively (Figure 24). The fruit damage range for the M4, M5, and M6 grippers were 7-10%, 2-6%, and 4-14%, respectively. In the first three datasets, about 10% of the control fruit were damaged. Only dataset 4 and 5 had undamaged control fruit. Ignoring datasets 1-3, the average fruit damage for the M5 and M6 grippers were 0% (no damage) and 8%, respectively (Figure 25). The control fruit used in the M4 gripper tests were not damaged (Figure 26).

Despite 10% of fruit in the control in datasets 1-3 showing signs of damage, the data was still useful. The M5 gripper fruit damage at any actuator pressure was typically zero but the maximum was 10%. Therefore, there was high confidence that the M5 fruit handling percentage was near zero. The damage percentage of the M6 varied. In the first dataset, the damage reached 25% at 3-bar, and in the fourth dataset, the damage reached 20% at 4-bar. In all other pressures and datasets, the damage was either 10% or lower.

Great care was taken to ensure that there was no damage during hand picking for lab testing. Damage may have occurred on the vine prior to harvesting, during transport, or during storage. In storage, if a fruit developed a fruit rot, the control fruit next to it may have been affected. Therefore, damaged fruit next to another fruit could be a confounding factor. Future testing should increase the sample size even more and use a controlled storage atmosphere to prevent confounding factors.

The results showed that the M4 gripper had worse fruit handling than the M5 gripper because the fruit tested with the M5 gripper were much softer with a firmness of 26.2 ± 4.9 N, whereas the M5 gripper was tested with a firmness of 50.8 ± 7.5 N. As softer fruit are more susceptible to damage, the actual fruit handling of the M4 gripper was expected to be much better. The M4 fruit handling was expected to have better fruit handling than the M5 because the silicone support structure allowed it to conform to the fruit more. Therefore, if the M4 was tested with firmer fruit, it is likely that there would be no fruit damage.

Fruit damage by the M6 gripper was most likely pressure concentrations. If the fruit was grasped at the wrong position, the racket frame could act as a pressure concentration. Furthermore, the M6 weaved silicone tube contact surface had peaks which could act as pressure concentrations. If there was no positioning error and a

soft silicone surface with no peaks were used, then the fruit handling performance of the gripper would likely not damage fruit.

3.4.2 Harvester

Both the M5 and M6 grippers were chosen for the full harvester test because individual gripper orchard test results revealed similar performance. The 2018 test results showed great improvement over the 2017 results (Table 7). The reachability decreased from 75% to 64% and the drop rate was decreased from 25% to 9%, which was a 64% reduction (Figure 27). The picked-detached percentage increased from 67% to 86% (Figure 28). Of the picked fruit, 93.8% of fruit were stemless. The average cycle time was almost halved from 5.37 s/fruit to 2.78 s/fruit which was a reduction of 48% (Figure 29). The cycle time calculation included the movement time of the platform (Table 8).

During the single gripper orchard tests, the M5 and M6 grippers achieved a picked-detached percentage of 90% and 89%, respectively. In the full system test, the M5 and M6 grippers achieved similar picked-detached percentages of 84% and 89%, respectively. The single arm tests showed that an arm was capable of harvesting with an average cycle time of 3.36 s/fruit which decreased to 2.78 s/fruit with three additional arms. The additional arms only decreased the cycle time by 17%. The current robot-manipulator configuration was unable to efficiently use the arm's harvesting capacity. If each arm could harvest at the individual capacity, the collective ideal cycle time and harvesting rate would be 0.84 s/fruit and 1.19 fruit/s, respectively. The current configuration only utilised 23% of the harvesting arm capacity. The harvesting arms were underutilised because the distribution of fruit clusters within the harvesting arm working envelopes were uneven because of natural variation. This caused some arms to pick many fruits while others were idle. The idle arms had to wait until all the other arms had picked the fruit in their workspace before the platform moved to a fresh part of the canopy. Furthermore, the second pass within a bay overlapped partly with the first pass.

A design from simulation approach based on research by Redmond R Shamshiri, Hameed, Karkee, & Weltzien (2018) and Redmond Ramin Shamshiri et al., (2018) was recommended for testing future kiwifruit harvester configurations. The focus of the robot configuration should be on the workload distribution. Decreasing the

number of arms to one per robot may utilise most of the harvesting capacity of one arm as it would not have to wait for other arms to finish picking. However, this is likely to be not as cost effective because each manipulator would need a separate robot platform. On the other extreme, fitting as many manipulators possible per robot may cause many of the manipulator's harvesting capacity to be unused. Therefore, the best approach would be to generate many configurations and to simulate the picking of fruit.

The actual performance of the harvester with the M5 and M6 grippers were 79% and 77%, respectively. The M5 actual performance was calculated from the product of the picked-detached, stemless, and fruit handling performance which was 84%, 93.8%, and 100%, respectively. The M6 actual performance was calculated from the product of the picked-detached, stemless, and fruit handling performance which was 86%, 93.8%, and 92%, respectively.

The following future research areas should be explored:

1. Increase reachability
 - a. The robot reachability could be increased significantly if more fruit were under the support wires. This would reduce the fruit left on the canopy. An investigation into vine training methods to maximise the reachability of kiwifruit for robotic harvesting would be valuable.
2. Increase manipulator workload sharing
 - a. Exploration of alternative robotic configurations to utilise the harvesting capacity of the manipulators could decrease the collective cycle time significantly.
3. Fruit loss reduction
 - a. A catching surface would have the greatest benefit because it could improve the picked-detached performance by redirecting all fruit drops, throws, and knock-offs to picked fruit. Reducing the positioning error of the end-effector prior to grasping would reduce fruit losses. This could be achieved by three additional degrees of freedom (gripper distance, tilt, and twist). An improved harvesting scheduling order could also reduce fruit losses. In the scheduler, avoiding the harvesting of difficult fruit or fruit near obstacles could

decrease the cycle time and reduce the likelihood of fruit losses. The additional complexity, time, and cost required to harvest difficult fruit is likely to outweigh the benefits of harvesting those fruit.

3.5 Conclusion

Laboratory testing showed that all the grippers could harvest almost 100% of single isolated fruit. As the number of fruits in a cluster increased, the harvest success percentage decreased and the cycle time increased. Fruit in larger clusters had more neighbouring fruit which magnified the two largest harvesting failure causes: gripper positioning and scheduling. The cluster picked success was about the same between the three new grippers, but the Flexi gripper had the lowest cycle time for every cluster scenario.

One arm gripper orchard testing revealed that the Flexi gripper had a significant design flaw where the coefficient of friction of the contact surface was too low. This combined with the low stiffness resulted in many failed grasps, high number of attempts, and hence, a long cycle time. A second version of the Flexi gripper was designed with high friction and rigidity. The new grippers (M5, M6, Flexi V2) were found to have similar performance which were all significantly better than the M4 gripper. The M5 and M6 were the best performers with an average picked-detached percentage of 90%, and a cycle time of 3.36 s/fruit. Therefore, both M5 and M6 grippers were chosen for the full system tests.

The fruit handling of the M4, M5, and M6 grippers in datasets where the control fruit were not damaged were 6%, 0%, and 8%. The M4 fruit handling was tested on fruit that were softer so the actual performance on firmer fruit was expected to be 0% as softer fruit were more susceptible to bruising. Damage to control fruit did not exceed 10% in the other datasets. The cause for control fruit damage was likely damage prior to picking, during transport, or storage.

The full system test with improved vision system and new grippers decreased the 2017 cycle time by half, from 5.37 s/fruit to 2.78 s/fruit. The picked-detached percentage was increased from 67% to 86%. The drop rate was decreased from 25% to 9%. The canopies tested had lower reachability. Of the picked fruit, 93.8% of fruit were stemless. The addition of 3 arms decreased the cycle time by only 17%

compared to a single arm due to poor workload sharing between arms for the current robot configuration.

Recommendations included increasing reachability, investigating alternative robot-manipulator configurations through simulation, and reduction of fruit loss. Fruit loss could be reduced by improving the gripper positioning, dexterity, harvest scheduling, and adding a catching system.

Chapter 4: Non-selective Harvester

4.1 Introduction

The objective of this chapter was to investigate the viability and potential of a non-selective kiwifruit harvester. Non-selective harvesting involves detaching many fruits at once rather than selectively detaching fruit one by one. In literature, there have not been any attempts on non-selective harvesting kiwifruit specifically. Therefore, there was an opportunity to explore kiwifruit non-selective harvesters. A non-selective harvester with good fruit handling could help solve the kiwifruit harvesting labour problem.

4.1.1 Background

Currently, all kiwifruit around the world are harvested by human pickers. Development of robotic selective harvesters for a wide variety of fruit are increasing. The key challenges of selective harvesters were the speed and total cost of the system. Non-selective harvesters attempted to solve this by increasing the harvesting rate significantly. The main barrier from the literature review was fruit handling. Commercial non-selective harvesters for other fruit were typically used for the process fruit market rather than the fresh fruit market due to poor fruit handling.

4.1.2 Objectives

1. Develop a kiwifruit non-selective harvester prototype
2. Determine the harvesting action effectiveness
3. Evaluate the non-selective harvester prototype performance on the orchard
4. Obtain insights into the viability of the harvesting prototype

4.1.3 Development

The development of the non-selective harvester was included to explain the reasoning behind design decisions. As this harvester was the first of its kind, it was important to document the development process.

4.1.3.1 Design Requirements

The design requirements of the bulk harvester were very simple

1. Harvest many fruits at once at a rate faster than comparable selective harvesters
2. Do not damage the fruit or the growing structure
3. Minimise the complexity and cost of the system

4.1.3.2 Shake-and-catch Harvester

A shake-and-catch harvester shakes fruit off the plant or growing structure. Some harvesters shook the trunk or main branches, while others shook the growing structure. Shake-and-catch harvesters have been tested for a variety of fruit such as apples and citrus fruit. There were two concerns regarding shake-and-catch systems. The first was damage to the fruit and plant during shaking. Fruit in clusters could hit other fruit, canes, or the support wire during shaking. Damage to the plant could affect subsequent yields. The second was that fruit shaking would be unlikely to consistently harvest fruit without the stem. If fruit are harvested with the stem, the stems can cause fruit damage in the kiwifruit bin, leading to post-harvest losses. Chemical abscission agents would likely be required to avoid excessive shaking excitation. Due to these issues, a shake-and-catch harvesting method was not used.

4.1.3.3 The Kiwifruit Wizard

A direct contact harvester was chosen based on a stem shear harvesting method. The Kiwifruit Wizard was a concept originally inspired by a nut gathering tool called the Nut Wizard®. The Nut Wizard® used parallel wires arranged in an ellipsoid cage to gather nuts and other objects on the ground by allowing the spacings between the wires to open and close. Further development created a concept that was completely different to the original concept both in form and function (Figure 30).

The Kiwifruit Wizard consisted of the cane deflector, stem puller cage, kiwifruit wall, and a catching surface (Figure 31). The Kiwifruit Wizard detached fruit by pushing at the stem while the fruit was supported against a soft padded surface (Figure 32). The stem puller had a zig-zag structure to position fruit stems. The cane deflector consisted of several parallel guides 100 mm apart to prevent kiwifruit canes from interfering with the rotating cage and to sort fruit into columns. The

tapers on the cane deflector were used to only let fruit under a certain height into the harvesting zone. The rotating cage was chain driven with a motor synchronised to the machine speed. Once detached, fruit dropped on a soft catching surface and rolled to a conveyer. The conveyer was designed to transfer fruit out of the rotating cage.

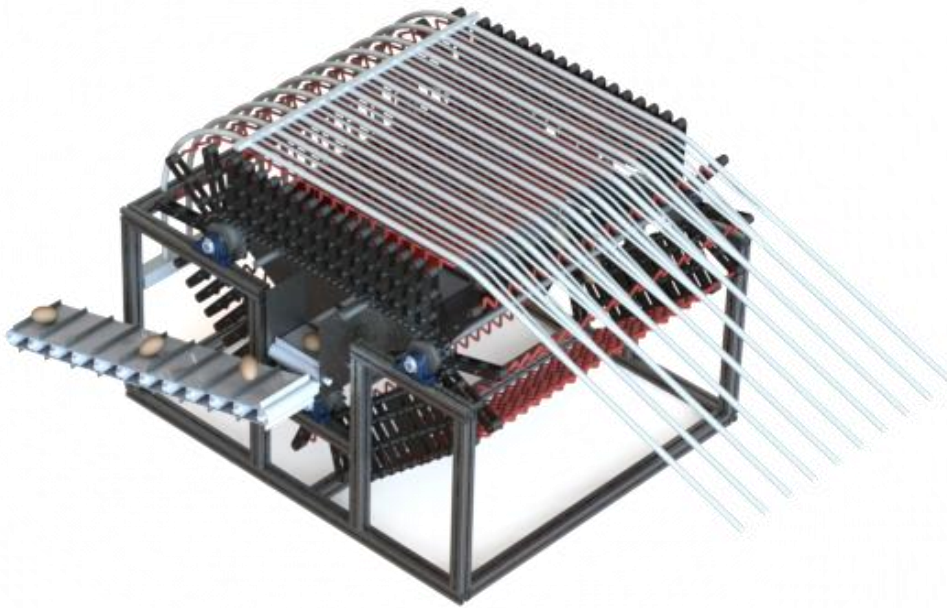


Figure 30: Stem-shear non-selective harvester concept

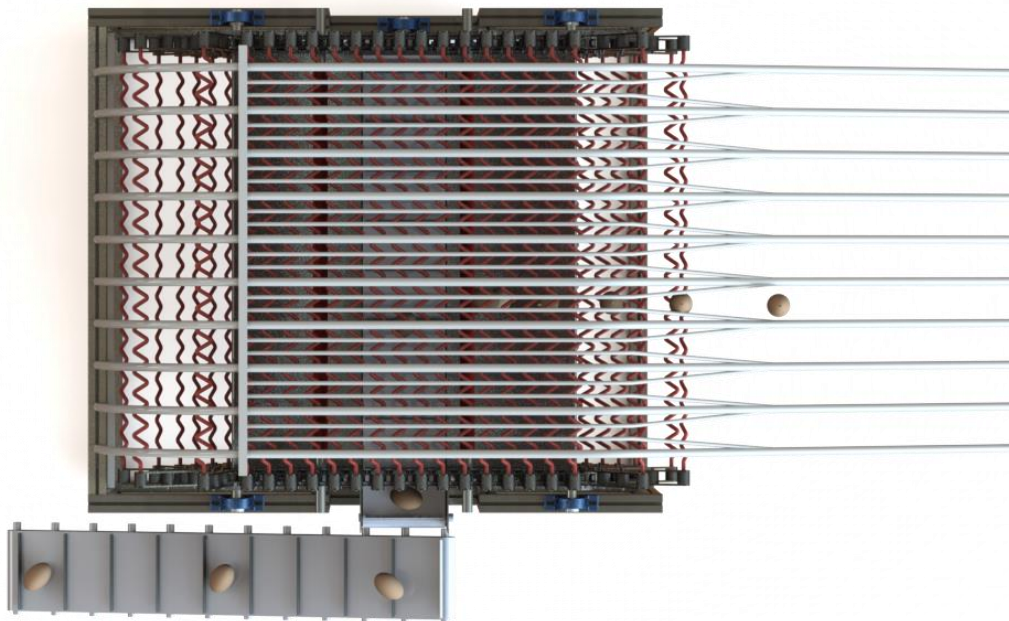


Figure 31: Top view of stem-shear detachment method

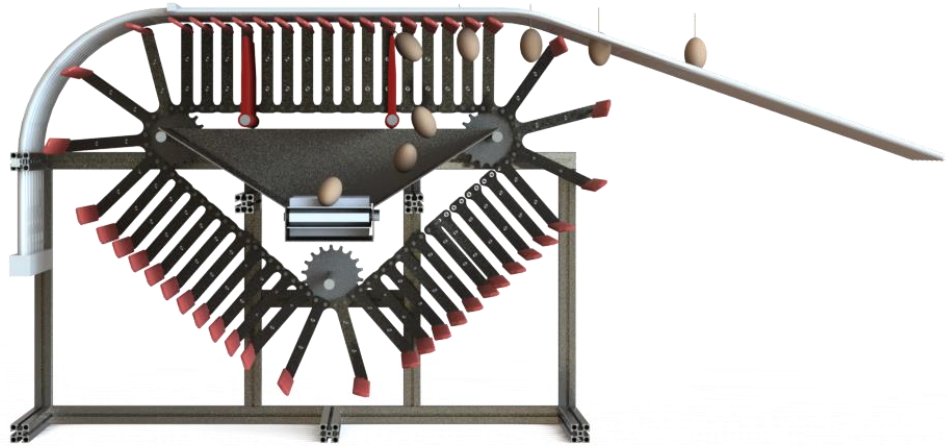


Figure 32: Side view of stem-shear detachment method

A small proof-of-concept prototype (Figure 33) was designed and built to test the effectiveness of the harvesting method and the cane deflector. The detachment method was the same as the original concept (Figure 34). The frame was built using reconfigurable aluminium extrusions. Off-the-shelf parts and low-cost laser-cut and folded parts were used to reduce cost and decrease the prototype build time. The cane deflector was made from welded stainless-steel bars and round rods. A table trolley jack was used to adjust the vertical position of the harvester (Figure 35).

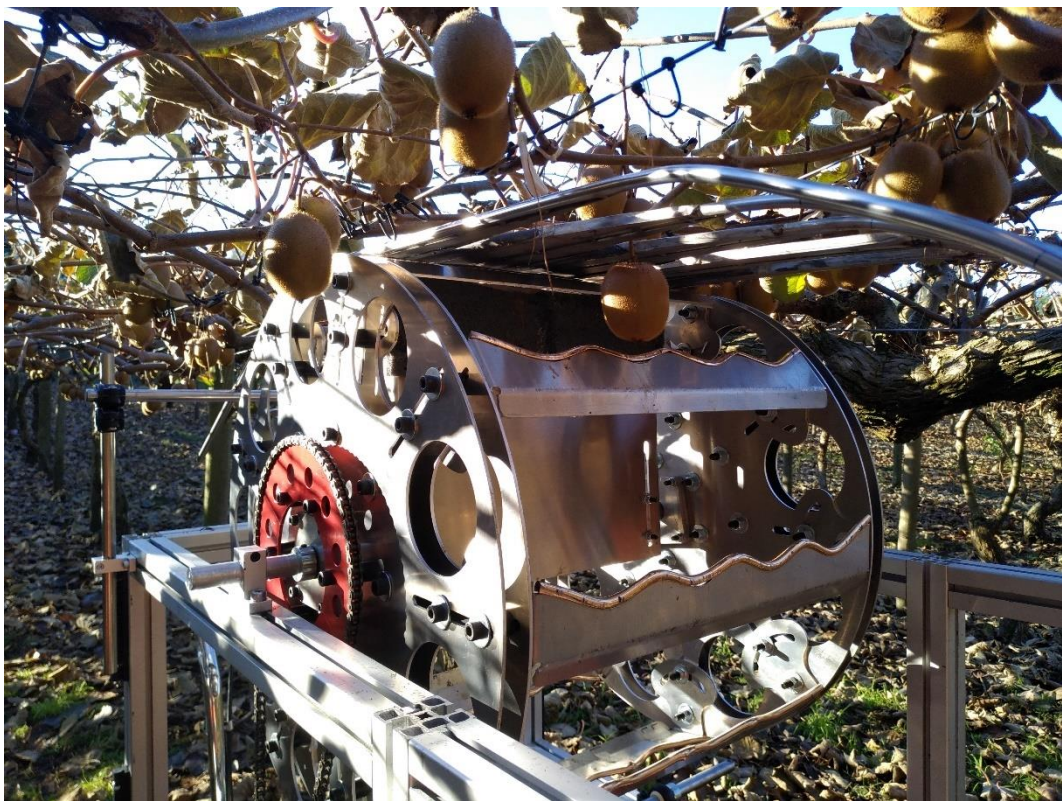


Figure 33: Proof-of-concept prototype closeup



Figure 34: Stem-shear detachment method as seen from below



Figure 35: Stem-shear non-selective harvester proof-of-concept prototype

4.2 Methodology

4.2.1 Lab Testing

The main objective of lab testing was to determine the feasibility of the prototype prior to harvesting season. The secondary objective was to find the testing parameters which influenced the success of the harvester. The testing results were used improve the concept further before orchard testing.

An aluminium lighting frame was used to hold silicone fruit models (Figure 36). Twenty-five silicone fruit were randomly placed in the lab canopy along the harvester path. The harvester height was positioned with the table trolley jack such that the top of the cane deflector was just under the wire. Movement of the rotating cage was done manually for the first 8 tests. A stepper motor was used for the next 6 tests. The stepper motor speed was synchronised with the direction and speed of the encoder on the wheel of the platform. The platform was pushed manually. Video of the harvester from different angles were used to observe the qualitative performance.



Figure 36: Non-selective harvester lab testing with silicone kiwifruit models

4.2.2 Preliminary Orchard Testing

The objective of preliminary orchard testing was to determine how the Kiwifruit Wizard interacted with a real kiwifruit canopy (Figure 37). This determined the effectiveness of the harvesting action on real fruit. The harvester was tested by moving the harvester to a fruit and manually rotating the cage to pick fruit. Two people were used to independently rotate the cage and move the harvester. Video of the harvesting from different angles were used to analyse the qualitative performance.



Figure 37: Non-selective harvester preliminary orchard testing

4.2.3 Orchard Testing

The objective of the full bay kiwifruit tests was to determine the quantitative performance of the harvester in unmodified gold and green kiwifruit orchards (Figure 38). The harvester was positioned at the right end of each bay prior to harvesting. Harvesting the length of the bay was defined as one pass. Seven to nine passes were required to cover the full width of the bay. The sides of the bay were not harvested due to the non-planar structure. Simultaneous platform movement and cage rotation were achieved using two people. After each pass, the number of detached fruit and the number of fruits with stems were counted. The harvester was moved back to the starting position but shifted one width across for the next pass.

The performance metrics of interest were detached fruit, detached fruit breakdown, picking rate, and stemless fruit. Video analysis was used to sort the detached fruit into picks, drops, and knock-offs. After all the passes had covered the entire bay, the rest of the fruit in the bay were manually picked and counted. One Hayward kiwifruit and one gold fruit bay were tested.

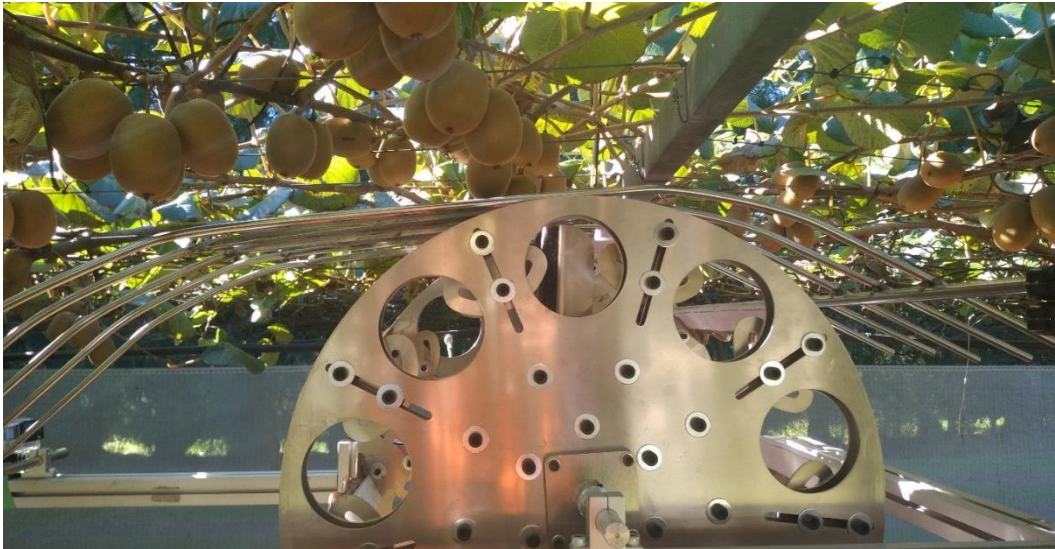


Figure 38: Non-selective harvester orchard testing

4.2.4 Combing Test

The objective of the combing test was to find the performance of harvester without the rotating cage. The same methodology as the previous full bay orchard tests for Hayward and gold fruit was used where several passes were made to cover the width of the bay (Figure 39). The fruit were harvested by a combing action with just the cane deflector and the kiwifruit wall. The reason for the combing method was because of the orchard test results for stem shear detachment method. A combing detachment method was thought to be more compatible (Figure 40). The results were the combined results of two bays of Hayward kiwifruit.



Figure 39: Non-selective harvester combing orchard testing



Figure 40: Combing detachment method close-up view

4.2.5 Fruit Damage Test

4.2.5.1 Stem Shear

The first objective was to determine the fruit handling performance of the fruit stem shear detachment method and the cane deflector. The harvester was positioned in the orchard near the support wire height and several passes were made. A total of 397 fruit were detached by the harvester. Of the detached fruit, fruit damage and stem detachment were recorded. Fruit damage was evaluated by observing the exterior of the fruit for obvious damage. Fruit without obvious external damage was not examined for internal damage because it was only of interest if fruit damage was low.

4.2.5.2 Stem Comb

The second objective was to determine the fruit handling performance of the combing detachment method. Laboratory testing was done to isolate the effect of the combing action. For the padded comb test, the contact surfaces on the kiwifruit wall and under the cane deflector had soft padded surfaces. A total of 106 fruit were carefully harvested with the stem attached for testing. 76 fruit were used for the padded comb test. 30 fruit were used for the unpadded comb test. 10 extra fruit were used as the control fruit. The fruit were harvested later on in the harvesting season so the fruit had lower firmness values than usual. Therefore, the fruit were more susceptible to damage. The fruit were positioned at the target position and a pull on the stem detached the fruit. The fruit was caught immediately and carefully stored in a padded box. A force gauge was used to obtain the stem harvesting force for some of the fruit.

Fruit were stored at ambient temperature for at least three weeks to let fruit damage develop and become obvious. Fruit damage was evaluated by visual observation and tactile touch of the fruit to find defects. If there was no obvious exterior damage, the fruit was cut open into several slices along the fruit longitudinal axis to examine the flesh for obvious signs of damage.

4.3 Results

4.3.1 Lab Testing

Qualitative results from lab testing are listed below.

1. Lab model kiwifruit could be harvested successfully only if fruit were in the target vertical position. If fruit were positioned such that the stem puller was between the fruit-stem and stem-vine connection, it could be harvested.
2. The ratio between the cage rotation speed and the machine movement speed was two for continuous harvesting.
3. A horizontal stem shearer was the most effective due to the flat cross-sectional area, as seen from the kiwifruit wall.
4. Long offshoots could get stuck for very low hanging fruit.
5. The cane deflector design required improvement to allow as many fruits in as possible because fruit were much higher than expected.

4.3.2 Preliminary Orchard Testing

Qualitative results from preliminary orchard testing are listed below.

1. Real kiwifruit could be harvested if fruit were in the target position. However, many fruits were squished between the stem zig-zag and the kiwifruit wall. Some fruit were knocked off by the cane deflectors before reaching the rotating cage. Many of the fruit near or above the support structure wire or canes were unreachable. The fruit along the edges of the bay were also unreachable. Only the fruit completely under the wire were reachable which was estimated to be about a third of the fruit.
2. The harvester needed to be pressed up against the top of the canopy consistently to reach as many fruits as possible. However, this increased the chance of kiwifruit, offshoots, canes, and the support wires getting stuck. The machine required momentum to work well, both in the cage rotation and machine movement to continuously harvest fruit.
3. Fruit got stuck between the start of the cane deflector tapers which damaged the fruit. The harvesting zone of the cane deflector was also not close enough which caused fruit to be too high. This resulted in fruit getting hit by the stem puller.

4.3.3 Orchard Testing

Table 9: Non-selective harvester orchard test results

Detachment Method	Fruit	Total fruit	Fruit Detached (%)	Fruit Left (%)	No-stems/Detached (%)	Fruit in net/Detached (%)	Detachment rate (fruit/s)	Detachment cycle time (s/fruit)
Stem-shear	Gold	774	42.4	57.6	-	n/a	0.32	3.14
Stem-shear	Hayward	1016	37.2	62.8	67.5	n/a	0.58	1.72
Combing	Hayward	2498	40.1	59.9	40.7	95.3	0.35	2.85

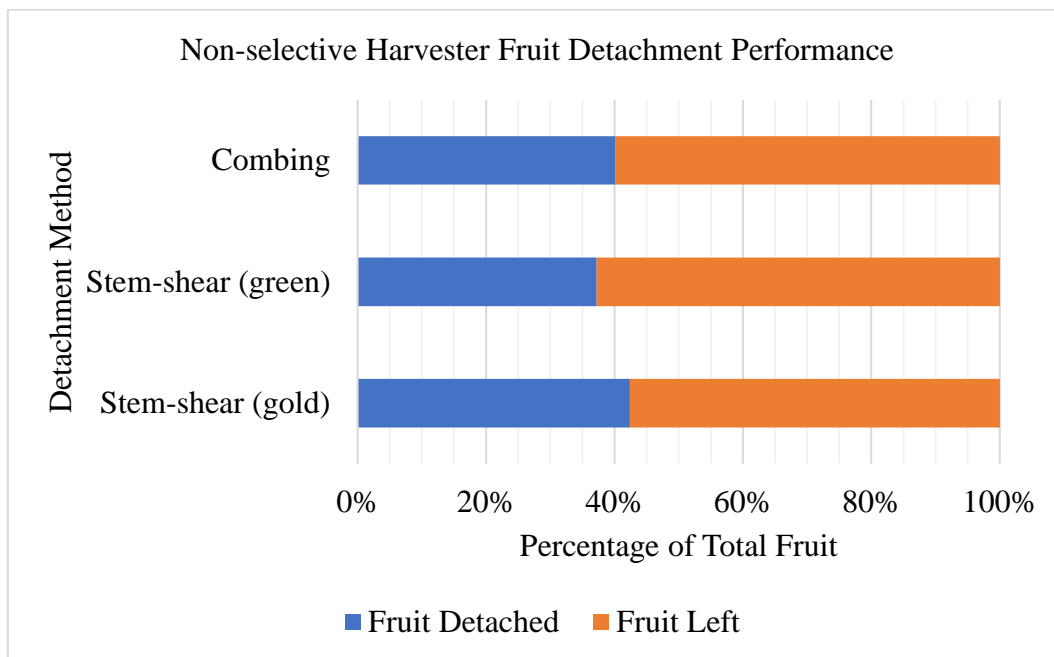


Figure 41: Non-selective harvester fruit detachment performance

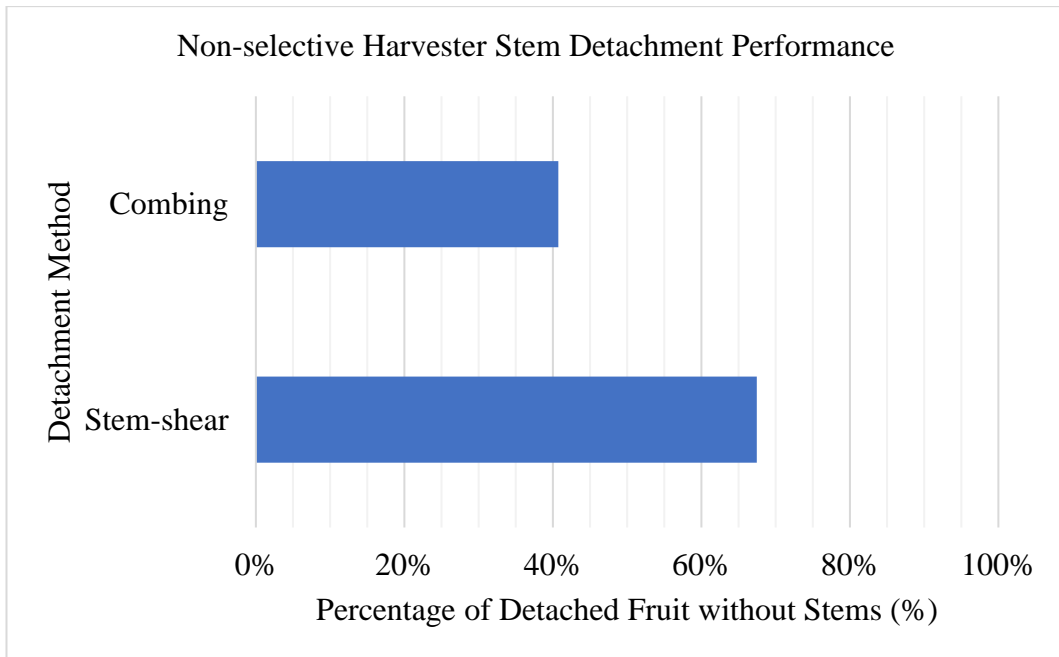


Figure 42: Non-selective harvester stem detachment performance

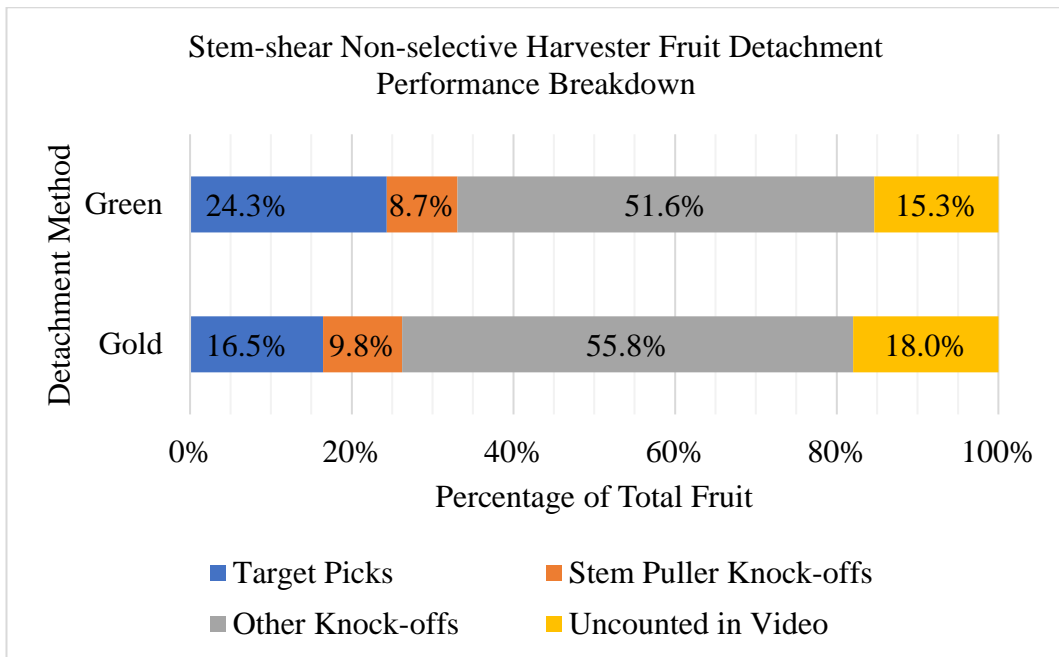


Figure 43: Stem-shear detachment performance breakdown

4.3.4 Combing Test

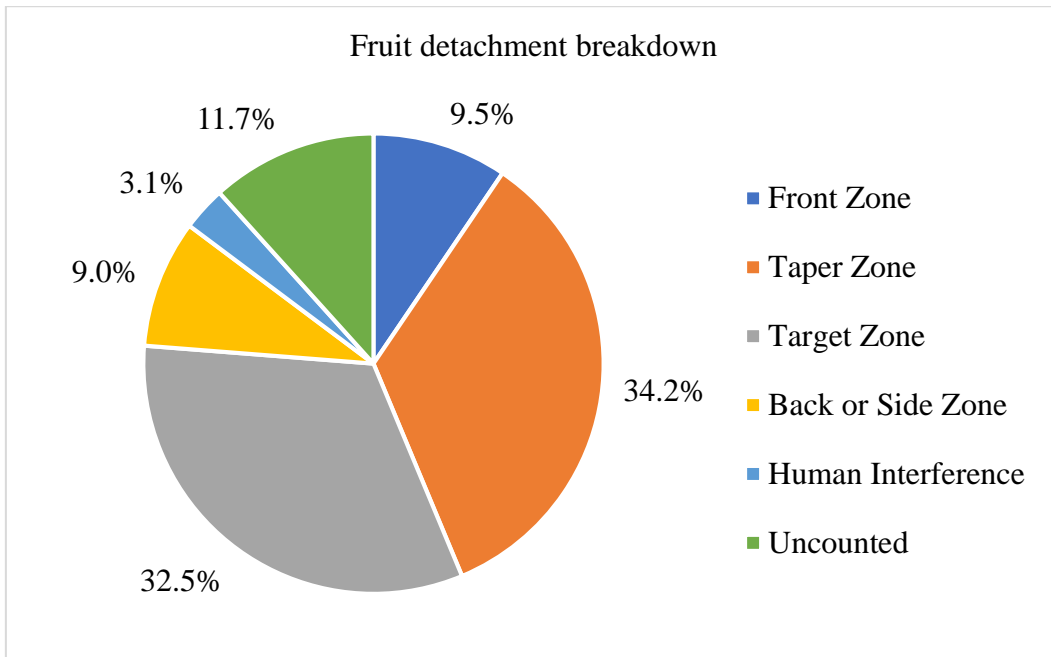


Figure 44: Combing detachment performance breakdown

4.3.5 Fruit Damage Test

4.3.5.1 Stem Shear

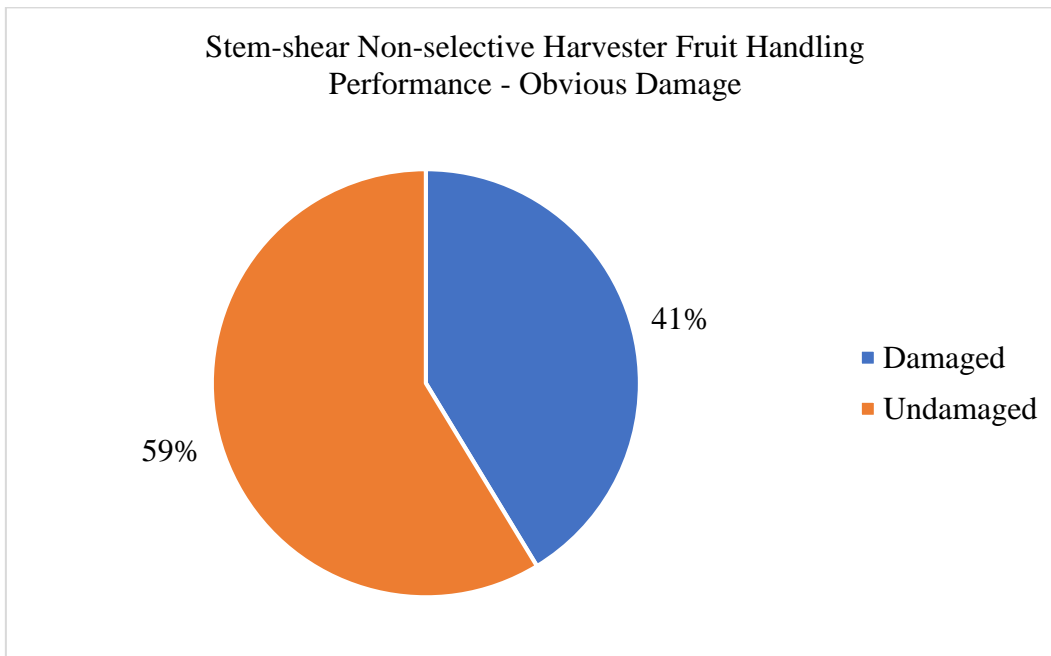


Figure 45: Stem-shear fruit handling performance

4.3.5.2 Stem Comb

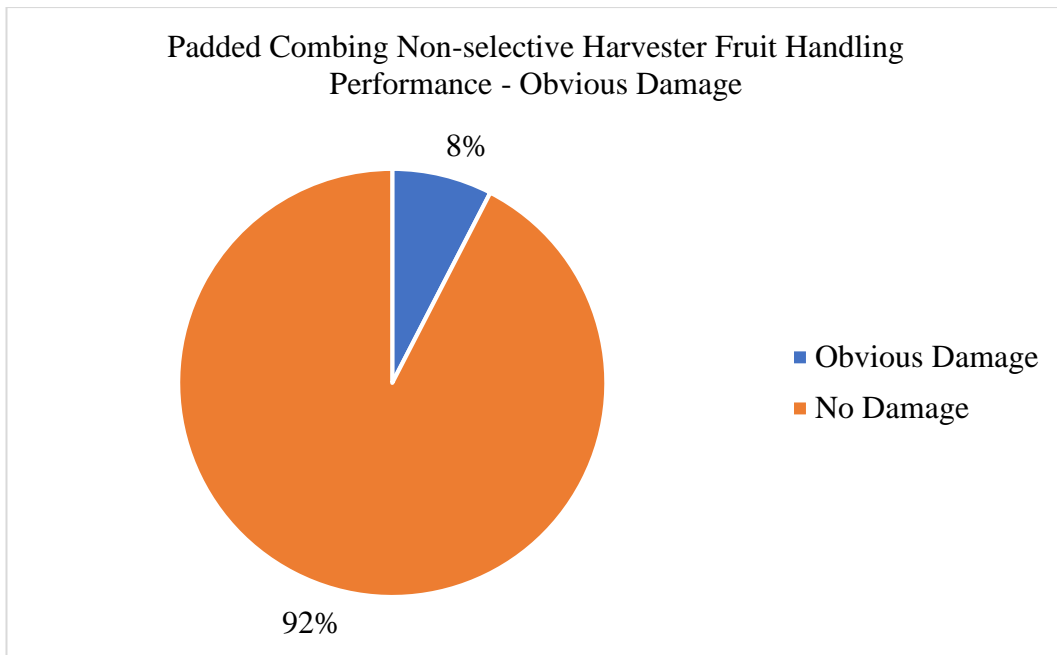


Figure 46: Combing fruit handling performance based on obvious damage

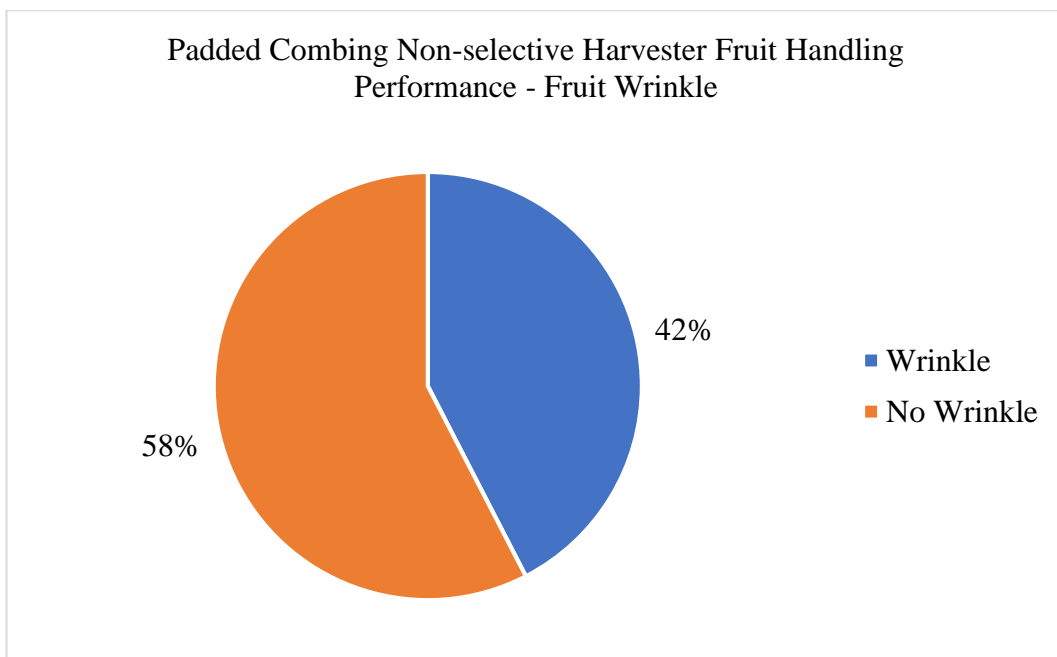


Figure 47: Stem-shear fruit handling fruit with wrinkles

4.4 Discussion

4.4.1 Lab Testing

Lab testing showed that the harvesting action was successful but only if fruit were in the target vertical position. When fruit were positioned such that the stem shearer

was between the fruit-stem and stem-vine, the harvesting action was successful (Figure 48). Fruit that were too high were squished which disrupted the rotation of the cage (Figure 49). Low-hanging offshoots with fruit could get pulled off (Figure 50). The cane deflector entry should allow as many fruit in as possible but filter out fruit that were too high (Figure 51).

Investigation into the testing parameters for successful harvest revealed that the speed of the rotating cage should be twice that of the platform. A one-to-one speed ratio was unsuitable because the stem shearer was unable to detach fruit at a faster rate as fruit entering the harvester.

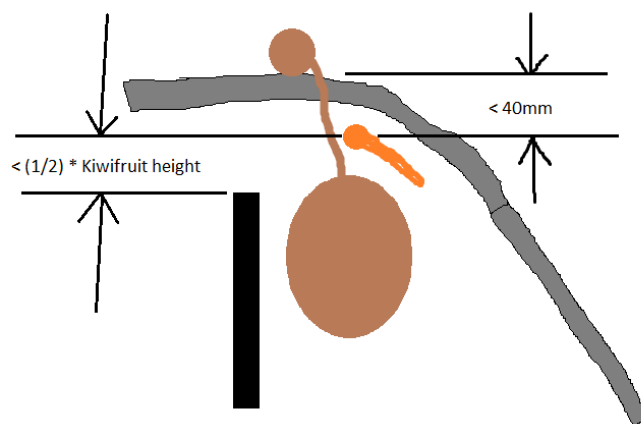


Figure 48: Target fruit position required for successful stem-shear detachment

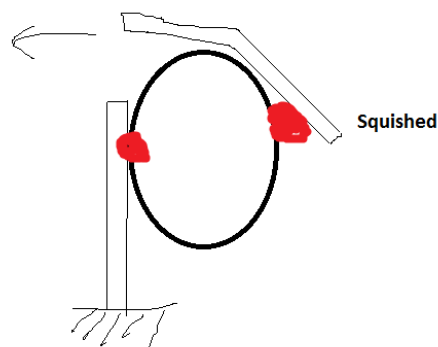


Figure 49: Squished fruit that were positioned too high

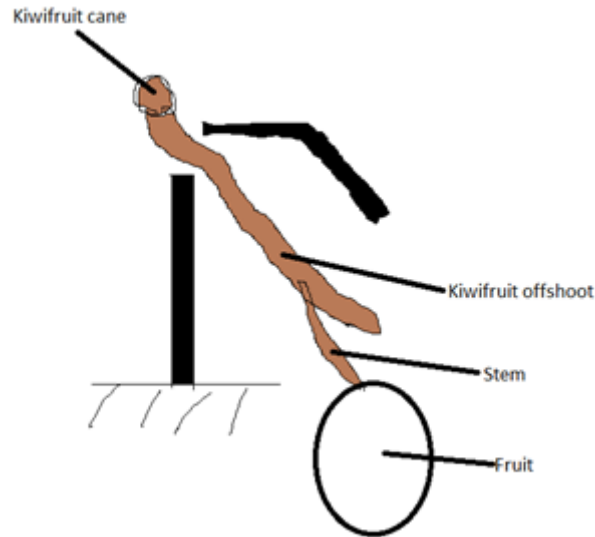


Figure 50: Drooping fruit offshoots

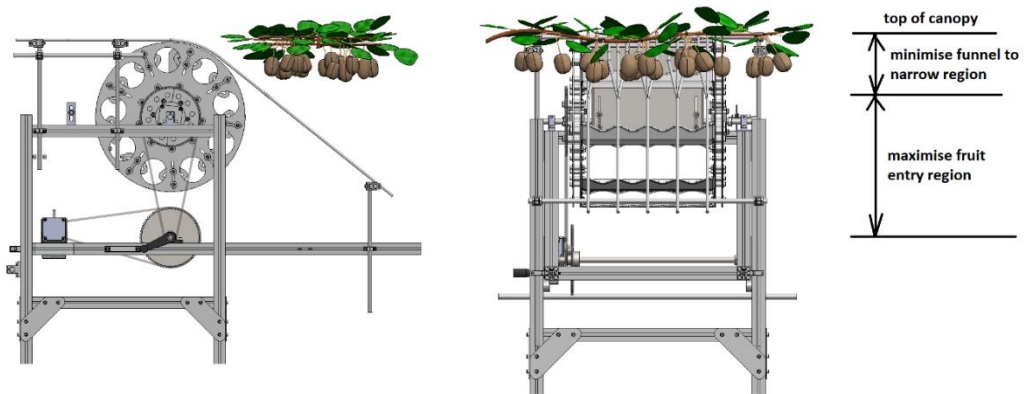


Figure 51: Cane deflector fruit entry fruit reachability

4.4.2 Preliminary Orchard Testing

Orchard testing confirmed many of the results from lab testing. Fruit were able to be harvested if they were at the target position. However, not many fruit were in the target position. The canopy was not planar and was highly unstructured when viewed up close. The canes and offshoots were not very straight with many twists and bends. Only about a third of the fruit in the canopy were reachable because the remaining fruit were near or above the canes or support wires (Figure 52). Figure 53 showed the fruit left in the canopy that were unreachable. Due to the canopy wire supports and the distribution of the fruit, the canopy drooped down near the centre of the canopy. The regions near the edges of the canopy were also unreachable (Figure 54). The region near the kiwifruit leaders consisted of highly unstructured thick canes due to past pruning. The regions near the support cross-

beams were unreachable because the cane deflector blocked the cross-beams, and the machine had to be positioned at the wire height before harvesting.

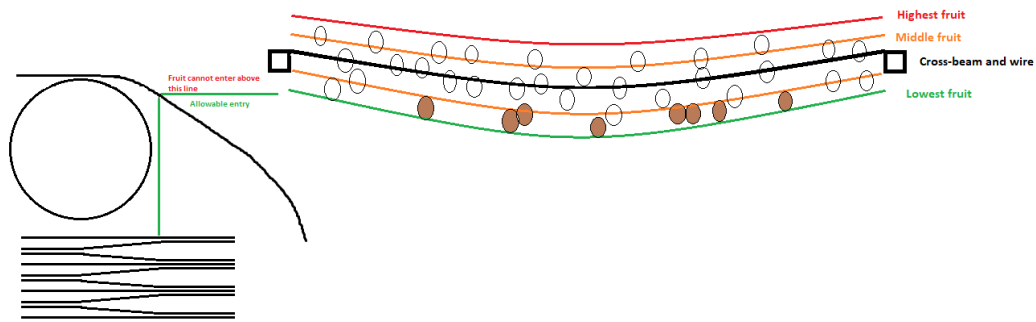


Figure 52: Side view of reachable fruit in the canopy by the non-selective harvester



Figure 53: Fruit left on the canopy by the non-selective harvester

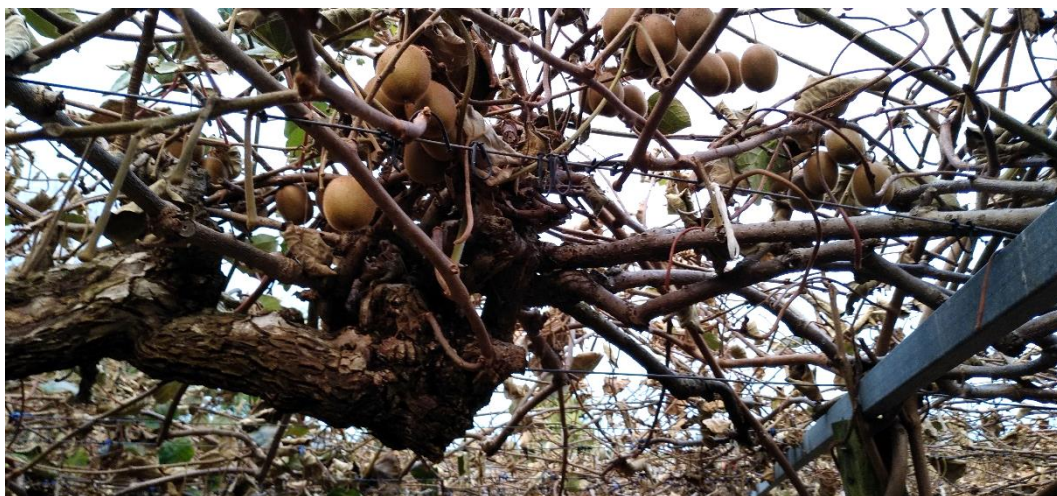


Figure 54: Unreachable fruit near leaders

By pushing the harvester up against the canopy, reachability was increased but there was also increased interference. Interference prevented continuous harvesting. Offshoots, previously pruned parts of a cane, and the support wire were often stuck. Low hanging offshoots were ripped off the main cane by the rotating cage. The support wires parallel to the harvester movement direction were at different heights depending on the supporting load. Sometimes, the wires that were lower hanging would get stuck between the cane deflectors. Some fruit were knocked off by the cane deflectors even before reaching the rotating cage or wall.

The cane deflector also had several problems. The first was that fruit at the cane deflector taper got stuck and squished. Fruit that were higher up were able to pass along the top, but they may have also been damaged or knocked off due to the interference with the canopy.

Many kiwifruits were squished between the stem shearer and the kiwifruit wall because they were positioned too high up, even when they were already under the cane deflector. A decrease in that distance between the harvesting zone filter was used to position fruit further down.

4.4.3 Gold Fruit Test

The harvester detached 42% of fruit in the gold kiwifruit bay (Table 9, Figure 41). Of the detached fruit, only 16.5% were picked by the stem shearing method and 9.8% were knocked off by the stem puller. The rest of the fruit were knocked off or pulled off by the cane deflector or dropped from the canopy. The intended fruit detachment method only picked 7% out of all the fruit in the canopy.

The cycle times mentioned excluded fruit damage and stemless harvest metrics. The detached fruit cycle time was 3.14 s per detached fruit. As only 16.5% of the detached fruit were picked intentionally at the target position, the actual cycle time was 19 s/fruit. The high cycle time was due to most fruit being detached unintentionally from knock-offs and drops. Furthermore, the harvester was tested slow deliberately to prevent damage to the canopy. Scaling the current prototype to eight times the current width could increase the harvesting rate by eight times.

Gold kiwifruit canopies were observed to be more planar than Hayward kiwifruit canopies. Hence, there was an assumption that gold fruit would be easier to harvest. The result was the opposite. Gold fruit have shorter stems than Hayward which

reduced reachability of the fruit through the cane deflector. The harvesting time was very late for the gold kiwifruit season, so fruit were much softer, prone to drops or knock offs, and had weak stem connections. Cane deflector tapers needed to be significantly narrower to only allow fruit stems to pass. The current taper was too far apart causing fruit that were funnelled in to be hit by the top of the stem puller.

4.4.4 Hayward Test

The harvester was able to detach 37% of fruit in the Hayward kiwifruit bay which was close to the 42% value for gold kiwifruit (Table 9, Figure 41). The stemless fruit was 67.5% (Figure 42). Of the detached fruit, only 24% of fruit were picked by the stem shearing method and 9% were knocked off by the stem puller (Figure 43). The intentionally detached fruit was only 8.9% of the total fruit in the canopy compared to the 7% for gold fruit. Most of the detached fruit were knocked off unintentionally in the cane deflector taper region.

The cycle times mentioned excluded fruit damage and stemless harvest metrics. The detachment cycle time was 1.72 s per detached fruit and was highly dependent on the number of times the canes or support wire got stuck. As only 24% of the detached fruit were picked intentionally at the target position, the actual cycle time was 7.2 s/fruit. Care was taken to minimise damage to the canopy, so the harvester was stopped whenever an object was stuck. The difference between the cycle time between Hayward and gold fruit was due to the testing speed.

The poor performance of the harvester was due to the incompatibility between the stem shear detachment method and the real-world kiwifruit orchard. The stem detachment method required fruit to be at a target height and position. Prior to reaching that location, most of the detached fruit were knocked off or dropped due to interference between the cane deflector and the canopy. Interference was inevitable because the harvester had to be pressed against the canopy to increase reachability.

As most fruit detached were knocked-off or dropped prior to detachment by the intended stem shearing method, a combing detachment method was explored. This was done by removing the steam shearing rotating cage. The remaining cane deflector and kiwifruit wall was used to comb and pick the fruit. A net was used for the catching surface.

4.4.5 Combing Test

Due to the issues found with the previous stem shearing method, a combing method was explored. In literature, a combing method was used for apples by Le Fluffy (1983). The results showed 40.1% fruit detachment which was close to the other values. The detachment percentage of 37% to 42% could be viewed as the maximum reachability of fruit under the support wires on current unmodified kiwifruit canopies. The fruit left on the canopy would still have to be picked. The non-selective harvester's potential was reducing the number of fruit picked. The reachability could be improved by increasing the number of fruits under the support wire with deliberate kiwifruit vine training. The detachment cycle time was 2.8 s/fruit which was mostly dependent on how fast the harvester was run during testing.

Of the fruit detached, about a third were picked in the cane deflector taper region and another third were picked at the stem detachment section (Figure 44). 9.5% of fruit detached were picked in the cane deflector front region whereas 9% of fruit detached were picked in the back and side regions. The 11.7% of fruit detached were uncategorised because they were not seen in video.

The percentage of fruit with stems left on was 42.7%, which was less than that of the stem shear detachment method of 67.5%. The low stem detachment of the stem shear and combing harvester methods were both low so additional processing to remove the stems will be required. Furthermore, the kiwifruit vine leaves and offshoots that were detached also required removal based on KVH regulations for Psa management. Almost all the fruit were that were detached were caught based on the 95.3% caught fruit. The remaining fruit could have been caught if the catching area was made larger.

4.4.6 Fruit Damage Test

The stem shear test showed 41% fruit damage (Figure 45). The remaining fruit without obvious external damage were not evaluated for internal damage because the fruit damage was already too high. Therefore, the fruit handling value of 59% was a maximum because it did not include internal bruising. Based on the fruit handling alone, the harvesting action was unsuitable due to the fruit loss associated with the fruit damage. The fruit damage results agreed with a similar study by

Longo & Muscato (2013) for artichokes where their non-selective harvester fruit damage was too high. Cembali, Folwell, Clary, & Mari (2008) also stated that their asparagus non-selective harvester was “suitable only when a market for processed product exists” indicating that their asparagus bulk harvester had poor fruit handling.

For the combing tests, the results were inconclusive because evaluation of damage was influenced by the storage of the fruit. Many of the fruit after the storage period were dehydrated which made it difficult to determine if the dehydration was solely due to storage conditions or damage from harvesting. Obvious damage was still easily observed at 8% (Figure 46). Of all the fruit tested, 42% were dehydrated with wrinkling starting near the stem end (Figure 47). Due to the uncertainty around the cause of the wrinkling, a conclusive evaluation could not be made.

The fruit used in the combing fruit handling tests were softer as they were harvested later in the harvesting season. Therefore, if the tests were repeated on firmer fruit, the fruit handling was likely to be better. If the 42% of fruit dehydrated were due to storage effects only, then a padded harvesting method may be suitable. The limitation of the data was that it only reflected the detachment at the kiwifruit wall by combing. This was only relevant to the third of fruit detached based on the combing test results.

4.5 Conclusion

The objective was to develop, build, and evaluate the performance of the first kiwifruit non-selective harvester prototype for viability. A proof-of-concept prototype was made and tested in lab and orchard. Testing revealed that the stem shear harvesting method was quite poor because it was only effective if fruit were in the target position which was rarely the case. Many of the fruit that were near or above the support wires were simply not reachable. Vine training to achieve flatter canopies with more fruit under the support wire could increase reachability significantly. Approximately 37% to 42% of the fruit in a kiwifruit bay were reachable. The fruit that were reachable were typically not in the target position.

Of the reachable fruit, many were knocked off by the cane deflector prior to entering the stem detachment zone. Fruit that had long stems and hung low relative to the

support wire were the easiest to harvest. The fruit handling during the stem shearing method was poor with a minimum of 41% of fruit damaged. The harvester also had trouble dealing with interference from the canopy. To increase reachability, the cane deflector had to be pushed up against the canopy. This increased the chance of the canes, offshoots, and support wires getting stuck. Therefore, the stem-shear non-selective harvester was not viable due to poor intentional detachment performance of 24% of detached fruit, and a maximum of 59% fruit handling of those intentionally detached fruit.

The combing method had more potential because fruit only had to enter the cane deflector. 40% of the fruit in the canopy were detached. Only about 66.8% of the fruit detached were combed by the cane deflector. The rest were knocked off or dropped. However, those fruit were caught with a net. The combing method had slightly more fruit with stems still attached. Fruit handling results showed that fruit harvested at the stem detachment area had 8% obvious fruit damage based on tests on softer fruit. The results show that combing of the kiwifruit canopy with a well-padded combing device and catching surface has potential. However, a catching surface close to the canopy is required to catch all the fruit dropped or knocked off by the cane deflector.

Chapter 5: Comparison for Economic Viability

5.1 Introduction

The objective of this chapter was to compare the performance of the improved selective kiwifruit harvester with the non-selective harvester, and to investigate the economic viability relative to human pickers. Economically viable performance was defined as the performance required of any robotic kiwifruit harvester to match the cost of a human picker group. The required performance considered the harvester fruit loss and reachability. The reachability determined the subsequent cost of human picker clean-up groups to pick the remaining fruit.

The collective harvesting performance of a human picker group was used because it is of interest from a kiwifruit grower's perspective. The harvester performance was defined as the reachability, success-picked-detached, and cycle time. Success-picked-detached was defined as the product of the picked-detached percentage, stemless percentage, and fruit handling percentage.

Based on the current and expected future performance, the barriers and assistance factors to commercial viability were stated and discussed. Potential robotic configurations were generated and discussed. Finally, recommendations were made on the future direction of kiwifruit harvesters to overcome the barriers to economic viability.

5.2 Methodology

5.2.1 Human Pickers

The objective was to determine the total harvesting cost to pick a grower's orchard. An orchard visit during harvesting was used to breakdown the total harvesting cost. Further literature reviews and conversations with orchard picking managers were used to obtain the total harvesting cost. A spreadsheet was used to calculate and update the total harvesting cost as a function of the inputs. Expected future data inputs were used to determine future costs. The cost calculation outputs were only

as accurate as the inputs. The result was compared to literature values to verify the results.

5.2.1.1 Fruit Value

The fruit value was required to determine the cost of fruit loss. The fruit value was defined as the OGR (orchard gate return) per fruit which was the value of the fruit as seen from the grower after post-harvest costs. In the kiwifruit industry, the yield was reported in trays per hectare. The yield in trays per hectare and OGR were used to calculate the value per tray. The individual fruit value was calculated by dividing the tray value by the fruit per tray. In each industry standard 3.6 kg tray, the number of fruits varied depending on the mass of the fruit. The minimum and maximum kiwifruit size grading were approximately 16 to 42 fruits per tray which corresponded to a fruit mass range of between 225 g and 85.7 g, respectively. The green and gold fruit value were calculated.

The average 2016/17 kiwifruit season yield and OGR were 11,838 trays/ha and \$68,868 NZD/ha, respectively (Zespri, 2017). For green kiwifruit, the yield and OGR were 11,933 trays/ha and \$53,555 NZD/ha, respectively (NZKGI, 2017). For gold kiwifruit (Gold3), the yield and OGR were 11,366 trays/ha and \$98,838 NZD/ha, respectively (NZKGI, 2017). The green and gold kiwifruit 2016/17 values were used for the calculation.

5.2.1.2 Fruit Yield

The fruit yield in fruit per hectare and fruit per grower were required. The fruit yield for green and gold in the 2016/17 season was quite close so the industry average of 11,838 trays/ha was used. New Zealand's 2,435 kiwifruit growers had a combined number of 12,578 producing hectares (NZKGI, 2017). The calculated average kiwifruit producing hectares per grower was 5.17 ha/grower. The average orchard size was 3.5 ha/grower for green, and 2.6 ha/grower for gold which added to 6.1 ha/grower (NZKGI, 2017). The 5.17 ha/grower value was used. The average number of trays supplied per grower was 59,906 trays/grower. The effect of fruit sizes between 16 and 42 fruit per 3.6 kg tray were used to determine the fruit yield. Fruit yields between 8,000 trays/ha and 16,000 trays/ha was also determined.

5.2.1.3 Human Picking Rate

Observation of human pickers and interviews with kiwifruit picking managers were used to calculate the human picking rate. Human pickers were able to harvest at peak picking rates of near 4 fruit/s. However, this could not be sustained. Picking managers stated 10 bins/working day for the average worker, and 12 bins/working day for good pickers. It was difficult to calculate the picking rate in terms of fruit rather than bins because the number of fruit per bin varied depending on the size of the bin and fruit.

To convert number of bins per working day to fruit per second, the number of fruit per bin was required. Picking rate sources did not include the size of the fruit being picked. Measurement of the kiwifruit bins revealed internal bin dimensions of 1170 mm x 1170 mm x 540 mm, which were used to calculate the bin volume. The kiwifruit packing density was calculated based on several factors and assumptions. The first was a 90% bin fill because bins had to be stacked on top of each other. Secondly, kiwifruit could be approximated as a prolate ellipsoid with an aspect ratio of 1.15 with a packing density of 68% for a maximally random jammed state (Donev et al., 2004). Kiwifruit were poured into the bins from the picker's kiwifruit pouches, so the fruit were not packed to the full potential. Furthermore, without shaking of the bin to let the fruit settle, even less fruit can fit in. Kiwifruit were also not frictionless so there was another loss to the packing density. To approximate these losses, 5% was taken off the packing density for an effective packing density of 63%. A mean kiwifruit mass of 130 g was used based on orchard measurements. The mean mass and bin dimensions were used to calculate the mean number of fruits per kiwifruit bin (Equation 1). The lower and upper number of fruit per bin were calculated using the lower and upper kiwifruit masses of 100 g and 160 g respectively.

A typical human picker working day was 8 hours. It was assumed that there was an hour break during the day. The breaks were included in the total picking time to calculate the average picking rate throughout the day (Equation 2).

Equation 1: Fruit per kiwifruit bin

$$b = \frac{V_b}{V_k} a(\rho - 5\%) \quad (1)$$

where:

b	=	fruit per kiwifruit bin (fruit/bin)
V_b	=	volume of kiwifruit bin (m ³ /bin)
V_k	=	volume of kiwifruit (m ³ /fruit)
a	=	bin fill percentage (%)
ρ	=	packing density (%)

Equation 2: Human kiwifruit picking rate

$$r = \frac{r_d b}{28800} \quad (2)$$

where:

r	=	human picking rate (fruit/s)
r_d	=	Human picking rate (bins/day)
b	=	fruit per kiwifruit bin (fruit/bin)

5.2.1.4 Human Picker Harvesting Cost

A visit to the orchard and literature data was used to break down the total harvesting cost. During a visit to a grower, it was observed that there were four types of workers present: the managers, tractor-trailer drivers, forklift driver, and the kiwifruit pickers. In total, two managers, four tractor-trailer drivers, one forklift driver, and twenty pickers were present during an orchard visit.

The total picking cost consisted of the fixed costs, variable costs, and the worker wages (Table 10). The fixed costs were the machinery transport fee, and the tractor & trailer machinery cost. The variable costs were a function of the number of bins picked and the time it took (in hours) to pick the fruit. The variable costs included the forklift machinery cost, and bin transport fee, plus the wages of all the workers involved. Equation 3 was used to calculate the total number of hours. Equation 4 was used to calculate the total harvesting cost.

Equation 3: Total number of hours

$$n_h = \frac{n_k}{3600r} \quad (3)$$

where:

n_h	=	number of hours (h)
n_k	=	number of kiwifruit to be harvested (fruit)
r	=	picker picking rate (fruit/s)

Equation 4: Total kiwifruit harvesting cost

$$X = n_h(n_p W_p + n_t W_t + n_f W_f + n_m W_m) + (n_t f_t + n_b(R_{bf} + R_{bt})) + T \quad (4)$$

where:

n_h	=	number of hours (h)
n_p	=	number of pickers (picker)
n_t	=	number of tractor drivers (tractor driver)
n_f	=	number of forklift drivers (forklift drivers)
n_m	=	number of managers (managers)
n_b	=	number of bins picked (bins)
W_p	=	picker hourly wage (\$/h)
W_t	=	tractor driver hourly wage (\$/h)
W_f	=	forklift driver hourly wage (\$/h)
W_m	=	picker manager hourly wage (\$/h)
f_t	=	tractor machinery cost (\$/tractor driver)
R_{bf}	=	forklift machinery cost per bin (\$/bin)
R_{bt}	=	transport fee per bin (\$/bin)
T	=	machinery transport fee (\$)

Table 10: Total harvesting cost calculation inputs

symbol	input
b	3337 fruit/bin, Equation 1
V_b	0.739 m ³ /bin
V_k	0.000126 (m ³ /fruit)
a	90%
ρ	68%
r	1.16 fruit/s, Equation 2
r_d	10 bins/day
n_h	number of hours (h), Equation 3
n_k	number of fruit, input
n_p	20
n_t	4
n_f	1
n_m	2
n_b	number of bins picked (bins)
W_p	\$21/h
W_t	\$25.7/h
W_f	\$25.7/h
W_m	\$30/h

f_t	\$125 (full working day) \$80 (half working day)
R_{bf}	\$1.75/bin
R_{bt}	\$5.10/bin
T	\$75

The effect of picker wages and number of fruit on the total harvesting cost was calculated. At a constant tray/hectare yield, the number of fruit was determined by fruit mass. Fruit masses of 100 g, 130 g, and 160g, and picker wages of \$16.50/h, \$21/h, \$25/h, and \$30/h were used as inputs. The \$16.50 was used because it was the current minimum wage in 2018 (Employment New Zealand, 2018). The total harvesting cost, number of picker working days, harvesting cost per fruit, and fruit value to harvesting cost ratio was calculated for each fruit number and picker wage combination.

5.2.2 Harvester Breakeven Requirements

The objective was to determine the harvester breakeven performance. The breakeven performance was defined as the performance required of a robotic harvester to match the cost of human pickers. The only robotic harvester cost considered was fruit loss. The breakeven was defined as the point where the sum of the robotic harvester fruit loss and human clean-up picker group cost was equal to the human picker only cost (Equation 5). Fruit loss was treated as a harvest cost because it reduces the orchard gate return. Human picker fruit loss was not considered as it was expected to be small. The breakeven performance did not consider the harvesting rate or the cost of the robot.

Equation 5: Kiwifruit breakeven

$$X = Y + Z \quad (5)$$

where:

X	=	Human-only picker cost (\$)
Y	=	Robot picker fruit loss cost (\$)
Z	=	Human clean-up picker cost (\$)

The three inputs were the robotic harvester success-picked-detached performance, reachability, and human picker clean-up group efficiency loss. The output was the total harvesting cost. The reachability determined the number of fruit left in the

canopy for the clean-up pickers, and hence their harvesting cost. The efficiency loss was affected by the reachability. As the reachability of the robot increased, less fruit were left in the canopy for the clean-up crews to pick. The remaining fruit were harder to pick as they were less reachable and required more effort to find and pick. The effect of reachability on the harvesting rate efficiency was approximated based on an inverted parabola and an estimated 25% minimum pick efficiency.

The breakeven success-picked-detached performance was the metric of the interest for the robotic harvester. The breakeven requirement was independent of harvesting rate. The reachability was of high interest because fruit left in the canopy still must be picked by human pickers. Even if the fruit on the vine was not useful, the New Zealand KVH (Kiwifruit Vine Heath) states that all unpicked fruit must be removed from the vines by the 1st of July each year as part of the National Psa Pest Management Plan (Zespri, 2018). The effect of fruit mass (and hence number of fruit), picker wage, robot reachability and success-detached percentage on the economic viable performance was determined.

5.2.3 Performance Comparison

The objective was to compare the performance of the two harvesters and human pickers. The performance was broken down into four performance metrics: reachability, picked-detached, stemless, fruit handling, and speed. The success-picked-detached metric used previously was the product of the picked-detached, stemless, and fruit-handling. The success-picked-detached metric represented the standard that human pickers were measured at. The results from previous chapters were consolidated for the comparison. (Longo & Muscato, 2013) compared a selective and non-selective artichoke harvester with similar performance metrics including the total harvested, damage, and harvesting speed.

Reachability gave an indication on how effective a harvester could reach into a kiwifruit canopy. Reachability was approximated as the total fruit detached. However, the reachability could be greatly influenced by the management of an orchard itself as less structured canopies had worse reachability. The picked-detached percentage was used because it was independent of reachability. Therefore, it could be used to compare the performance of harvesters directly. The speed was often given as a harvesting rate in terms of fruit per second, or the inverse

in the form of a harvesting cycle time of seconds per fruit. Fruit handling was given as a percent damaged of successfully detached fruit.

The performance to cost ratio could not be calculated for human workers because wages were not a fixed cost. However, for robotic harvesters, the performance-to-cost ratio could be used to compare different harvesters. The performance was defined as the success-picked-detached cycle time in fruit per second. The capital cost of the harvesters was calculated by breaking down the harvesters into the components and obtaining the cost of each component. The performance to cost ratio was calculated. The cost-to-performance ratio was easier to interpret due to the cost per cycle time metric (Equation 6).

Equation 6: Cost performance ratio

$$R_{CP} = \frac{C}{P} \quad (6)$$

where:

R_{CP}	=	Cost performance ratio (\$/(fruit/s))
C	=	Robot cost (\$)
P	=	Robot performance (fruit/s)

5.3 Results

5.3.1 Human Pickers

5.3.1.1 Fruit Value

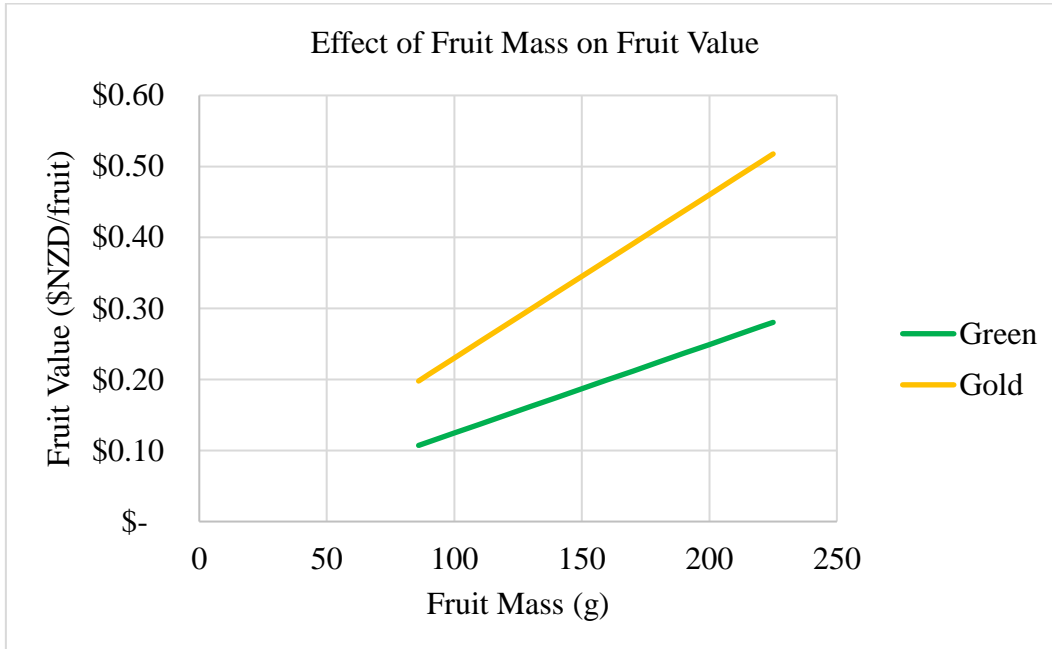


Figure 55: Effect of fruit mass on fruit value

5.3.1.2 Fruit Yield

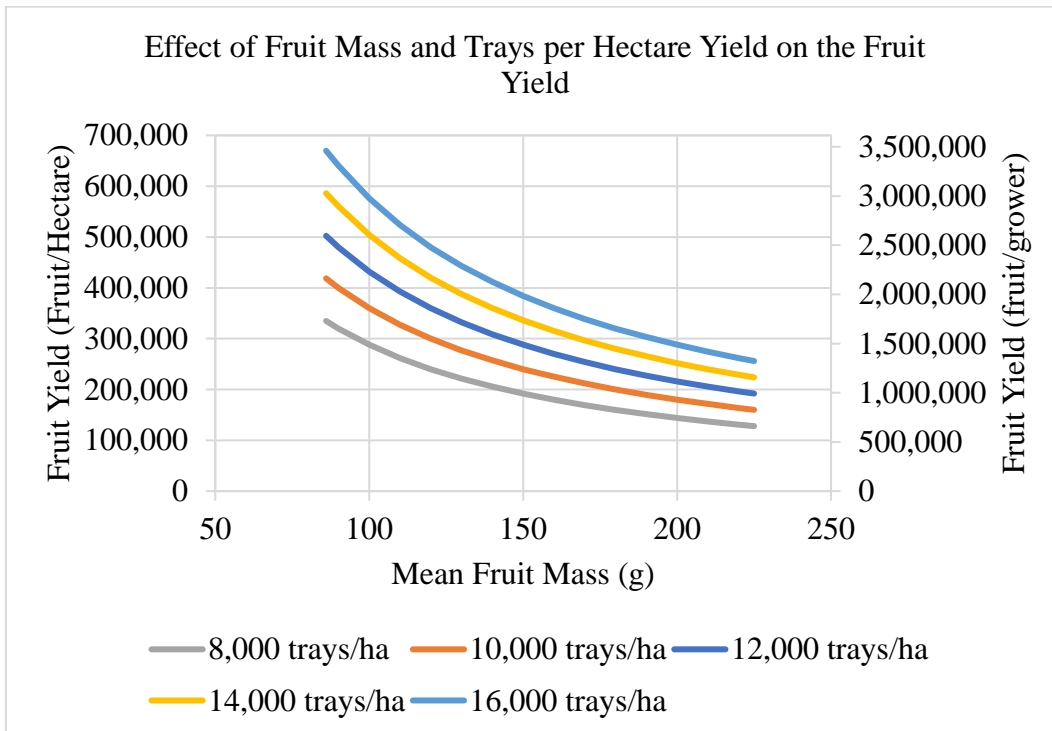


Figure 56: Effect of average fruit mass on fruit per hectare yield

5.3.1.3 Human Picking Rate

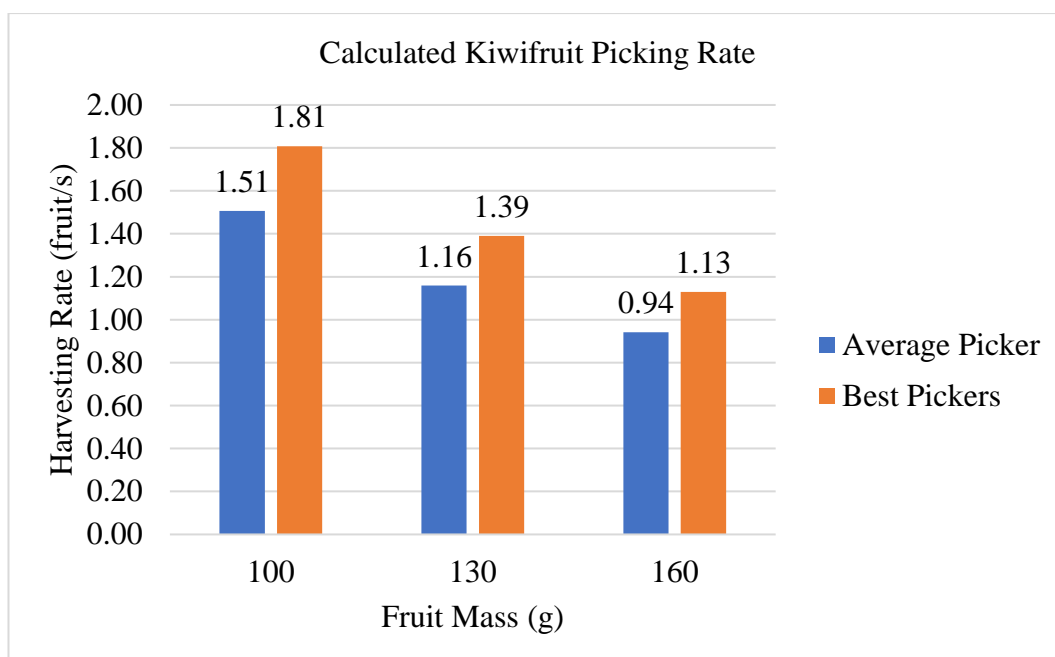


Figure 57: Human picker harvesting rate

5.3.1.4 Human Picker Harvesting Cost

Table 11: Human picker harvesting cost

Key Results	Result (unit)
Workdays required per grower (average)	2.5 workdays
Total picking cost for grower	\$17,549 /grower
Total picking cost per ha	\$3397.33/ha
20 picker picking rate	23.2 fruit/s
Harvesting cost per working day	\$6,820/workday
Harvesting cost per half working day	\$3,517/half-workday
Total picking cost	\$0.01/fruit
Picking cost as a percentage of fruit value	6.3%
Green fruit value ratio	16
Green fruit labour value ratio	32

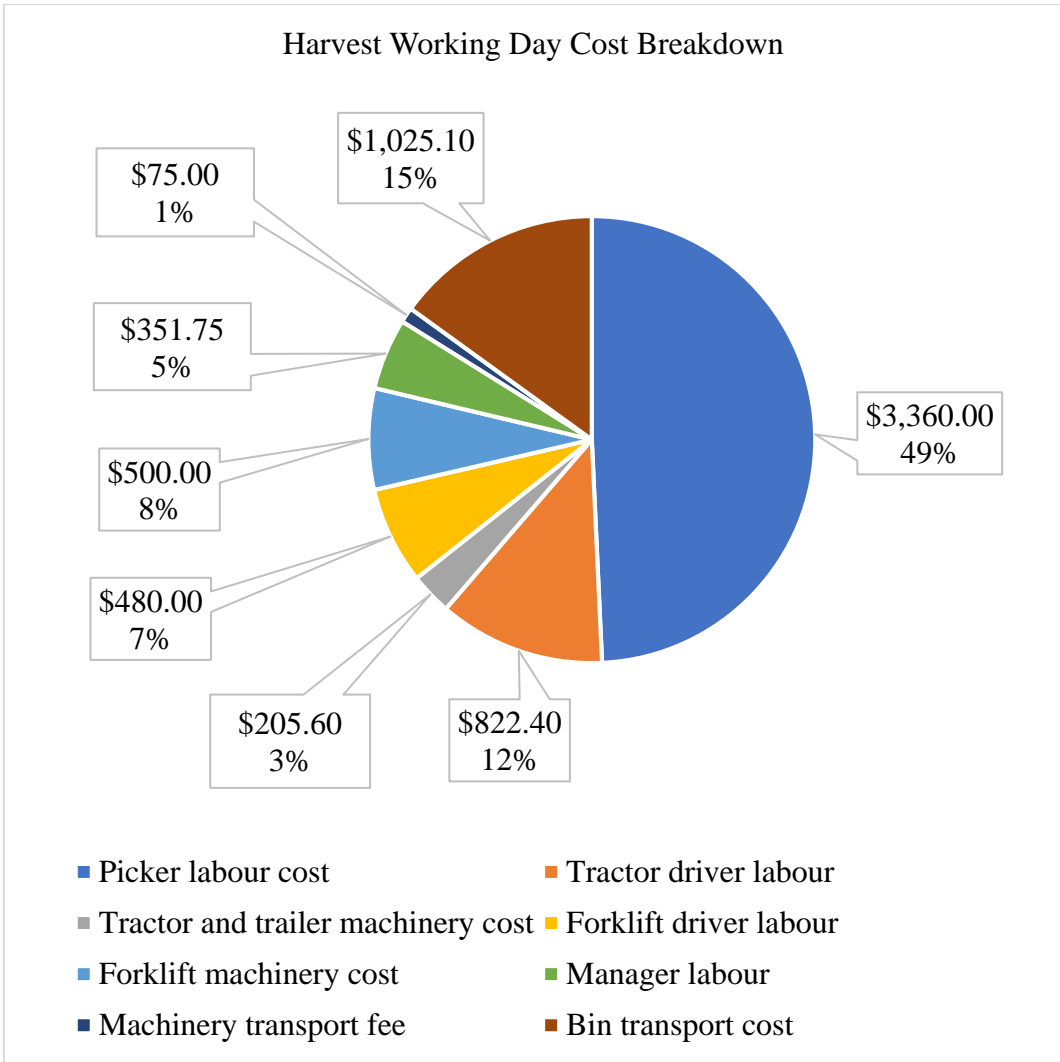


Figure 58: Harvesting cost breakdown

Table 12: Effect of fruit mass and picker wages on harvesting cost

Fruit Mass	Performance	Picking Wage (\$/h)			
		\$16.50	\$21	\$25	\$30
100g	Total harvesting cost/grower	\$19,282	\$21,655	\$23,763	\$26,399
	Total harvesting cost/ha	\$3,733	\$4,192	\$4,600	\$5,111
	Total number of fruit per grower	2,201,372	2,201,372	2,201,372	2,201,372
	Number of harvesting workdays	3.3	3.3	3.3	3.3
130g	Total picking cost per fruit	\$0.0087	\$0.0097	\$0.0107	\$0.0119
	Green fruit value ratio	15	13	12	11
	Gold fruit value ratio	27	24	22	20
	Total harvesting cost/grower	\$15,724	\$17,549	\$19,171	\$21,198
160g	Total harvesting cost/ha	\$3,044	\$3,397	\$3,711	\$4,104
	Total number of fruit per grower	1,693,363	1,693,363	1,693,363	1,693,363
	Number of harvesting workdays	2.5	2.5	2.5	2.5
	Total picking cost per fruit	\$0.0091	\$0.0102	\$0.0112	\$0.0124
160g	Green fruit value ratio	18	16	15	13
	Gold fruit value ratio	33	30	27	24
	Total harvesting cost/grower	\$13,570	\$15,053	\$16,371	\$18,018
	Total harvesting cost/ha	\$2,627	\$2,914	\$3,169	\$3,488
160g	Total number of fruit per grower	1,375,858	1,375,858	1,375,858	1,375,858
	Number of harvesting workdays	2.1	2.1	2.1	2.1
	Total picking cost per fruit	\$0.0096	\$0.0107	\$0.0116	\$0.0128
	Green fruit value ratio	21	19	17	16
160g	Gold fruit value ratio	39	35	32	29

5.3.2 Harvester Breakeven Requirements

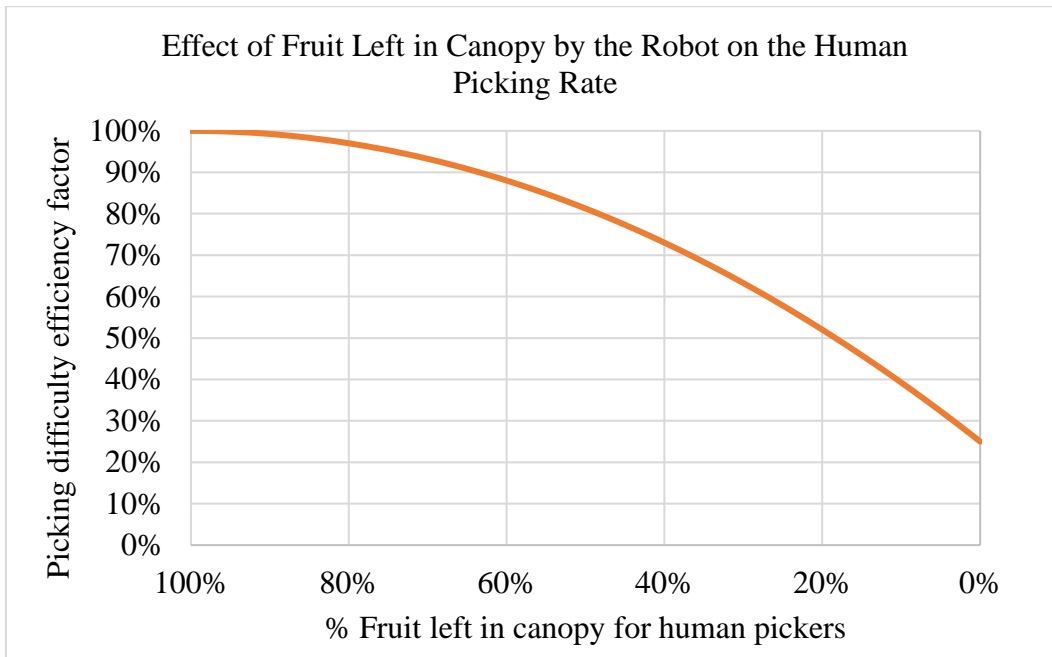


Figure 59: Effect of robot reachability on human clean-up picker efficiency loss

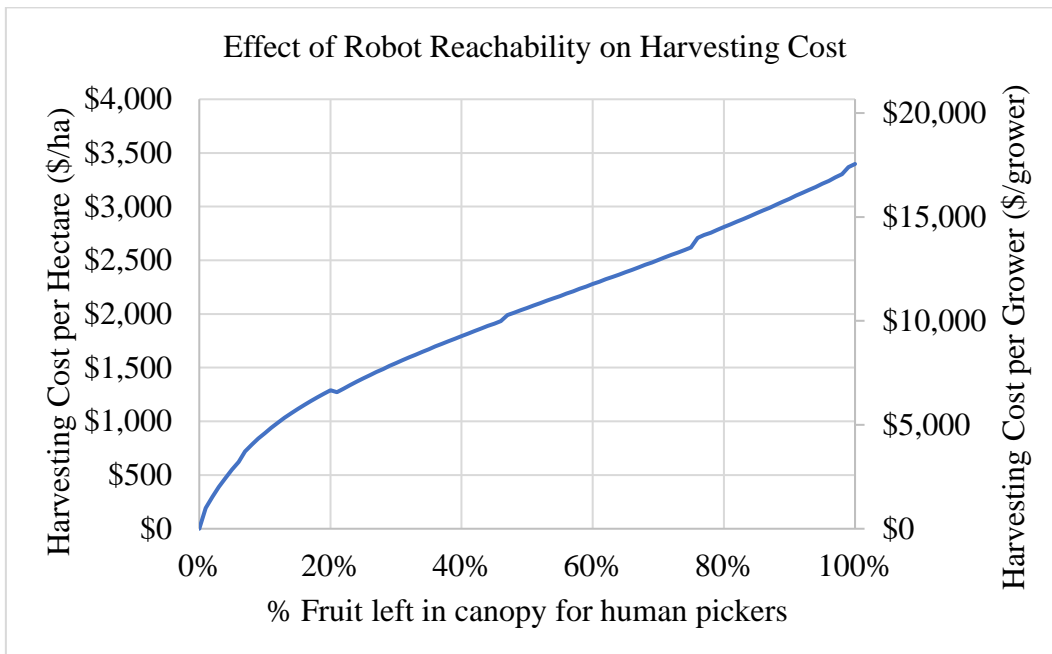


Figure 60: Effect of robot reachability on harvesting cost

Effect of Harvesting Robot Reachability and Success-Detached Performance on the Gain Potential Relative to Human-only Pickers

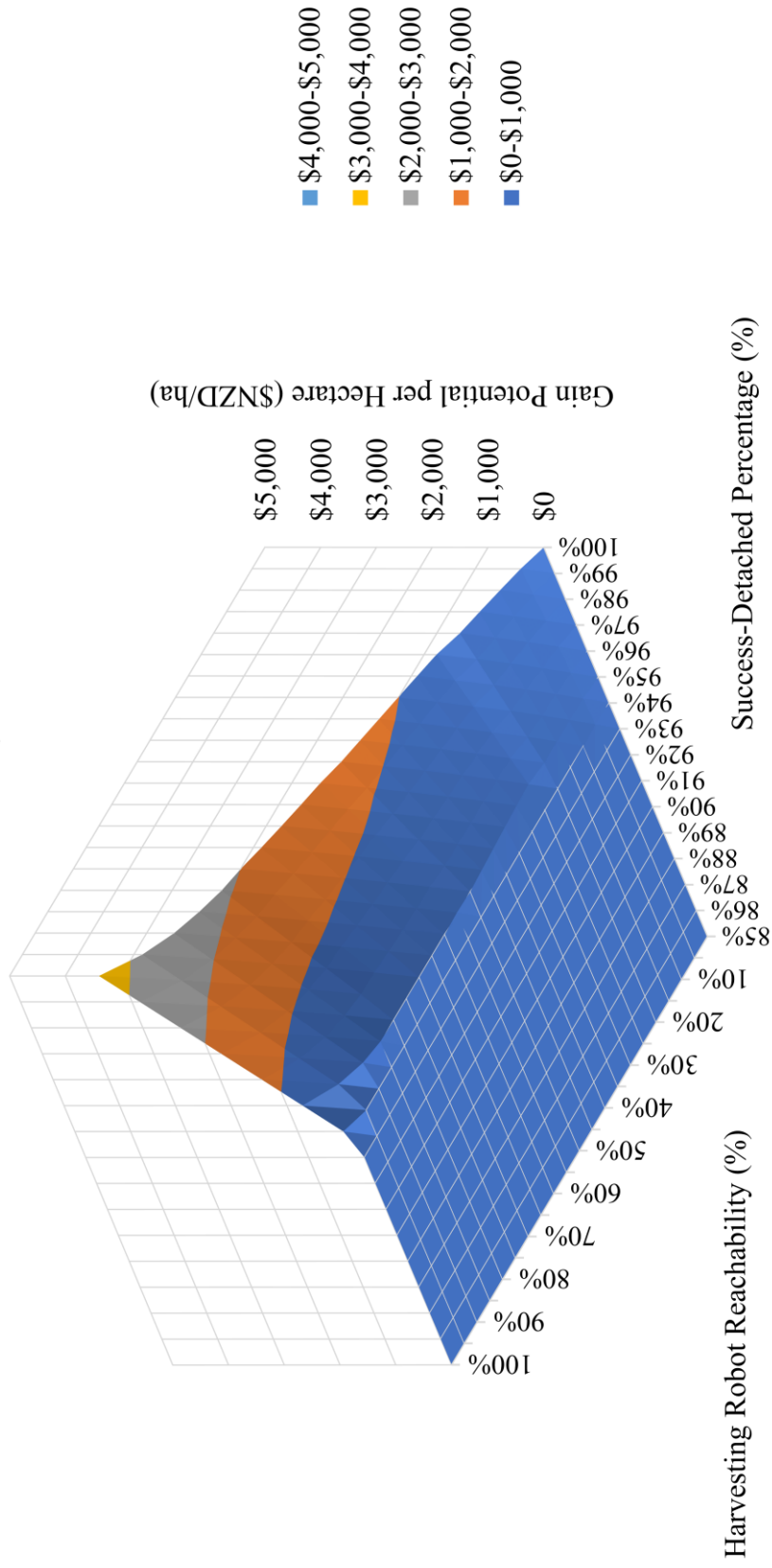


Figure 61: Breakeven success-detached performance for 130 g mean mass green fruit at \$21/h wage and \$53,555 OGR

Effect of Harvesting Robot Reachability and Success-Detached Performance on the Gain Potential Relative to Human-only Pickers

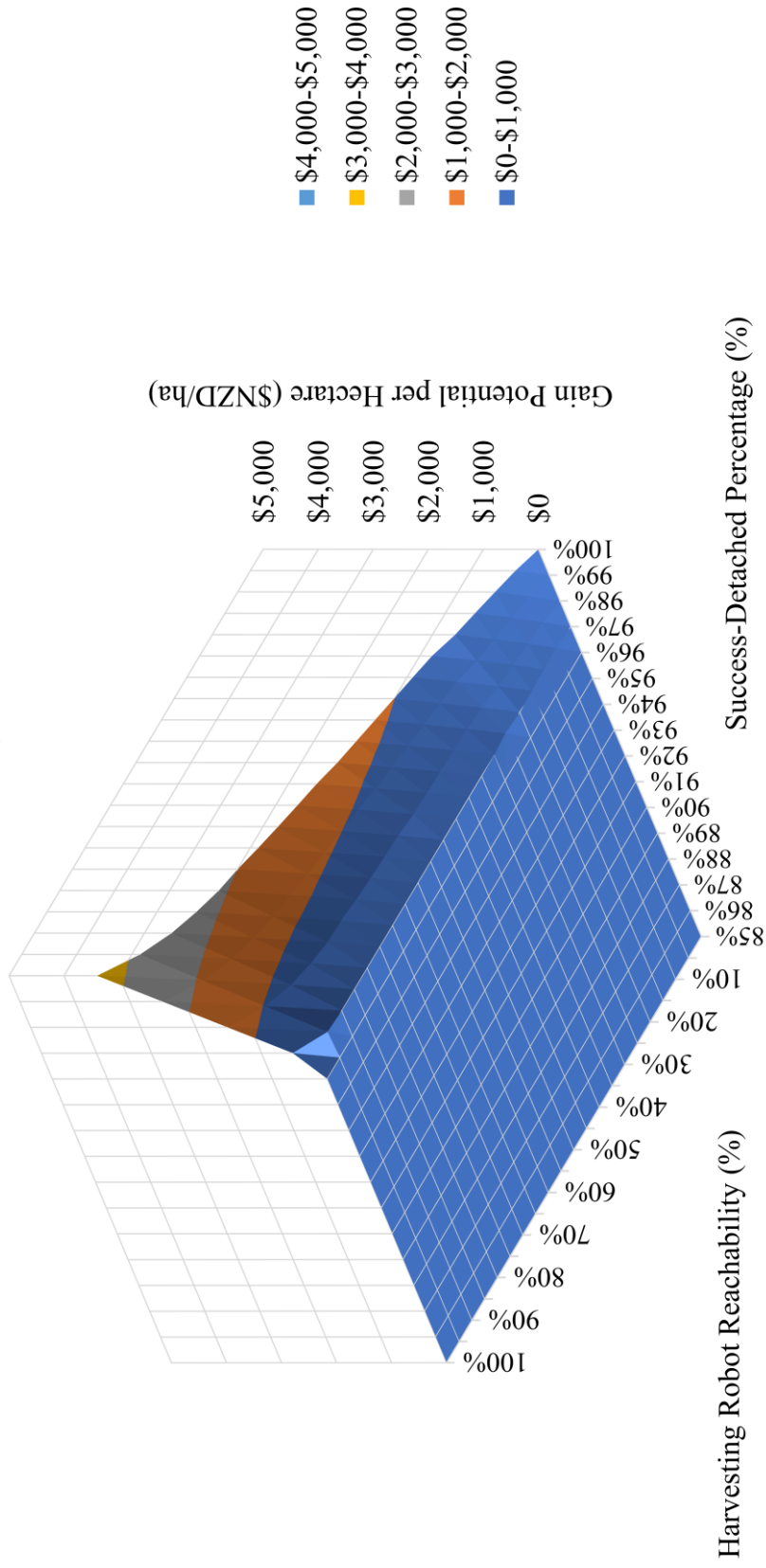


Figure 62: Breakeven success-detached performance for 130 g mean mass gold fruit at \$21/h wage and \$98,838 OGR

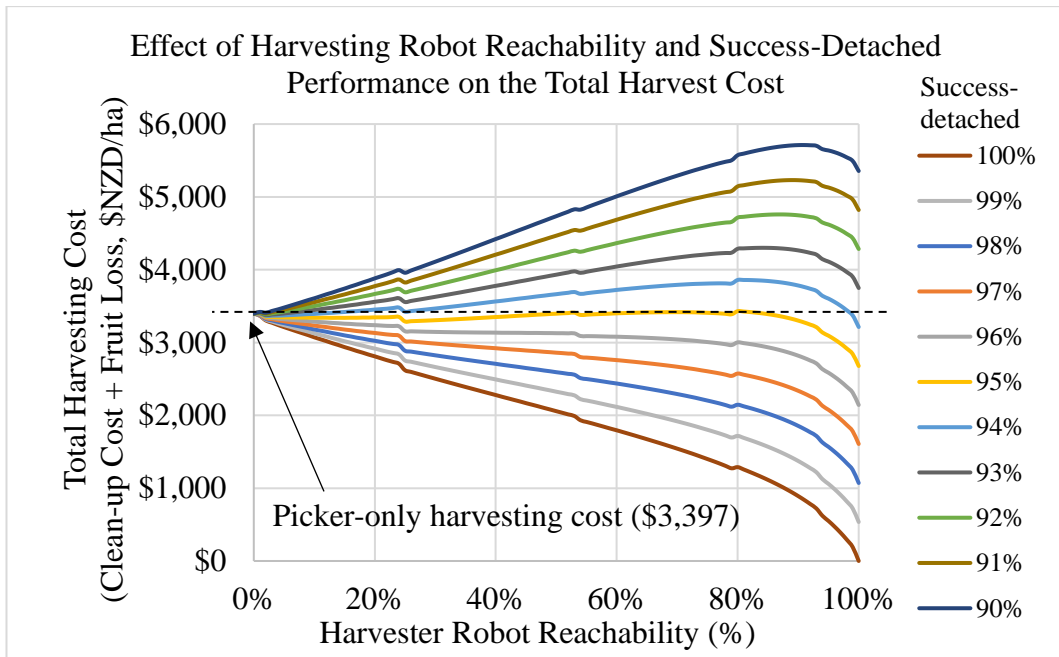


Figure 63: Breakeven success-detached performance for 130 g mean mass green fruit at \$21/h wage and \$53,555 OGR

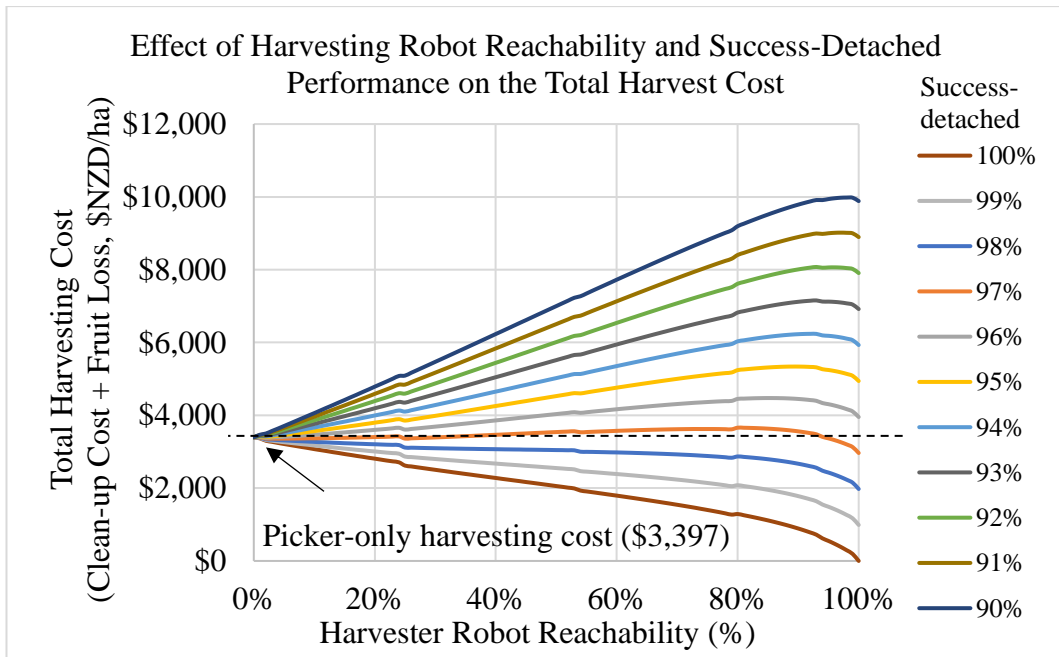


Figure 64: Breakeven success-detached performance for 130 g mean mass gold fruit at \$21/h wage and \$89,838 OGR

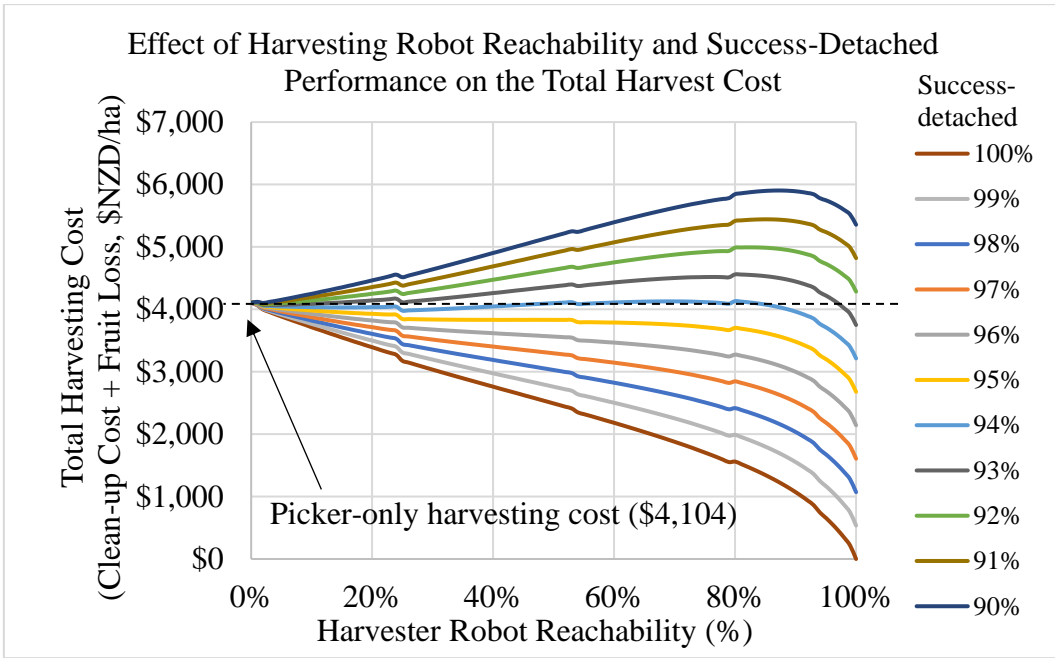


Figure 65: Breakeven success-detached performance for 130 g mean mass green fruit at \$30/h wage and \$53,555 OGR

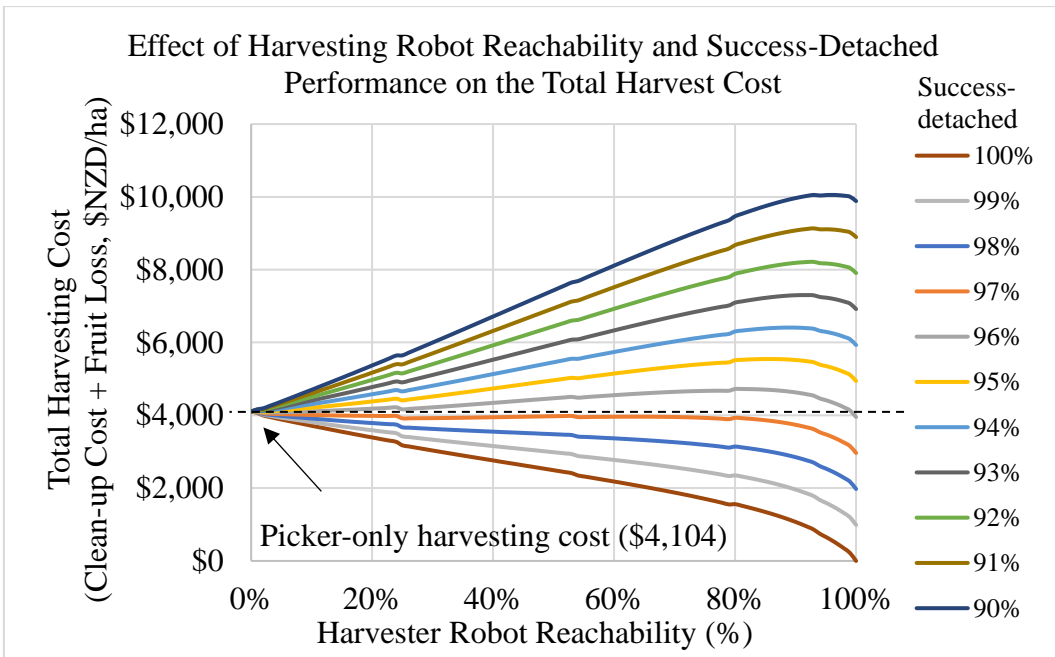


Figure 66: Breakeven success-detached performance for 130 g mean mass gold fruit at \$30/h wage and \$89,838 OGR

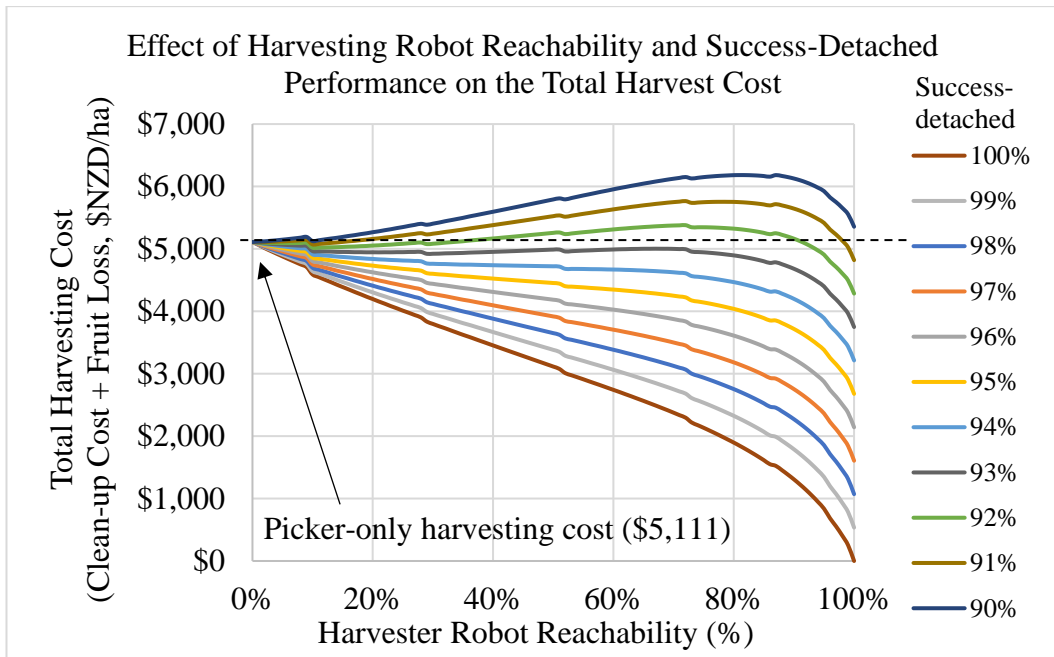


Figure 67: Breakeven success-detached performance for 100 g mean mass green fruit at \$30/h wage and \$53,555 OGR

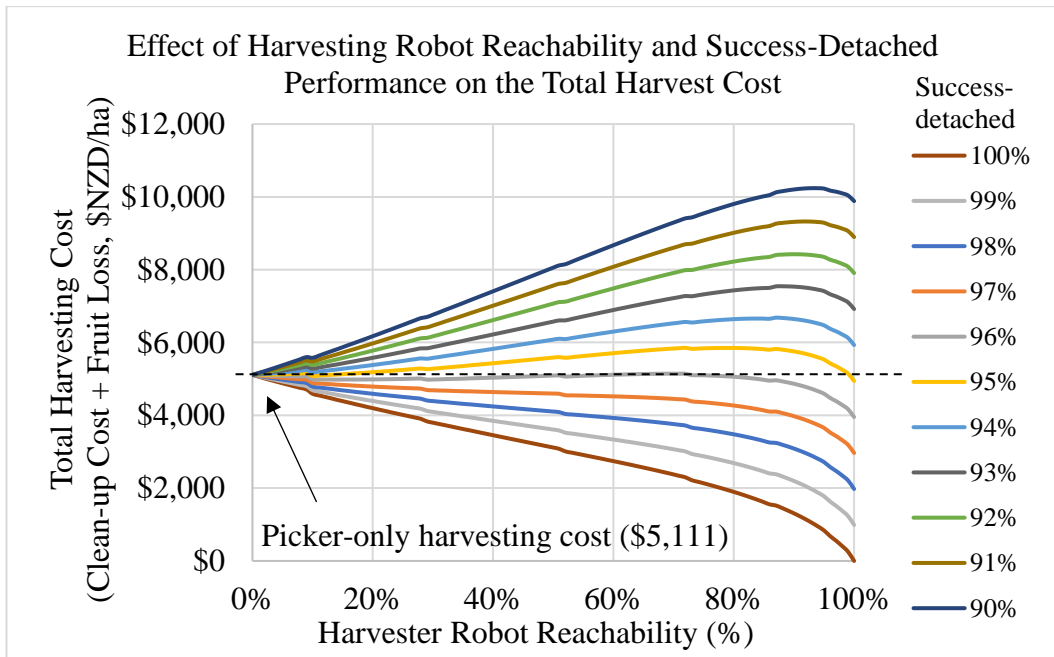


Figure 68: Breakeven success-detached performance for 100 g mean mass gold fruit at \$30/h wage and \$89,838 OGR

5.3.3 Performance Comparison

Table 13: Performance of the kiwifruit harvesters

Harvester	Reachability (%)	Picked-Detached (%)	Harvesting Rate (fruit/s)	Cycle Time (s/fruit)	Fruit Handling (%)
Human Pickers	99.0	99.4	1.16	0.86	99.5
Selective AKH 2017	75.4	67.4	0.19	5.37	93.0
Selective AKH 2018	64.5	86.4	0.36	2.78	96.0
Non-selective Stem-shear (green)	37.2	24.3	0.58	1.72	58.7
Non-selective Stem-shear (gold)	42.4	16.5	0.32	3.14	-
Non-selective Combing (green)	40.1	32.5	0.35	2.85	-

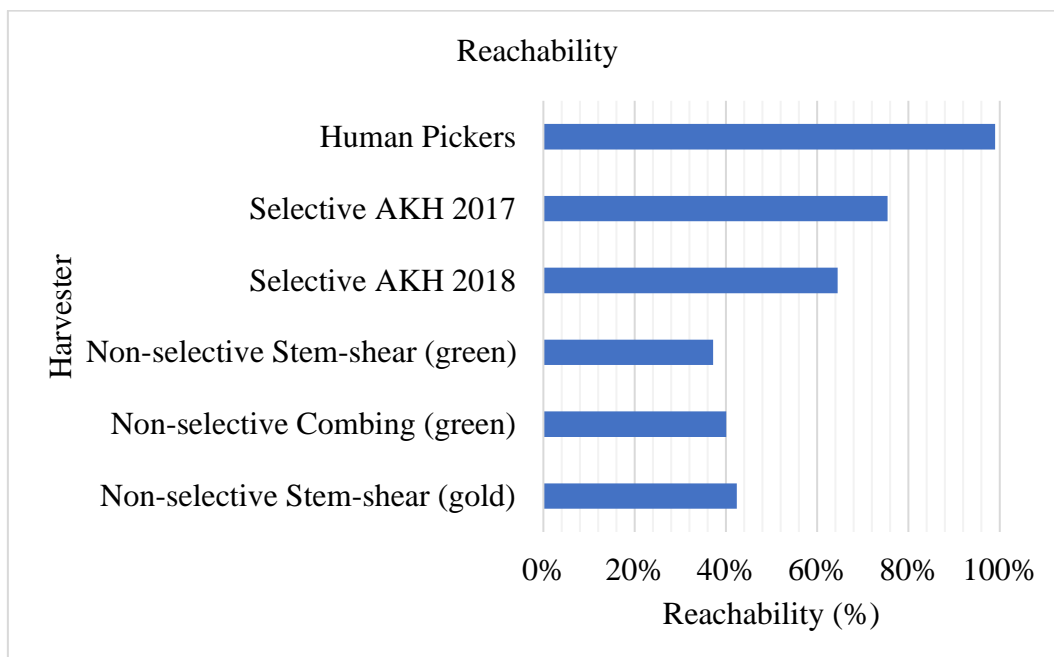


Figure 69: Kiwifruit harvester reachability comparison

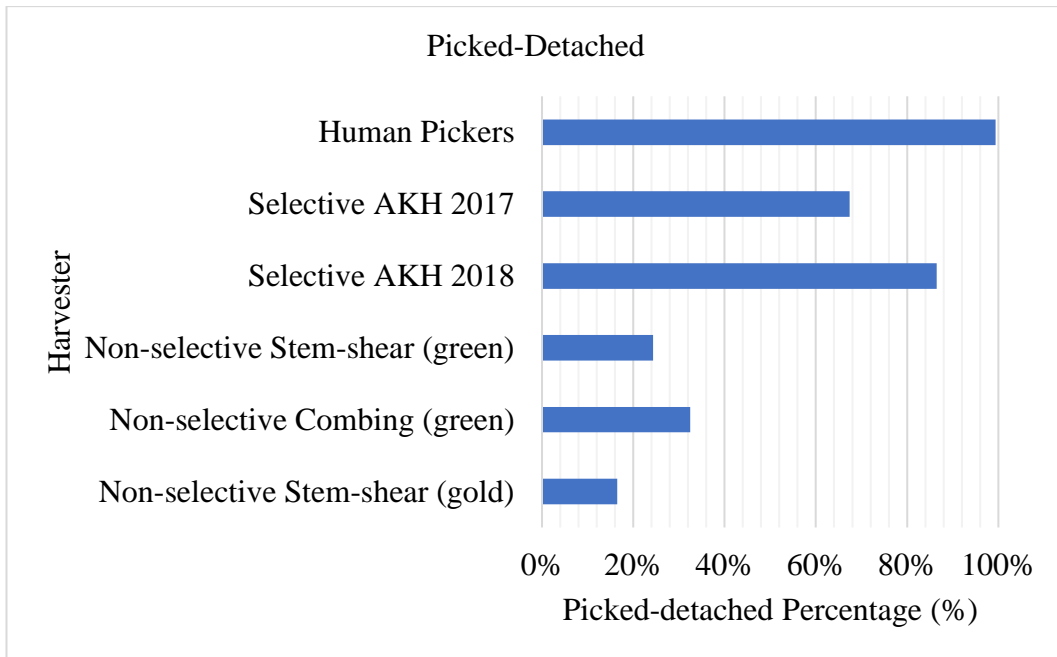


Figure 70: Kiwifruit harvester picked-detached comparison

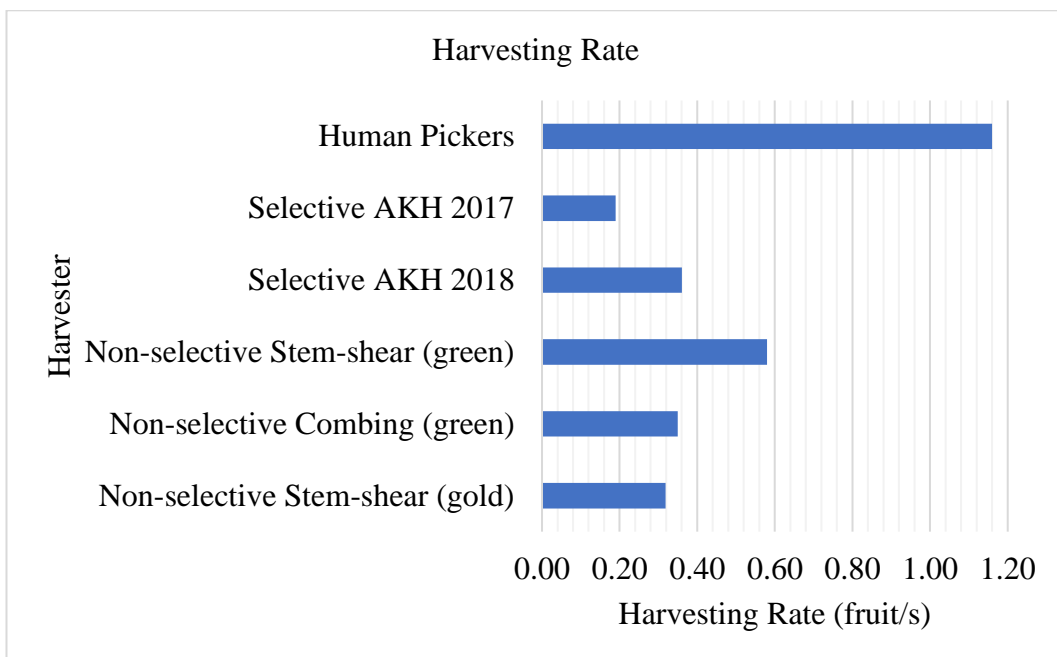


Figure 71: Kiwifruit harvester harvesting rate comparison

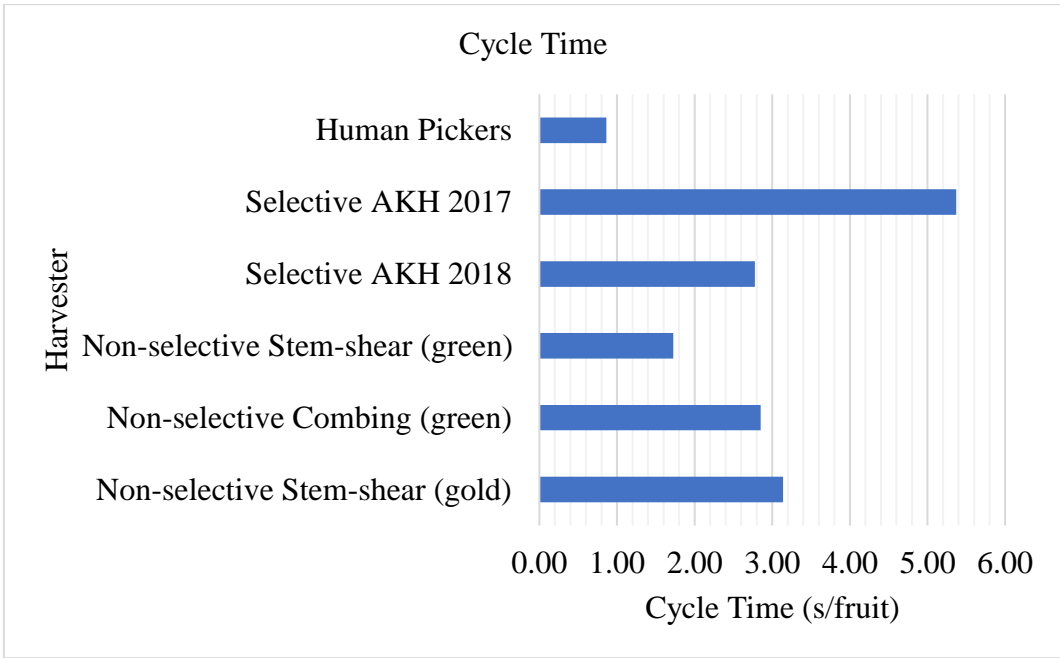


Figure 72: Kiwifruit harvester cycle time comparison

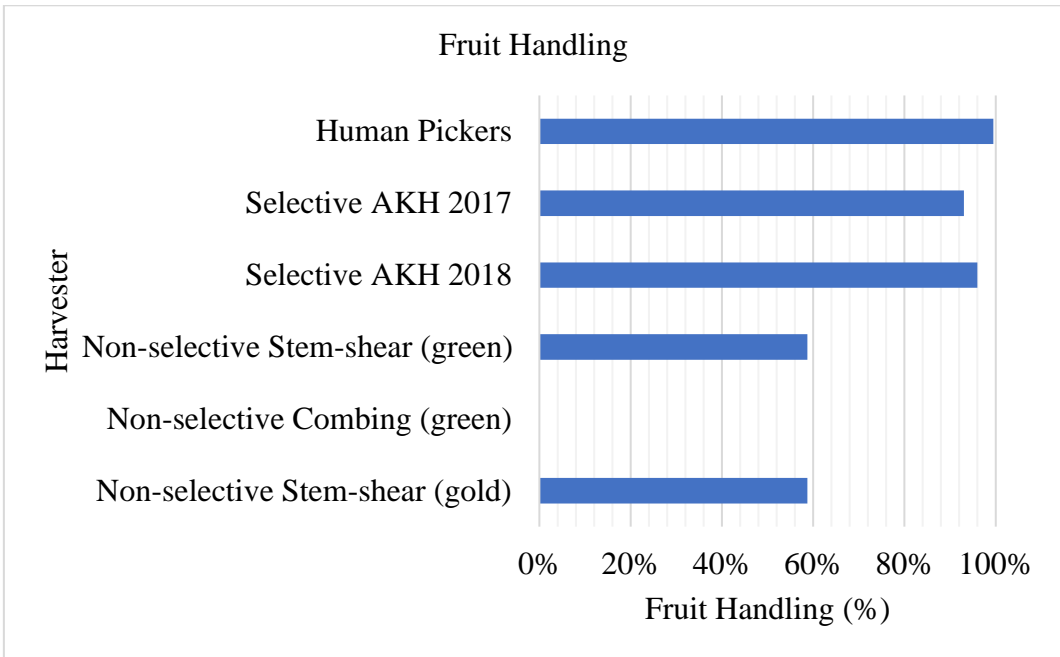


Figure 73: Kiwifruit harvester fruit handling comparison

Table 14: Cost-performance calculation inputs

	Non-selective	Non-selective (perfect picked-detached and fruit handling)	Selective	Selective (no efficiency loss)
Picked-detached (%)	74.8	100.0	86.4	86.4
Fruit handling (%)	59.0	100.0	96.0	96.0
Stemless (%)	67.5	67.5	93.8	93.8
Harvesting rate (fruit/s)	0.58	0.58	0.36	1.21
Success harvesting rate (fruit/s)	0.17	0.39	0.28	0.94

Table 15: Cost-performance results

Non-selective				
Harvester cost (\$)	2,500	5,000	10,000	15,000
Cost performance (\$/(fruit/s))	14,470	28,939	57,878	86,817
Non-selective (perfect picked-detached and fruit handling)				
Harvester cost (\$)	2,500	5,000	10,000	15,000
Cost performance (\$/(fruit/s))	6,386	12,771	25,543	38,314
Selective				
Harvester cost (\$)	50,000	75,000	125,000	150,000
Cost performance (\$/(fruit/s))	178,517	267,776	446,293	535,551
Selective (no efficiency loss)				
Harvester cost (\$)	50,000	75,000	125,000	150,000
Cost performance (\$/(fruit/s))	53,180	79,770	132,951	159,541

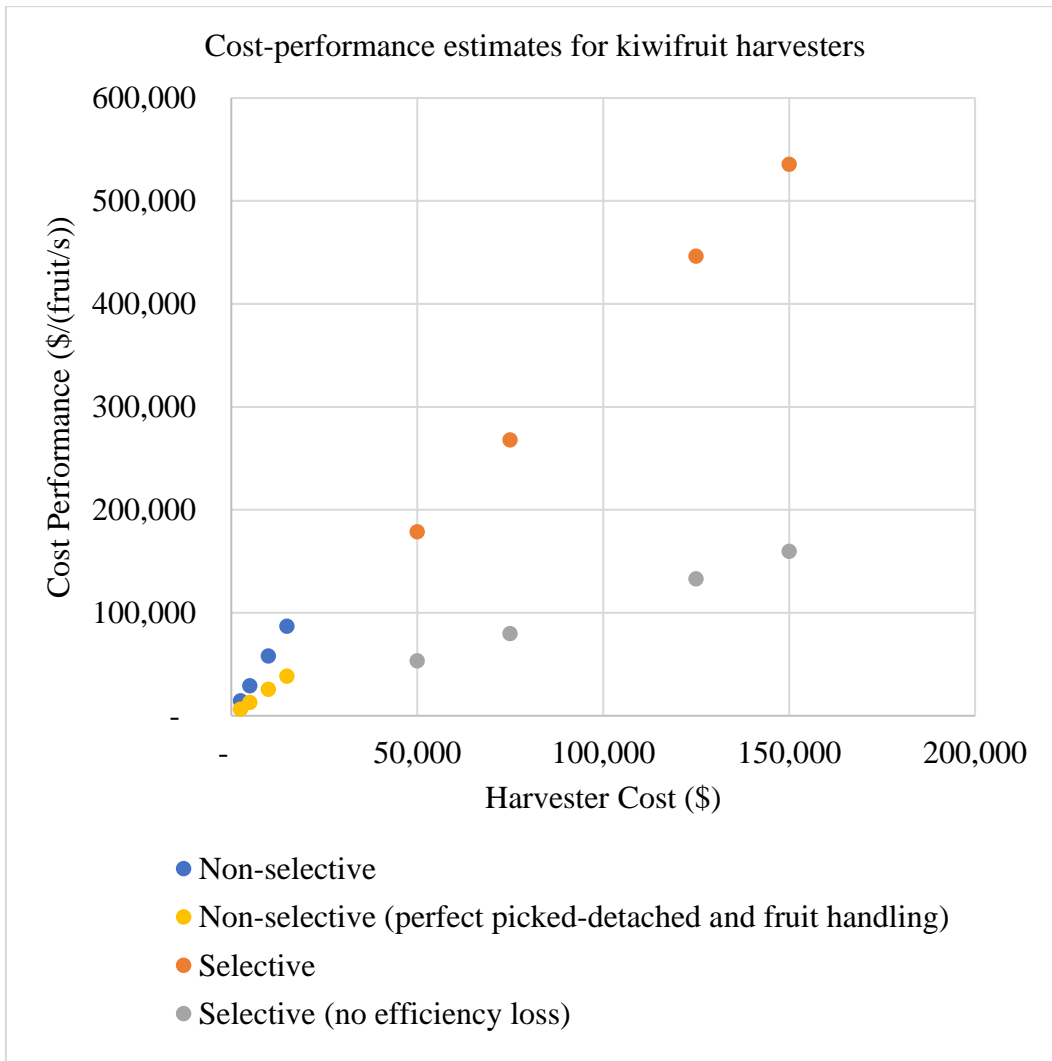


Figure 74: Cost-performance comparison

5.4 Discussion

5.4.1 Human Pickers

5.4.1.1 Fruit Value

Larger fruit were much more valuable than smaller fruit. Gold fruit were significantly more valuable than green fruit (Figure 55). The green fruit value for fruit masses of 100 g, 130 g, and 160 g were \$0.12 per fruit, \$0.16 per fruit, and \$0.20 per fruit, respectively. In comparison, the gold fruit value for fruit masses of 100 g, 130 g, and 160 g were \$0.23 per fruit, \$0.30 per fruit, and \$0.37 per fruit, respectively. The fruit value was determined by the OGR for a given harvesting season.

5.4.1.2 Fruit Yield

At a constant tray per hectare yield, an increase in the mean fruit mass decreased the number of fruit (Figure 56). At a constant tray per hectare yield of 11,838 trays/ha, the yield in fruit per hectare for fruit masses of 100 g, 130 g, and 160 g, were 426,168 fruit/ha, 327,822 fruit/ha, and 266,355 fruit/ha, respectively. The difference between the maximum and minimum was 159,813 fruit/ha which was quite significant.

Each grower had many fruits to be harvested over an average grower's 5.17 ha orchard. Based on a fruit mass of 130 g, each grower had a yield of 1.69 million fruit/grower. For fruit masses of 100 g and 160 g, the yields were 2.20 million fruit/grower and 1.38 million fruit/grower, respectively. Growers aimed to maximise their yield in terms of trays per hectare. At a constant tray per hectare yield, it would be advantageous for the grower to grow less but larger fruit. This would decrease the number of fruits to be picked and hence, the harvesting cost. However, each fruit would be more valuable.

5.4.1.3 Human Picking Rate

Due to the uncertainty in the number of fruit per bin, several fruit masses were used to calculate the likely harvesting rate. Based on an average fruit mass of 130 g, a picking rate of 1.16 fruit/s or a cycle time of 0.86 s/fruit could be achieved (Figure 57). However, it could range from 0.94 fruit/s to 1.51 fruit/s, depending on the fruit mass used in the calculation. The best pickers were about 20% faster than average pickers with a picking rate of 1.39 fruit/s and a range between 1.13-1.81 fruit/s.

The harvesting rate was the average across the entire working day, including break times. The actual peak harvesting rates could be near 4 fruit/s or even higher, but this rate was only briefly sustained when fruit were in very large clusters. The actual harvesting rate was lower because the search time for fruit increased as the kiwifruit bay was picked. Human fatigue also decreased the harvesting rate throughout the day.

The harvesting cycle rate of 10-12 bins/working day was 5.4-6.5 times faster than the 100 kg of fruit per hour per person reported by Warrington et al. (1990). The low picking literature value did not reflect what was observed on orchard. The 10-12 bins/working day value was supplied by an experienced picking manager so

there was confidence on their harvesting rate value. Furthermore, observations of the pickers supported the faster value.

5.4.1.4 Human Picker Harvesting Cost

Table 11 revealed the key results. From the total harvesting cost breakdown, an interesting result was that the picker labour cost was only half the total harvesting cost (Figure 58). The picker labour cost percentage was likely to remain near half even if more pickers were added. This was because the ratio between tractor drivers to pickers were chosen to prevent pickers from waiting for new bins. If there were not enough tractor drivers, the pickers would have been held up. The implication of this to robotic harvesting was that the other costs associated with the clean-up pickers were still required such as the managers, tractor drivers, and the forklift driver. This meant that the potential savings were limited. Unless a robotic harvester could reach and pick all the fruit, a clean-up crew was required.

For an average picking wage of \$21/hour and average fruit mass of 130 g, the cost to pick the 1.7 million fruit in an average grower's 5.17 ha orchard was \$17,549 NZD. It would take two and a half working days to pick an average grower's orchard. The averaged per hectare total harvesting cost was \$3,397 NZD/ha. The actual cost for just one hectare was \$3,456 NZD/ha which would have taken just under half a workday to harvest. These values were approximately 2-3.6% higher than a 2016 literature value of \$3,333 NZ/ha (NZKGI, 2017). On a per bin basis, this was \$34 NZD/bin which was slightly lower than a commercial rate of \$38 NZD/bin including transport cost from one source (Trevelyan's, 2018).

The effect of fruit mass (and hence number of fruit in an orchard), and picker labour cost on the total harvesting costs were calculated (Table 12). As expected, an increase in labour cost increased the overall harvesting cost and picking cost per fruit. However, because the picking labour cost was only about half the total harvesting cost, each percentage increase in the picker wages only increased the total harvesting cost by half a percent.

What was truly alarming was the value of each fruit relative to the total harvesting cost per fruit. For the average case stated above, each green fruit was worth approximately 16 times the total harvesting cost. This was only about 6% of the value of the fruit. For average sized green fruit, the value of the fruit was \$0.16

NZD/fruit whereas the total harvesting cost per fruit was \$0.01 NZD/fruit. For smaller (100 g) and larger fruit (160 g) at a \$21/hr picking wage, the ratios were 13 and 19, respectively. As the picker labour was only half the total harvesting cost, the value of each fruit relative to the value of the picker labour was double at 32 times the value of the fruit. The implication of this for both human and robotic harvesters was that each fruit lost was a huge waste and must be avoided at all costs. The fruit value forced a high-performance requirement of any robotic or mechanised kiwifruit harvester to be near perfect.

Golden kiwifruit had a higher value than green fruit, so the fruit value to harvesting cost ratios were even higher for gold fruit. The fruit value to total harvesting cost for the average gold fruit (130 g) was 30. For smaller (100 g) and larger fruit (160 g) at a \$21/hr picking wage, the ratios were 24 and 35, respectively. Therefore, the performance requirement of a kiwifruit harvester for gold was even higher than green fruit.

During the 2012/13 season, the gold fruit made up only a calculated 23.3% of total tray exports (NZKGI, 2017). (NZKGI, 2018) predicted an increase from 45% gold fruit trays (of total trays) in 2018 to 70% gold fruit trays by 2027. The proportion of green and gold fruit produced was reported by (NZ MPI, 2018), which showed the historical and projected green and gold kiwifruit proportions. Furthermore, gold kiwifruit were more susceptible to bruising. Any economically viable kiwifruit harvester must focus on minimising fruit loss because each fruit is so valuable relative to the cost of harvesting. With gold kiwifruit becoming the majority in the future, the performance requirement increases. For kiwifruit harvesting, fruit loss could be decreased by improving fruit handling and reducing in fruit drops, throws, and knock-offs.

5.4.2 Harvester Breakeven Requirements

An inverted parabola with a minimum of 25% efficiency for the clean-up pickers was used (Figure 59). The subsequent clean-up picker harvesting costs based on robot reachability were determined (Figure 60). The required harvester breakeven performance in terms of picked-detached success percentage was quite high. The breakeven performance required at the current \$21 NZD/hour picker wage was 95% for green fruit (Figure 61), and slightly over 97% for gold fruit (Figure 62).

Therefore, the fruit loss by a harvester must be less than 5% for green fruit and under 3% for gold fruit. The breakeven performance could be determined by the picked-detached success under the human-only picker cost in Figure 63 for green fruit, and Figure 64 for gold fruit.

The breakeven values were close to the 95% value from the EU CROPS project for sweet-pepper harvesting which stated that “The critical factor for economic feasibility is the yield rate which must be at least 95% to ensure successful market entrance” (Stichting Dienst Landbouwkundig Onderzoek, 2014). Folley & Wicks (1975, as cited in Child & LeFlufy, 1980) estimated that for apples, a harvester would require at least 80% efficiency of hand picking to be economical. Compared to an asparagus harvester, the breakeven requirement was lower at 70% (Clary et al., 2007) and 73.55% (Cembali, Folwell, & Ball, 2004).

The fruit value ratio was calculated based on the revenue divided by the harvest labour only cost. This was used for comparison between different crops because the other associated costs with certain crops may not apply to another crop. The reason why asparagus had a much lower breakeven requirement was because of the repetitive harvesting requirement throughout the harvesting season. The asparagus fruit value labour ratio was 2.68 (Neibergs & Waters, 2009) to 3.6 (Talley & Werling, 2016). Similarly, for strawberries, the fruit value to harvest cost ratio was calculated as 2.0 (Bolda, Tourte, Murdock, & Sumner, 2016) to 3.3 (Takele, n.d.). Apples had a ratio of 9.6 (Wilson, Emms, & Corbett, 2009). For sweet peppers, the ratio was approximately 17.8 (University of California, 2001). Fruit with a high harvesting cost relative to the fruit value had lower performance requirements as each fruit loss was less significant.

The effect of the picking labour wages and fruit mass at a constant yield of 11,838 trays/ha (2016/17 harvesting season) was investigated. At a constant trays per hectare yield, the mean fruit mass affected the fruit per hectare yield. The fruit mass levels were 100 g, 130 g, 160 g, which corresponded with 426,168, 327,822, and 266,355 fruit per hectare, respectively. The picking labour wage levels were \$16.50 (current April 2018 minimum wage), \$21 (current average kiwifruit picker wage), \$25, \$30.

An increase in the picker wages only slightly decreased the breakeven performance requirement. At an average fruit mass of 130 g and \$21 NZD/hour picker wage, the breakeven performance for green fruit was 95%. At the same fruit mass but with an increased wage of \$30 NZD/hour, the breakeven performance only decreased by only about 1% to 94% (Figure 65). For gold fruit, a \$30 NZD/hour picker wage increase only decreased the breakeven performance very slightly to under 97% (Figure 66). An increase in the picker wage increased the harvesting cost and decreased the fruit value ratio.

The effect of mean fruit mass on the breakeven performance was also small. Decreasing the mean fruit mass decreased the value of each fruit and the fruit value ratio. Therefore, each fruit loss was slightly less significant. In the best case with 100 g fruit and \$30 NZD/hour picking wage, the breakeven performance was reduced to under 93% for green (Figure 67), and 96% for gold fruit (Figure 68).

The greatest contributing factor for the high breakeven performance was the high value ratio. Each fruit loss had a significant impact on the total harvesting cost. For human pickers, the fruit loss was assumed to be near zero. For any kiwifruit harvester, the single most important factor was the success-picked-detached percentage. The harvesting robot reachability had little effect on the breakeven performance. However, an increase in reachability increased the gain or loss potential at a given success-detached percentage.

With deliberate orchard management for robotic harvesting, the reachability could increase to 90%. If an improved robotic harvester could pick 99% of the reachable fruit, then there was a potential gain of \$2,024 per hectare and \$10,455 per grower. Assuming each harvesting season lasted 90 days and each grower on average took 2.5 days to harvest, then 36 grower's orchards could be harvested. The potential savings per harvesting season was \$376,380 per season. However, if the success was only 95%, then the potential gain was only \$96 per hectare, \$496 per grower, and \$17,867 per season. Likewise, if the success was 90%, then the grower would have to pay an extra \$2,314 per hectare or \$11,952 per grower. The gains above used for the calculations did not include the running and overhead costs of the robotic harvester. Therefore, the net potential gain would be lower depending on

those costs. The implication of the results was that the harvester breakeven performance was extremely important.

From a grower's perspective, the fruit must be picked, regardless of the cost as without harvesting, there are no fruit for the packhouses, and hence no orchard gate returns. Therefore, growers will always find a way to have their kiwifruit crop harvested, even if they must do it themselves. If the average picker labour wage was raised to \$30 per hour, then the labour shortage could potentially be solved due to the increased incentive. However, this would decrease the orchard profitability. The short-term solution would be for New Zealand immigration to increase the seasonal labour work visa quota to match the labour demands. The combination of increased visa quotas and picker labour wages would encourage workers to come to New Zealand and pick kiwifruit. However, in the long-term, robotic harvesting is highly desirable for labour security and for orchard profitability.

5.4.3 Performance Comparison

Human pickers were great at fruit picking with 100% reachability, near 100% fruit handling, and fast harvesting speed of 1.16 fruit /s. A harvesting robot that achieves similar performance was a challenge. Table 13 displayed the overall results of the kiwifruit harvesters.

5.4.3.1 Reachability

The reachability of the AKH showed that it was highly orchard dependent. The orchard management affected the structure and reachability of fruit. The AKH was able to reach 75% of the fruit in 2017 but only 65% in 2018 (Figure 69). The difference was likely the orchard itself as the picking action was the same. The non-selective harvester had low reachability of between 37-42%. It was only able to reach fruit that were below the support wire. Therefore, the 37-42% reflected the percentage of fruit under the wire. The AKH had higher reachability because it could reach into the canopy and pick fruit above the support wire. However, the AKH still could not reach fruit with obstacles or in fruit in high positions. Even for human pickers, some fruit were very difficult to reach.

The orchard reachability for the selective harvester could surpass 90% if deliberate orchard management and training was done to increase the number of fruit under

the support wire. However, it is unlikely to reach over 95% because there were always fruit near the leaders, support structures, or in very high positions. Some fruit could not be seen easily due to occlusion by leaves. Therefore, there will likely always be human pickers to pick the remaining fruit.

5.4.3.2 Picked-detached

The performance of the harvester during 2018 testing did not reach the breakeven performance, so it was not viable. However, the AKH had a significantly improved picked-detached percentage from 67.4% in 2017 to 86.4% in 2018 (Figure 70). The breakeven performance percentage included fruit that were picked successfully without stems and damage. Therefore, each of the picked-detached, stem-less, and fruit handling percentages must be higher than 95% as the product of the percentages was the breakeven performance. The AKH results with the M6 gripper reached 89% which was promising. With further development to reduce fruit loss, it could be significantly higher. Furthermore, the fruit picked without stems was 94%. The M5 gripper had 100% fruit handling based on tests where the control fruit were not damaged. Therefore, the current harvester had very high performance relative to many other harvesters for other crops. With further development, it could reach the harvester breakeven performance of at least 95% for green fruit and 97% for gold fruit. The current results of the selective harvester agreed with a study on a selective artichoke harvester by Longo & Muscato (2013) which concluded that it had low damage but was too slow, complex, and expensive.

The non-selective harvester was not viable because the performance did not achieve the breakeven requirement. For the stem shear non-selective harvester concept, the picked detached percentage was only 16.5%-24.3% which was nowhere near the 97% breakeven requirement. Furthermore, the fruit handling was quite poor with a minimum of 41% fruit damage.

The combing bulk harvester however, had a better picked-detached performance as all dropped and knocked off fruit were counted as picked due to the catching net. The greatest challenge with the non-selective harvester was achieving a stemless and damage-free harvest. The picked-detached percentage could be 100% if a large catching surface was used. However, it was unlikely that most of the fruit would be harvested without stems and without damage.

5.4.3.3 Speed (cycle time)

The speed of human pickers was quite high at 1.16 fruit/s and 0.86 s/fruit. The harvester with four manipulators was able to harvest at 2.78 s/fruit or 0.36 fruit/s (Figure 71, Figure 72). However, in the single manipulator testing, one manipulator was already able to harvest at 3.31 s/fruit. Therefore, the current robotic harvester configuration could not utilise the full potential of the manipulators. If there were no efficiency losses due to poor workspace sharing and idle manipulators, a four-manipulator robot would have been capable of harvesting at 1.21 fruit/s, which was about the same as a human picker. An advantage of the robotic harvester over human pickers was that the robots can pick continuously without fatigue. Therefore, robotic harvesters could pick 24/7 during the harvesting season. If a robot picker could pick continuously for 24 hours and one human worker shift was eight hours, then the robot picker could pick three times longer than human pickers. The advantage of this on the robot requirements was that the robot picking speed may only need to be a third of human pickers. Picking for triple the time but at a third of the picking speed still had the equivalent performance to a human picker. One potential issue with this method was the weather as kiwifruit cannot be picked when there was moisture on the fruit. This was due to moisture increasing the likelihood of post-harvest losses.

The speed of the non-selective harvester represented the testing speed of a prototype with a width of only 400 mm. Therefore, the harvesting speed did not represent a full system non-selective harvester. However, the picking speed of the harvester could be estimated. During testing, the harvester was run deliberately slow at 0.58 fruit/s to avoid damage to the growing structure. If the actual harvesting speed was double this, it would be 1.16 fruit/s which was like a human picker. Furthermore, if the width of the harvester was extended to 4 m, the harvesting rate could increase by ten times. Therefore, a 4 m wide non-selective harvester at full speed could potentially harvest at 11.6 fruit/s. Just two of these harvesters could harvest at the rate of a twenty-picker crew. Furthermore, the non-selective harvester cost was likely to be much lower than a selective harvester so ten of these units could be used to increase the harvesting rate tenfold.

5.4.3.4 Fruit Handling

The fruit handling of human pickers was quite good due to the tactile sensing ability of human hands. The 2018 AKH gripper (M5) however, was able to achieve damage-free fruit handling performance (Figure 73). Testing revealed that the M5 gripper was able to harvest all the fruit without damage based on a test dataset where the control fruit were not damaged. Tests of the M4 gripper showed a 94% fruit handling performance. The test however, was done on softer fruit which meant that it had a fruit handling performance of at least 94% if tested on firmer fruit. Softer fruit have higher bruising susceptibility, so the actual fruit handling performance was likely also 100% because the M4 gripper could conform better than the M5 gripper. The 2018 M6 gripper had a fruit handling performance of 92% which was most likely due to pressure concentrations of the gripper frame.

The fruit handling of the stem shear non-selective harvester was poor at a maximum of 59%. The value represented the obvious damages right after testing and did not include internal damage analysis. Unfortunately, due to fruit storage confounding factors, the fruit handling performance of the combing non-selective harvester method result was inconclusive. However, with good padding, the fruit handling may have been near 92-93% based on test results with obvious damage.

5.4.3.5 Performance to Cost Ratio

Table 14 displayed the inputs for the cost-performance calculations. For the non-selective harvester, \$2,500-\$15,000 inputs were used. For the selective harvester, \$50,000-\$150,000 inputs were used. The cost-performance was also calculated for a selective harvester with no efficiency loss by approximating the harvesting rate as four times the single arm harvesting rate. The cost-performance was also calculated for the non-selective harvester assuming all fruit were caught (perfect picked-detached), and no fruit were damaged.

Table 15 revealed that the selective harvester had a cost-performance an order of magnitude greater than the non-selective harvester (Figure 74). Assuming a cost of \$5,000 for the non-selective harvester, the current cost-performance was \$28,939 per fruit/s. Assuming a \$125,000 cost for the selective harvester, the current cost-performance was \$446,293 per fruit/s which was much higher. If the non-selective harvester caught all fruit drops and had perfect handling, the cost-performance

would more than halve to \$12,771 per fruit/s. If the selective harvester was able to pick with no efficiency loss due to additional arms, the cost-performance would be \$132,951 per fruit/s.

Despite the excellent performance to cost ratio of the non-selective harvester, it was not economically viable due to fruit damage and the number of stems left on the fruit. The cost performance ratio of the selective harvester should be decreased significantly by increasing performance and decreasing cost. Improving the cost performance ratio would decrease the payback period of the selective harvester.

The picked-detached percentage could be maximised by including a catching system by turning fruit drops and knock-offs into picked fruit. The M5 gripper should be used due to its proven fruit handling performance. The speed of the robot should be as high as possible, however, it may be more practical and economical to use more, slower but cheaper robots, rather than less, faster but more expensive robots. This was because increasing the performance to near perfect was a greater challenge than decreasing the cost. For example, if the robot cost was halved, and the performance was not halved, the new cheaper but slower robot would still have a higher cost-performance ratio.

Cost reduction would be required to make more, slower robots economically viable. Like the Agrobot strawberry harvester, reducing the number of axis to 2 (third axis is the robot movement itself), and sharing an axis for multiple manipulators, plus adding many manipulators to a robot, can decrease the total robot cost and increase the performance to cost ratio greatly. Decrease in every part of the robot will also help to increase the performance to cost ratio.

5.5 Conclusion

The high fruit value to harvesting cost ratio forced any selective or non-selective harvester to have a successful picked-detached percentage of at least 95% for green fruit and 97% for gold fruit. The successful picked-detached percentage was the product of the picked-detached percentage, damage-free percentage, and stemless percentage.

Despite the high performance of the current selective harvester relative to other harvesters, the performance did not meet the breakeven requirements, so it was not

economically viable. However, the performance of the improved AKH was high with a picked-detached percentage, damage-free percentage, and stemless percentage of 86.4%, 100%, and 93.8%, respectively. With further development, the performance could likely meet the breakeven requirements.

The non-selective harvester had an extremely high harvesting speed potential, but the limitation was fruit handling and fruit with stems. A combing method had better performance than the stem-shear method as all the fruit that were dropped or knocked off were caught in a net and considered picked. Direct contact methods with the canopy were likely to damage more than 5% of fruit. Furthermore, many of the stems remained on which would have further damaged fruit. Without a rotate and snap motion, it was unlikely for fruit to be harvested without the stem. Therefore, it was unlikely that a non-selective harvester method would be viable unless it had excellent fruit handling and a secondary stem removal process.

Chapter 6: Future Kiwifruit Harvesters

6.1 Introduction

The objectives of this chapter were to define and discuss the barriers to economic viability. Recommendations were provided on the future direction of the selective and non-selective kiwifruit harvester developments. Possible robotic configurations with a high performance to cost ratio were discussed.

6.2 Barriers to Economic Viability

6.2.1 Fruit Value Ratio

The main barrier to success was the high fruit value ratio which was 16 times the total harvesting cost for green fruit, and 30 times for gold fruit. The fruit value ratio for the picker only cost was double this at 32 times for green fruit, and 60 times for gold fruit. The high fruit value forced near perfect breakeven performance requirements of robotic kiwifruit harvesters as each fruit loss was significant. The breakeven performance in terms of the successful picked-detached performance was 95% for green fruit, and 97% for gold fruit. Successful picked detached performance was the product of picked-detached percentage, damage-free percentage, and stemless percentage.

An increase in harvesting picker wages and decrease in the mean fruit mass had only a little effect on the breakeven requirements based on the results from chapter 5. The yield of gold kiwifruit will surpass Hayward kiwifruit soon making gold kiwifruit the most commonly grown kiwifruit. Gold kiwifruit were about 1.5-2 times more valuable than green kiwifruit based on historical data. Gold fruit were more susceptible to fruit damage so the fruit handling of the harvester must be even better.

This barrier could be overcome by improving the performance of the selective harvester to surpass the breakeven performance requirement. The picked-detached-ratio of the selective harvester could be increased by adding a catching system. This would turn all the fruit drops, throws, and knock-offs into picked fruit. Fruit loss could also be reduced by improving the gripper positioning, dexterity, and harvest scheduling. The breakeven performance requirement could be decreased a few

percent by a lower OGR, a smaller mean fruit mass and increased picker wages. These changes would decrease the fruit value ratio which would decrease the breakeven performance requirement.

For the non-selective harvester, the focus should be on the fruit handling during detachment. A soft planar catching system very close to the canopy could catch most of the fruit without damage. A secondary stem removing process would be necessary as harvesting without a rotate and pull action cannot consistently harvest fruit without stems.

6.2.2 Reachability

The second barrier was the reachability in an orchard. The reachability in an orchard will likely never achieve 100% because there were almost always fruit in hard to reach positions, even for human pickers. The consequence of this was that clean-up human picker crews will be required to pick the remaining fruit in the canopy because the fruit have high value. Furthermore, the KVH stated that all fruit must be removed by the 1st of July each year. As the picker's wages only made up half of the total harvesting costs, the other overheads costs were still required for the clean-up human picker groups. The harvesting robot typically picked the easier reachable fruit so the remaining fruit left were more difficult to pick. With decreased reachability, the efficiency of the clean-up pickers was also decreased. The harvesting speed was decreased as fruit were further apart with low reachability.

Deliberate orchard management could increase reachability to over 90%. Furthermore, using experienced pickers for picking the remaining fruit could reduce the efficiency loss of the clean-up crew. If the reachability was near 100%, pickers could be instructed to pick and drop fruit on the ground to avoid the overhead costs, as all fruit must be removed.

6.2.3 Harvesting Speed

The harvesting rate needed to be increased. The robot harvesting speed requirement was defined as the equivalent to human workers such that from a grower's perspective, the fruit were harvested in the same amount of time. The 23.2 fruit/s speed requirement was the equivalent picking rate of twenty pickers as found in a typical picking group. If each manipulator could pick at the individual arm

harvesting rate of 3.31 s/fruit, then 77 manipulators would be required assuming no efficiency loss with an increasing number of manipulators. During lab testing with one arm in a two-fruit cluster case, the arm was able to harvest with a cycle time of 2 s/fruit. Based on this value, 47 manipulators would still be required. Due to the high number of manipulators, it was unlikely for one robot platform to meet the requirements. Therefore, several robots each with many manipulators would be required. With increasing number of manipulators per robot, the efficiency of each manipulator decreased. Therefore, the number of manipulators required would be even higher.

The high-speed requirement was reduced because the robotic harvester could run 24/7 with no breaks and loss of harvesting rate. If the selective harvesters could pick 24/7, then it could pick three times a normal 8-hour shift. Picking for triple the time allowed the harvester to have a third of the harvesting speed requirement, to harvest the same amount of fruit in the same effective time. For example, if a selective harvester harvested for triple the time, it would be required to only harvest at 7.73 fruit/s which was a third of the 23.2 fruit/s rate of a 20-picker crew. This would reduce the number of manipulators required to only a third which was 26 and 16 manipulators based on manipulator cycles times of 3.31 s/fruit and 2 s/fruit. Fruit were unable to be harvested when there was moisture on the fruit as wet fruit had a higher risk for bacterial and fungal infection. Therefore, the weather could limit the ability of the harvester to pick fruit continuously. A study on selective harvesting of tomatoes stated that it would require 8 robots each with one manipulator and cycle time of 3 s/fruit to harvest 2 hectares of tomatoes (Gieling, Van Henten, Van Os, Sakaue, & Hendrix, 1996). The differences between tomatoes and kiwifruit however, was the growing structure and yield, and that kiwifruit were harvested all at once.

For the non-selective harvester, the harvesting speed was not an issue because a scaled-up version could easily surpass the speed requirements.

6.2.4 Cost

The cost of the current harvesters was a barrier because the harvester must be profitable for it be used. If the breakeven performance was met but the machine was too expensive, then the payback period may be too long. It was likely that several

robot platforms each with several manipulators were required to meet the collective harvesting rate requirement of a 20-picker group. The cost of each manipulator and platform, and the associated costs with the vision system must also be minimised. It may be more cost-effective to use a greater number of less expensive robots with lower speeds than to use a lower number of more expensive robots with higher speeds. The cost performance ratio should be used to compare different robotic configurations.

The harvester unit was only used for 3 months during the year for the harvesting seasons. This increased the payback period as it was unused during the non-harvesting seasons. If the harvester was sent overseas to China, Italy, or Chile for their harvesting seasons to utilise the harvester year-round, the payback period could be decreased significantly.

6.3 Assistance Factors to Economic Viability

The greatest economic viability assistance factor was the long-term labour shortage coupled with a growing kiwifruit industry. A temporary worker shortage of 1,200 during 2018 was declared by the (NZ MSD, 2018). It was expected to get worse over the next decade with an additional 7,000 seasonal workers required by 2027 (NZKGI, 2018). Regardless of the cost of picking labour, without picking the fruit, the grower has no orchard gate returns and has a net loss. The advantage of robotic harvesters was labour security and performance predictability. Growers could know with confidence that fruit would be able to be harvested when required.

6.4 Robotic Configurations

A robotic configuration consisted of a platform and robotic manipulators. The manipulator was the part of the robot that moved the end-effector into position. The manipulators were fixed to the platform. Examples of manipulators included cartesian robots, articulated robot arms, SCARA robots, and delta robots. The AKH used four articulated robotic arms as the manipulators.

The performance-to-cost ratio of robotic selective harvester configurations were explored to find the optimum number of manipulators per robot. The optimal number of manipulators per robot based on the efficiency loss of the robot per extra manipulator was determined. Configurations with good workload sharing could achieve minimal efficiency losses whereas poor configurations could not utilise the

harvesting capacity of each manipulator. Several configurations were discussed based on improvement to the performance-to-cost ratio.

Achieving a near perfect success-detached percentage typically required high cost for high performance. The current breakeven performance requirement only specified the success-picked-detached performance of the harvester. The configuration of the robot group was determined by the equivalent harvesting speed of a 20 human picker crew of 23.2 fruit/s. Assuming a manipulator harvesting cycle time of 3 s (hence 0.33 fruit/s), there would need to be 70 manipulators. Assuming 10 manipulators per robot and no efficiency loss, 7 robots were required.

If the efficiency loss on the whole robot per manipulator was low, it was best to fit as many manipulators per robot as practically possible. Otherwise, it was better to stick with a one-manipulator per robot for high efficiency losses.

To reduce the total robotic fleet cost, the number of manipulators per robot platform should be maximised, provided that the manipulators do not lose efficiency. When there was more than one manipulator per platform, then the platform cost was shared between the manipulators, decreasing the total cost of the fleet relative to a one manipulator per robot configuration. However, if the efficiency loss on the overall robot was very high, then a one manipulator per robot configuration had the highest performance to cost ratio. If the efficiency loss for additional manipulators was very low, then adding more manipulators per platform was desirable.

The optimal robotic configuration was dependent on both the cost of the manipulator and the platform. It is also dependent on the efficiency loss per extra manipulator. As the cost of the platform relative to each manipulator increased, it become increasingly desirable to add more manipulators per platform. However, if the platform cost relative to the manipulator cost was small, then single manipulator robots were ideal. The actual optimal robotic configuration was dependent on actual costs and efficiency loss.

The current harvesting unit configuration has poor workload sharing resulting in huge efficiency losses. For the current performance and costs used, a 1-2 articulated arm manipulator per robot would be ideal.

Performance increase and cost reduction would both increase the performance to cost ratio. To reduce the cost of the robotics system, it may be favourable to remove the platform altogether, and put a permanent guide railing system on kiwifruit orchards. This would initially have a high upfront capital cost, but this cost could be spread over multiple orchard processes. Spraying, thinning, pruning, harvesting, counting, moving could all utilise the guide system which could reduce the payback period significantly. By adding a guide system, the cost of the harvesting fleet would be mostly dependent on the manipulator cost. This was evident in current greenhouse harvesters where there were already guide rails in the form of heating pipes on the ground.

The AMMP platform had a similar advantage to guide rails but the additional advantage was that it could be used in any orchard for a variety of applications. Standalone platforms could be put in any compatible growing environment, so it did not require a high capital cost per growing farm. The drawback was that the autonomous navigation must be robust such that it could deal orchard variability.

A similar method of reducing costs could be to combine the manipulator and platform actuators such that they are one and the same. A fleet of one-manipulator robots could be used to maximise efficiency per manipulator.

Other methods include fitting as many manipulators as practical onto a platform and sharing manipulator axes. For example, the Agrobot strawberry harvester utilises twenty-four manipulators per platform. The manipulators also only have two DOF as the forward motion of the platform provides the third DOF. Furthermore, every four manipulators share the same guide rail DOF. Therefore, the Agrobot could maximise the number of manipulators whilst reducing cost per manipulator.

Figure 75 showed a possible kiwifruit harvester configuration with 72 manipulators. This concept could only work if the individual manipulator cost was kept very low. With a large number of manipulators, there were expected high efficiency losses but due to the low cost of each manipulator, the effect would be less significant.

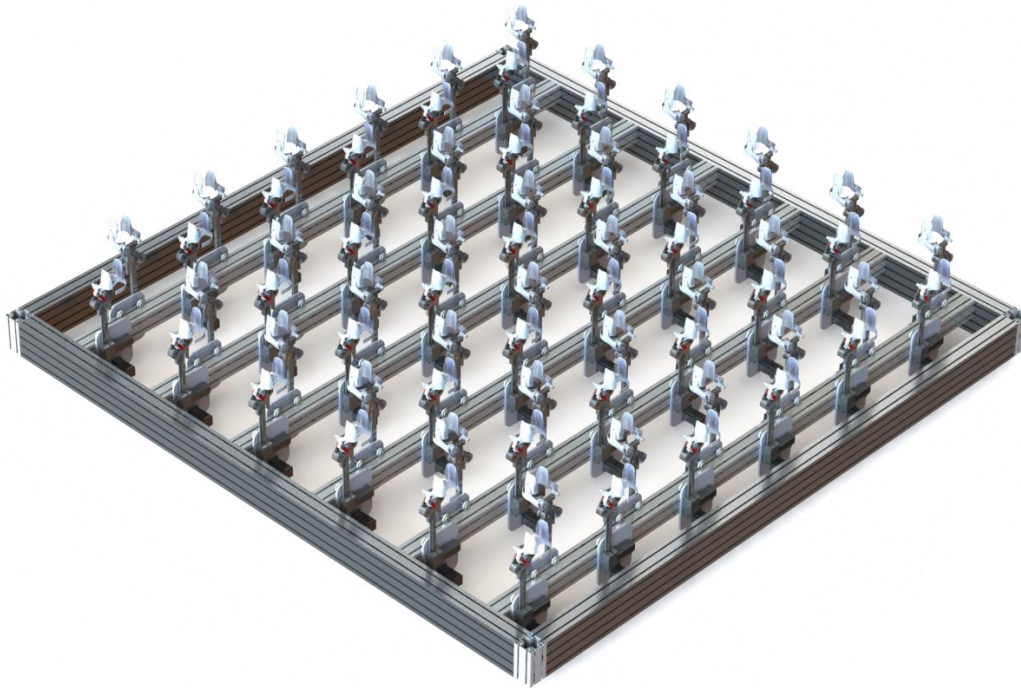


Figure 75: Kiwifruit harvester 72-manipulator configuration

6.5 Conclusions

The main barrier to economic viability was the fruit value ratio which forced a high breakeven performance requirement of the harvester. The reachability of the robot was a barrier because clean-up pickers were required. The robot reachability could increase with improved orchard management. Clean-up pickers had reduced efficiency when there were less fruit left in the canopy. As the harvesting picker harvesting cost was only half the total harvesting cost, the overhead costs associated with harvesting still had to be paid. The high harvesting speed requirement was reduced in proportion to the time the harvester was used during a 24-hour period. The cost performance ratio must be considered during comparisons. The greatest assistance factor was the labour shortage itself. The optimal number of manipulators per robot depended on the platform and manipulator costs, and the relative costs between them. It is also dependent on the efficiency loss per extra manipulator.

Chapter 7: Conclusion

7.1 Selective Harvester

New end-effector grippers were developed to reduce fruit loss. Lab testing revealed that the Flexi gripper had best performance but during orchard testing it did not perform well. Single-arm manipulator tests revealed that an arm was able to pick at 3.31 s/fruit. The new grippers and vision software were able to halve the 2017 cycle time from 5.37 s/fruit to 2.78 s/fruit and increase the picked-detached percentage from 67.4% to 86.4%. The highest success-detached percentage was 89.2% with the M6 gripper. The new selective harvester picked 93.8% of fruit without stems and had a perfect fruit handling performance of 100%. The robot was unable to utilise the full harvest capacity of each arm due to poor manipulator workload sharing because of the robot configuration. The addition of 3 arms decreased the cycle time by only 17% compared to a single arm. Recommendations included increasing reachability, investigating alternative robot-manipulator configurations through simulation, and reduction of fruit loss. Fruit loss could be reduced by improving the gripper positioning, dexterity, harvest scheduling, and adding a catching system.

7.2 Non-selective Harvester

A non-selective harvester concept was designed, built, and testing on the lab and in the orchard. Approximately 37% to 42% of the fruit in a kiwifruit bay were reachable with the current orchard management. To increase reachability, the harvester had to be pushed up against the canopy which increased interference. The stem-shear harvesting method performed quite poorly because fruit had to be at a target position for it to be effective, which was rarely the case. Testing showed that it could only pick a small number of detached fruit intentionally whereas the rest of the detached fruit were knocked off. Furthermore, the design often caused fruit to be impacted by the stem shearing part which caused a minimum of 41% of fruit to be damaged. Of the detached fruit, 67.5% were stemless.

An alternative combing method was tested and was much more effective. The reachability was 40% of the fruit in a kiwifruit bay and 66.8% of the fruit detached were combed by the cane deflector. The rest were knocked off or dropped.

However, those fruit were caught with a net. The combing method picked 43% of the fruit without stems. Fruit handling results showed that fruit harvested at the stem detachment area had 8% obvious fruit damage based on tests on softer fruit. The results showed that combing of the kiwifruit canopy with a well-padded combing device and catching surface had potential. A catching surface close to the canopy was required to catch all the fruit. Any new attempt at non-selective harvesting of kiwifruit must focus on fruit handling during detachment.

7.3 Comparison for Economic Viability

The current selective and non-selective harvesters were not economically viable. The main challenge to kiwifruit harvesting was the high value ratio which forced any kiwifruit harvester to have a near perfect breakeven picked-detached performance of 95% for green and 97% for gold kiwifruit.

The selective harvester did not meet the breakeven performance requirement despite its high performance relative to other harvesters. Furthermore, the current high cost of the robot coupled with the poor workload sharing between manipulators reduced the total effective harvesting rate. However, the performance of the improved AKH was still high with a picked-detached percentage, damage-free percentage, and stemless percentage of 86.4%, 100%, and 93.8%. With further development, the selective harvester could reach the breakeven performance.

Despite the high harvesting speed potential of a non-selective harvester, it was unlikely to meet the breakeven performance requirement due to fruit handling and fruit with stems. It was unlikely that a non-selective harvester method would be viable unless it had excellent fruit handling and a secondary stem removal operation.

7.4 Future Kiwifruit Harvesters

The greatest assistance factor to economic viability was the labour shortage itself coupled with the growing kiwifruit industry. The main barriers to economic viability were the fruit value ratio, reachability, harvesting speed, and cost. The fruit value ratio caused a high breakeven performance requirement. Due to the reachability of the robot, clean-up pickers were required. The picker cost was only half of the harvesting cost, so the overhead costs associated with the pickers were still required. Furthermore, their efficiency decreased with less fruit in the canopy.

The harvesting speed requirement was high due to the human picker speed. However, the robot requirement may be lower in proportion to the picking time relative to human pickers. The cost performance ratio was of great importance in the comparison between robotic harvester configurations. The optimal robotic configurations were determined by the cost of the platform and manipulators, and the efficiency loss on the whole system with each additional manipulator. If the efficiency loss was low, it was better to add only a few manipulators per robot. If the efficiency loss was high, maximising the number of manipulators per robot was ideal. However, if the efficiency loss was high, then minimising the manipulator number per robot would be optimal.

7.5 Recommendations

Several recommendations were made in the order of importance. The first recommendation was to improve the success picked-detached percentage by reducing fruit loss, improving fruit handling, and improving stem detachment. For fruit loss, a catching system would have the greatest benefit because it could turn all the fruit loss into picked fruit. The catching system should be as close to the canopy as possible to reduce the drop height. Fruit loss could also be reduced by additional degrees of freedom and sensing of the fruit pose. Fruit handling could be improved by removing pressure concentrations and using an even softer grade of silicone. Stem-detachment could be improved by a better snapping action. A higher gripper compression force with good fruit positioning could improve the stem-detachment.

The second recommendation was to improve the cost performance ratio. The performance could be improved greatly by minimising efficiency loss of each manipulator through robot configuration design. The cost of each platform and manipulator should be minimised. Lower cost components with the same performance should be used. It may be better to use a greater number of lower cost and low performance manipulators than a lower number of higher cost and high-performance manipulators. For example, if a new manipulator was a tenth of the current cost but five times slower, the cost performance ratio would still be double the current performance. Cost reduction could include removing the platform and installing a permanent guide, reducing the manipulator DOF, sharing DOF

hardware, fitting as many manipulators per platform, and positioning actuators away from the payload to decrease actuator requirements.

The third recommendation was to simplify the task which was recommended by (Bac et al., 2014). The task could be simplified by increasing reachability by training the vine to have most of the fruit below the wire.

The fourth recommendation was to reduce the speed requirement of the robot by allowing it to pick continuously, even in bad weather. By allowing it pick continuous for 24 hours, the harvesting rate requirement would only be a third of the requirement. Currently kiwifruit cannot be picked unless dry to reduce post-harvest losses. Investigation into kiwifruit drying methods before, during, or after picking would be beneficial.

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Appendices

Appendix A – Individual Dataset Gripper Fruit Handling Results

Table 16: Gripper fruit handling detailed results

Dataset #	Fruit Pick Date (day/month)	Fruit Process Date	Hold Duration (days)	Fruit firmness (N)	Gripper	Pressure (bar)	# Fruit Damaged	Total Fruit Tested	Fruit Damaged (%)					
1	2/06	24/06	22	68.3 +/- 3.2	Control	0	3	40	8					
					M5	2.5	2	20	10					
						3	1	20	5					
						3.5	1	20	5					
						4	2	20	10					
												Average	8	
					M6	2.5	0	20	0					
						3	5	20	25					
						3.5	2	20	10					
						4	2	20	10					
												Average	11	
					2	10/06	9/07	29	(60.5 +/- 8)	Control	0	2	20	10
										M5	2.5	0	10	0
											3	0	10	0
3.5	0	10	0											
4	1	10	10											
										Average	4			
M6	2.5	1	10	10										
	3	0	10	0										
	3.5	1	10	10										
	4	1	10	10										
							Average	8						

3	13/06	9/07	26	(60.5 +/- 8)	Control	0	2	20	10					
					M5	2.5	0	10	0					
						3	0	10	0					
						3.5	0	10	0					
						4	0	10	0					
									Average				2	
					M6	2.5	1	10	10					
						3	1	10	10					
						3.5	0	10	0					
						4	1	10	10					
									Average				11	
					4	16/06	16/07	30	50.8 +/- 7.5	Control	0	0	20	0
										M5	2.5	0	10	0
											3	0	10	0
3.5	0	10	0											
4	0	10	0											
				Average									0	
M6	2.5	0	10	0										
	3	1	10	10										
	3.5	1	10	10										
	4	2	10	20										
				Average									8	
5	5/07	27/07	22	(26.2 +/- 4.9)						Control	0	0	10	0
										M4	3	2	30	7
											4	3	30	10
					5	2	30	7						
									Average				6	

Note: Firmness values in brackets were not direct measurements

The 60.5 +/- 8 N firmness value was measured on 16/06

The 26.2 +/- 4.9 N firmness value was measured on 04/07