Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.

An Integrated Modelling Approach to Inform Package Design for Optimal Cooling of Horticultural Produce

A thesis presented in partial fulfilment of the requirements for the degree of

Doctor of Philosophy

in

Food Technology

at Massey University, Palmerston North, New Zealand

Jamal Rimkeit Olatunji

2018

Abstract

Forced-air cooling is a widely used pre-cooling process that enables the New Zealand horticultural industry, valued at over NZD $8B in 2016, to maintain the quality of perishable exports. In the typical systems used in New Zealand's horticultural industry, forced-air cooling involves stacking fruit boxes into pallets, which are stacked together in a refrigerated room, and a fan is used to create a pressure drop through the pallets. This forces cold air through the packaging ventilation and over the fruit, facilitating heat transfer and rapidly cooling the product from the field heat (~20 °C) to the storage temperature (0-2 °C), thus prolonging shelf life and preserving fruit quality.

Package design is linked with cooling performance, as the specifics of the ventilation (i.e. placement and size of vents in the boxes) results in different airflow patterns. Unfortunately, it is not well understood how to predict the performance of a hypothetical design, which is partly why in industry and academia there has been a focus on package design testing – where through experimental or computational means, the performance of a given design is thoroughly tested. Trial-and-error experimental work represents a steep materials cost, and construction and validation of detailed mathematical models can be a highly arduous and specialised task. It would therefore be beneficial to the New Zealand horticulture industry and academia to have a suite of methodologies that can simply and rapidly predict performance of a hypothetical package design. It was proposed that such methods are based upon mathematical modelling, with a focus on flexibility, computational efficiency, and automation. The goal is that such a model can be used to rapidly develop mathematical descriptions of a wide variety of products and cooling scenarios, and if integrated with optimisation routines, will allow swift iteration toward an optimised design.

To meet this goal a new interpretation of the zonal modelling approach was developed and validated at the single box scale for the forced-air cooling of modular bulk packages of polylined kiwifruit – kiwifruit representing the largest horticultural crop in New Zealand (worth NZD $1.7B in 2016). The model focused on developing a simplified heat transfer model, with airflow considerations being a separate research project. The model is fast – with heat transfer solution times on the order of 1-2

seconds; flexible – as the model will solve for any input geometry; and automated – as the model was capable of algorithmically generating the zonal network, requiring no manual input beyond initial configuration settings.

A random stacking model was also developed to complement the heat transfer model. This is capable of automatically generating a realistic bulk fruit geometry inside of any package size or shape in only 150 seconds, relying on only a shape equation for kiwifruit and a weight distribution index as inputs. The stacking model can also simulate the presence of a polyliner wrapping, which is used in many horticultural packaging systems, including for many kiwifruit systems. The model was validated against empirically measured bulk fruit shapes, collected via CT scanning. The random stacking model increased the flexibility of the methodology and opened up the design space considerably for building models of a wide variety of package designs and products, without requiring physical prototypes or requiring "idealised" packaging configurations. The stacking model has an added functionality of predicting the volumetric efficiency of different package types.

Cooling uniformity was identified as a key performance metric for the forced-air cooling process. The airflow pattern imposes a range of rates of cooling for different fruit positions throughout the same pallet. This can have large impacts on the quality and shelf-life of individual fruit, which causes significant logistical problems for pack-house/product managers. A new quantitative heterogeneity index was developed, capable of condensing total process heterogeneity into one dimensionless number, the Overall Heterogeneity Index, or OHI.

This suite of tools can be used for a variety of tasks. Although the modelling work was only applied to the forced-air cooling of polylined kiwifruit inside of modular bulk packages, building models for other crops, package designs and cooling scenarios is trivial to implement. The speed of the zonal heat transfer model makes it ideal for integration with an iterative optimisation routine, so that many hundreds or thousands of designs can be investigated in a short period of time. The heat transfer model could also be combined with a machine learning algorithm (such as a genetic algorithm) to iteratively approach an optimised design. However, such an implementation requires an equally fast and flexible pallet scale airflow model, which remains a task for further work.

Acknowledgements

Thanks to my supervisors Dr. Richard Love (chief supervisor), Prof. Andrew East (co-supervisor) and Dr. Young-Min Shim (co-supervisor) for their technical, moral and professional help during my years of study. Thanks to Prof. John Bronlund, who saw potential in me as an undergraduate and convinced me to pursue my doctorate; and Dr. Maria Ferrua who co-supervised at the beginning of the project.

A huge thank you to industrial partners OJI Fibre Solutions and Zespri International who provided vital material and financial support.

Thanks to students Alicia Tan, Lyall McDonald, Julia Zhou, Angela Yang and Tim Cook for their help collecting experimental data. The volume of information collected would not have been possible without your assistance. Integral experimental equipment that made the pallet scale experiments possible were inherited from work done by Dr. Justin O'Sullivan, so a great deal of thanks to him too.

Also thanks to Nicki Moffat for allowing us to use your departments CT scanning equipment.

This PhD was the result of funding from the New Zealand Ministry of Business, Innovation and Employment (Fibreboard Packaging Design Project, MAUX1302).

This thesis is dedicated to my parents and their incredible journey.

Table of Contents

Abstract i

Acknowledgements iii

List of Tables xiv

List of Figures xv

Nomenclature xxxvii

1 Introduction and Literature Review 1

1.1: Background and Context 1

1.2: Literature Review 3

- 1.2.1: New Zealand Export Industry 3
- 1.2.2: Pre-Cooling Operations 6
  - 1.2.2.1: Room Cooling 6
  - 1.2.2.2: Forced-Air Cooling 8
  - 1.2.2.3: Other Pre-Cooling Operations 10
- 1.2.3: Package Design 11
  - 1.2.3.1: Definition of Cooling Performance 11
  - 1.2.3.2: Vent Size 13
  - 1.2.3.3: Vent Number 14
  - 1.2.3.4: Vent Shape 15
  - 1.2.3.5: Package Orientation 15

1.2.4: Heat and Mass Transfer Mechanisms 17

1.2.4.1: Conduction Heat Transfer 17

1.2.4.2: Convection Heat Transfer 18

1.2.4.3: Mass Transfer and Evaporative Heat Transfer 20

1.2.4.4: Radiation Heat Transfer 21

1.2.5: Mathematical Modelling Considerations 22

1.2.5.1: Important Model Variables 23

1.2.5.2: Direct Numerical Simulation 25

1.2.5.3: Porous Media Approach 27

1.2.5.4: Zonal Approach 29

1.2.6: Literature Summary 31

2 Research Objectives 33

3 Empirical Forced-Air Cooling Performance 34

3.1: Introduction 34

3.2: Development of a New Temperature Heterogeneity Index 34

3.2.1: Introduction 34

3.2.2: Dimensionless Units 36

3.2.2.1: Dimensionless Temperature Change 36

3.2.2.2: Characteristic Index of Process Progression 37

3.2.3: Heterogeneity 38

3.2.3.1: Heterogeneity at Single Points in Time 39

3.2.3.2: Heterogeneity over Time 42

3.2.3.2.1: Visualising Heterogeneity over Time 42

3.2.3.2.2: Quantifying Heterogeneity over Time 44

3.3: Performance Impact on Operational Changes During Pre-Cooling 48

3.3.1: Introduction 48

3.3.2: Objectives 49

3.3.3: Materials and Methods 49

3.3.3.1: Laboratory Scale Pre-Cooler 49

3.3.3.2: Temperature Measurement 52

3.3.3.3: Pressure Measurement 59

3.3.3.4: Changes in Key Variables Affecting Performance 60

3.3.4: Results and Discussion 64

3.3.4.1: Experimental Results 64

3.3.4.2: Impact on Cooling Rate 66

3.3.4.2.1: Cooling Rate Impact of Pressure Drop 67

3.3.4.2.2: Cooling Rate Impact of Decreasing Vent Size 68

3.3.4.2.3: Cooling Rate Impact of Increasing Vent Size 68

3.3.4.2.4: Cooling Rate Impact of Changing Vent Number 69

3.3.4.3: Impact on Heterogeneity 71

3.3.4.3.1: Shortcomings of the Relative Standard Deviation 71

3.3.4.3.2: Application of the New Heterogeneity Index 73

3.3.4.3.3: Heterogeneity Impact of Pressure Drop 78

3.3.4.3.4: Heterogeneity Impact of Decreasing Vent Size 79

3.3.4.3.5: Heterogeneity Impact of Increasing Vent Size 80

3.3.4.3.6: Heterogeneity Impact of Changing Vent Number 80

3.3.5: Conclusions 81

3.4: Single Box Cooling Validation Data 83

3.4.1: Introduction 83

3.4.2: Materials and Methods 83

3.4.3: Results and Discussion 85

4 Bulk Fruit Geometry 88

4.1: Introduction 88

4.2: X-Ray Tomography of Bulk Fruit Shape 88

4.2.1: Introduction to X-ray tomography 88

4.2.2: Raw CT Data Collection 91

4.2.3: CT Scan Data Processing 92

4.2.4: CT Scanning Results 104

4.3: Kiwifruit Shape Equation 105

4.3.1: Development of Kiwifruit Shape Equation 105

4.3.1.1: Lateral Profile 109

4.3.1.2: Longitudinal Profiles 110

4.3.2: Application of Shape Equation 116

4.3.2.1: Volume and Surface Area 116

4.3.2.2: CAD Software 118

4.3.3: Natural Size Variability 122

4.3.3.1: Empirical Weight Distribution 122

4.3.3.2: Shape Index 126

4.4: Random Stacking Model 133

4.4.1: Chute Creation 136

4.4.2: Fruit Creation 138

4.4.3: Gravity and Rigid Body Dynamics Simulation 143

4.4.4: Elimination of Overfill 152

4.4.5: Polyliner Creation 155

4.5: Validation of Random Stacking Model 164

4.5.1: Position of Individual Fruits 164

4.5.2: Manually Stacked Package 167

4.5.3: Randomly Stacked Package 172

4.6: Conclusions 177

5 Model Development 179

5.1: Introduction 179

5.2: Direct Numerical Simulation 179

5.2.1: Model Geometry 180

5.3: Transport Mechanisms 184

- 5.3.1: Conduction 184
- 5.3.2: Convection 185
  - 5.3.2.1: Forced Convection 185
  - 5.3.2.2: Natural Convection 189
- 5.3.3: Direct Contact Between Fruit and Polyliner 192
- 5.3.4: Respiration ` 194
- 5.3.5: Evaporation, Condensation and Diffusion 196
- 5.3.6: Thermal Radiation 197

5.4: Thermophysical Properties 199

5.5: Zonal Model Development 201

- 5.5.1: Introduction 201
- 5.5.2: General Description of a Zonal System 203
- 5.5.3: Formulation of Heat and Mass Transfer Equations 207
- 5.5.4: Voxelisation 212
- 5.5.5: Zoning Procedure 218
- 5.5.6: Zone Builder 223
  - 5.5.6.1: Geometric Procedures for Intra-Zonal Properties 226
    - 5.5.6.1.1: Volume 226
    - 5.5.6.1.2: Heat Transfer Surface Area 227
    - 5.5.6.1.3: Conduction: Average Voxel Distance Calculator 229
    - 5.5.6.1.4: Natural Convection 246

5.5.6.1.5: Forced Convection 253

5.5.6.2: Inter-Zonal Properties 254

5.5.6.2.1: Heat Transfer Surface Area 254

5.5.6.2.2: Conduction 255

5.5.6.2.3: Natural Convection 266

5.5.6.2.4: Airflow 266

5.5.7: Zone Solver 268

5.5.8: Overall Model Structure 271

5.6: Conclusions 272

6 Model Validation 274

6.1: Introduction 274

6.2: Numerical Validation 274

6.2.1: Introduction 274

6.2.2: Validation of Intra-Zonal Geometric Procedures 275

6.2.3: Validation of Zonal Network 287

6.2.3.1: Introduction 287

6.2.3.2: Validation of Single Box Zonal Network 287

6.3: Experimental Validation 300

6.3.1: Introduction 300

6.3.2: Airflow Model (Computational Fluid Dynamics) 302

6.3.3: External Heat Transfer Coefficient Correlation 310

6.3.4: Characteristic Dimension of Bulk Air Phase 312

6.3.5: Experimental Validation Model Set-Up 313

6.3.6: Results and Discussion 317

6.3.6.1: Preliminary $\mathrm{Nu} = f(\mathrm{Pr}, \mathrm{Re})$ correlation 317

6.3.6.2: Derivation of New Airflow Correlation 322

6.3.7: Zonal Resolution 329

6.3.8: Conclusions 333

7 Conclusions and Discussion 335

7.1: Conclusions 335

7.2: Research Outputs 336

7.2.1: New Heterogeneity Index 336

7.2.2: New Interpretation of a Zonal Modelling Approach 336

7.2.3: Random Stacking Model 337

7.3: Potential Model Applications 338

7.3.1: Iterative Vent Optimization 338

7.3.2: Rapid Model Development 350

7.3.3: Package Design 353

7.4: Challenges and Data Sets Required 357

7.5: Recommendations 359

References 361

Appendix A Experimental Cooling Results 378

A.1: Introduction 378

A.2: Cooling Profiles 379

A.3: Heterogeneity Plots 383

A.4: Heterogeneity Maps 385

A.5: Validation of Representative Skew-Normal Distributions 387

Appendix B Additional Heat and Mass Transfer Mechanisms 396

B.1: Introduction 396

B.2: Formulation of Mass Transfer Equations 396

B.3: Intra-Zonal Radiation 397

B.4: Intra-Zonal Evaporation 398

B.5: Intra-Zonal Diffusion 400

B.6: Inter-Zonal Diffusion 401

B.7: Inter-Zonal Radiation 402

List of Tables

Table 3.1: Shape of the temperature distribution at the end of the cooling process (SECT), as representative shape (α), scale (ω) and location (ξ) values. 78

Table 4.1: Minimum, average and maximum dimensions of count 36 Hayward kiwifruit, according to Anonymous (1997) and Figure 4.13. 127

Table 4.2: Stacking simulation parameters 149

Table 5.1: Summary of thermophysical properties used in modelling activity 200

Table 5.2: List of intra-zone heat and mass transport mechanisms that can occur within a zonal system. S = fruit phase, A = air inside the polyliner phase, P = packaging phase, O = bulk air (outside the polyliner) phase. 210

Table 5.3: List of inter-zone heat and mass transport mechanisms that can occur within a zonal system. S = fruit phase, A = air inside the polyliner phase, P = packaging phase, O = bulk air (outside the polyliner) phase. 211

Table 5.4: Thermal properties and initial conditions used to calculate the porous media modified Rayleigh number. 252

Table 6.1: Measured initial temperatures and refrigeration temperatures 317

Table 7.1: Limits imposed on the random selection of vent size, shape and position variables within the Monte-Carlo loop. 340

Table A.1: Vent number, ventilation total opening area and pressure drop of each experiment. 378

List of Figures

Figure 1.1: Exports from New Zealand to international markets over 2016-2017. Colours represent export values in NZD $ millions. This work is based on/includes Statistics NZ (2017b) data, which are licensed by Statistics NZ for re-use under the Creative Commons Attribution 4.0 International licence. 5

Figure 1.2: Static or room cooler for horticultural produce. Evaporator fans circulate refrigerated air around the room. 7

Figure 1.3: A tunnel cooler, a common forced-air cooling device. Pallets of horticultural produce are stacked into two rows and covered with a tarpaulin, where a fan is used to create a vacuum in the cavity to draw refrigerated air through the ventilation in the palletised produce, facilitating cooling. Pallet length is illustrative – real systems are typically 10 or more pallets long. 8

Figure 1.4: Half-cooling time vs opening vent ratio. As the vent ratio increases the half-cooling time improves at a diminishing rate. Figure based on de Castro et al., 2005. 13

Figure 1.5: Zespri® Modular Loose pallet configurations for international export: 10 packages per layer with a pallet base of 1.2m × 1m, orientated with a 4 box row and two 3 box rows, with either a.) the 4 box row to the side or b.) in the middle. 16

Figure 1.6: An example based on Sargent et al. (2007) of improved vent placement. This vent and pallet orientation allows for the maximum number of interactions between individual packages as air flows through the pallet structure as a whole. 17

Figure 1.7: The mathematical modelling process. Image based on Cheng, 2001 22

Figure 1.8: Cause and effect diagram (Ishikawa, 1982) for the forced-air cooling of polylined, palletised kiwifruit. 23

Figure 1.9: The zonal approach, with examples of the zone and zone boundary numbering and coding system. Based on Tanner et al., 2002a. 29

Figure 3.1: a.) Potential heterogeneity at a single instant in time, using a Gaussian distribution; b.) potential heterogeneity at a single instant in time modelled using a Skew-Normal distribution, to account for non-normal distributions of ΔY. 40

Figure 3.2: Idealised heterogeneity plots, plotting ΔY for each individual product against Y, for four theoretical systems: a.) System A, with a normal distribution of hot and cold spots, and a high level of heterogeneity; b.) System B, with a normal distribution of hot and cold spots, and a lower level of heterogeneity; c.) System C, with skewness-over-time behaviour, and; d.) System D with a short intermediary warming period, making Y an inappropriate process progression index. 43

Figure 3.3: Idealised heterogeneity plots, plotting ΔY for each individual product against τ for four theoretical systems: a.) System A, with a normal distribution of hot and cold spots, and a high level of heterogeneity; b.) System B, with a normal distribution of hot and cold spots, and a low level of heterogeneity; c.) System C, with skewness-over-time behaviour, and; d). System D, with a short intermediary warming period, making τ the appropriate process progression index. 44

Figure 3.4: Idealised heterogeneity maps. 3D heterogeneity maps (a and c) plot ΔY on the Z-axis, while the 2D heterogeneity maps (b and d) displays ΔY as a colour spectrum. a and b use Y as the process progression index, while c and d use τ. 45

Figure 3.5: Idealised heterogeneity maps of three hypothetical systems with varying levels of process heterogeneity: a.) a system with perfect temperature uniformity (OHI = 0); b.) a system with a low level of heterogeneity (OHI = 0.05); a system with a high level of heterogeneity (OHI = 0.1). 46

Figure 3.6:The laboratory forced-air cooling tunnel, consisting of an airflow screen, wind tunnel and variable speed drive fan. 51

Figure 3.7: Laboratory forced-air cooling tunnel set-up: 50 boxes of kiwifruit stacked into a pallet, connected to a VSD fan. 14 boxes were instrumented: 7 in layer B (highlighted in red) and 7 in layer D (highlighted in green). 52

Figure 3.8: Kiwifruit stacked into a repeatable pattern, consisting of 4 distinct layers of fruit, used during all experiments. 54

Figure 3.9: Experimental kiwifruit instrumentation: a.) Type-T thermocouples were inserted into the centre of a select number of kiwifruit; b and c.) fruit were stacked into a repeatable pattern to ensure thermocouples were placed in the same position for each trial. 55

Figure 3.10: Two sample sizes: a.) 12% sample size, and; b.) 16% sample size. Kiwifruit highlighted in red were instrumented with a type-T thermocouple. 57

Figure 3.11: Photos of experimental equipment: a.) the wind tunnel with kiwifruit boxes half-way through instrumentation; b.) a fully instrumented wind tunnel; c.) the airflow screen being attached to the wind tunnel; d.) the wind tunnel being attached to the VSD. 58

Figure 3.12: Pressure measurement positions in the laboratory tunnel pre-cooler. 59

Figure 3.13: Package and ventilation dimensions of the 7 package designs fabricated and tested during this experiment. 60

Figure 3.14: The 9 unique operational conditions tested, compared with the baseline package CP1 (7.5% TOA distributed over 2 vents, 130 Pa pressure drop). 61

Figure 3.15: A comparison chart, illustrating the direct comparisons between the 9 unique operational conditions. 63

Figure 3.16: Empirical cooling curve for pallet CP1: 2 vents, 7.5% TOA, 130 Pa pressure drop. a.) Layer B, and b.) Layer D. 64

Figure 3.17: Impact on the average pallet cooling rates when: a.) increasing pressure drop; b.) decreasing vent size; c.) increasing vent size, and; d.) redistributing the TOA over a different number of vents. Special cases marked with asterisks; see section 3.3.4.1. 67

Figure 3.18: Package bowing as a result of weakened packaging, due to increased vent sizes. This created an unexpected airflow bypass pathway. Note that the tears on the packages are just superficial damage to the surface as a result of handling and thermocouple attachment. This does not represent structural damage. 69

Figure 3.19: Heterogeneity analysis of pallets CP1 (green) and CP3 (blue) using the relative standard deviation, the previously used heterogeneity metric. The heterogeneity trends are not accurate due to mathematical instability in the case of a.) °C, and artefacts of the difference in overall pallet cooling rate in case of b.) K. 71

Figure 3.20: Temperature distributions from pallet CP1 (orange bars) and CP3 (blue bars) at a.) Y = 0.875; b.) Y = 0.5 and c.) Y = 0.125. W = Shapiro-Wilks test statistic, p = p-value. 72

Figure 3.21: Experimental heterogeneity plots for pallets a.) and b.) CP1; c.) and d.) CP2 and e.) and f.) CP3..74

Figure 3.22: Total process heterogeneities, represented by the overall heterogeneity index (OHI), comparing a.) changes in pressure drop; b.) decreases to vent size; c.) increases to vent size, and; d.) the same TOA distributed over a different number of vents..75

Figure 3.23: Differences in the distribution of temperatures, expressed by representative shape (α), scale (ω) and location (ξ) values, when the pressure drop is increased: pallets CP1, CP2 and CP3. 76

Figure 3.24: Differences in the distribution of temperatures, as expressed by representative shape (α), scale (ω) and location (ξ) values, when the size of vents was decreased: pallets CP1, SV1 and SV2. 76

Figure 3.25: Differences in the distribution of temperatures, as expressed by representative shape (α), scale (ω) and location (ξ) values, when the size of vents was increased: pallets CP1, LV1 and LV2. 77

Figure 3.26: Differences in the distribution of temperatures, as expressed by representative shape (α), scale (ω) and location (ξ) values, when the same TOA is distributed over a different number of vents: pallets CP1, VN1 and VN2. 77

Figure 3.27: Performance of each package design, reported by the average cooling rate (SECT, hours) and cooling uniformity (OHI). a.) absolute performance; b.) performance relative to the baseline package, CP1...82

Figure 3.28: Laboratory forced-air cooling tunnel set-up for single box cooling: 5 boxes of kiwifruit stacked into a column in the wind tunnel, connected to a VSD fan. 3 boxes were instrumented, highlighted as red...84

Figure 3.29: Fruit temperature positions...84

Figure 3.30: Individual temperature position cooling profiles, ΔPpallet = 15 Pa. 85

Figure 3.31: Individual temperature position cooling profiles, ΔPpallet = 32 Pa 85

Figure 3.32: Individual temperature position cooling profiles, ΔPpallet = 65 Pa 86

Figure 3.33: Individual temperature position cooling profiles, ΔPpallet = 118 Pa 86

Figure 3.34: Box average temperature profiles. Error bars are the 95% confidence interval. 87

Figure 4.1: a.) Illustration of the CT scanner and its major components; b.) Photograph of kiwifruit boxes inside the Massey University Veterinary Hospital CT scanner; c.) a single CT scan image from the CT scanner, showing the cross-section of a box of kiwifruit, colour representing the CT number (level of X-ray absorption). 90

Figure 4.2: a.) a typical 2D pixel set, a regular 2D grid, with individual pixels defined by $\mathbb{p}n$ of size dx and dy; b.) a typical voxel set, a regular 3D grid, individual voxels defined by $\mathbb{v}n$ of size dx, dy and dz. 93

Figure 4.3: A raw CT scan slice of fruit inside of a modular bulk package. Colours represent CT number. a.) raw CT scan slice; b.) raw CT scan slice with superfluous information cropped out. 94

Figure 4.4: CT scan slice subjected to the ‘multithresh’ function (Otsu, 1979), with an increasing amount of discretization levels: a.) 2 levels; b.) 3 levels; c.) 4 levels; d.) 5 levels; e.) 6 levels; f.) 7 levels. 96

Figure 4.5: Enlarged result of applying Otsu’s method (Otsu, 1979) with 3 discretization levels to the raw CT scan slice, with mischaracterised pixels (fruit injuries, epidermis pixels and pixels in the table the box is resting on). 97

Figure 4.6: Illustrations of processes undertaken to compensate for mischaracterised pixels: a.) packaging pixels removed, then the remaining pixels were converted to binary; b.) ‘regionprops’ MATLAB function was applied to find the number of connected regions and their pixel size; c.) all regions under $\theta\text{fruit} = 100$ threshold removed, and the binary image was then inverted; d.) ‘regionprops’ applied again, and all regions except for the largest was eliminated. 98

Figure 4.7: Visualisation of the cumulative proximity routine developed to assess whether a pixel within the fruit epidermis has been mischaracterised as a packaging pixel. 99

Figure 4.8: Results of the cumulative proximity routine applied to all pixels recognised as packaging ($\mathbb{p}n = 2$); green having positive CP and were flipped ($\mathbb{p}n = 2 \rightarrow 3$), red having negative CP and were not flipped ($\mathbb{p}n = 2 \rightarrow 2$). 101

Figure 4.9: a.) application of the cumulative proximity routine to compensate for mischaracterised packaging pixels in the fruit epidermis; b.) final phase separated image, with mischaracterised pixels compensated for or removed. 102

Figure 4.10: a.) CT scan slices combined and separated into phases (discretization levels: air, 𝕧n < 167; packaging, 𝕧n = 167-674; fruit, 𝕧n > 674); b.) mischaracterised voxels compensated for and cleaned; c.) packaging voxels transparent to better show the fruit geometry. 103

Figure 4.11: CT scans of count size 36 Hayward kiwifruit in multiple stacking configurations: a.) a manually stacked box (according to section X); b and c.) randomly (naturally) stacked boxes of kiwifruit. 104

Figure 4.12: A generic ‘Hayward’ kiwifruit with the major geometrical attributes highlighted: DX = major diameter; DY = minor diameter; L = length. 106

Figure 4.13: Empirical shape profiles in the a.) X-Z, b.) Y-Z and c.) X-Y directions for count 36 Hayward kiwifruit. Minimum, average and maximum profiles are the result of tracing the shape of 117 fruit (Anonymous, 1997). Images not to scale; scale omitted to preserve data confidentiality. 108

Figure 4.14: Comparison between empirical a.) minimum, b.) average and c.) maximum lateral profiles with an ellipse of the same DX and DY. 109

Figure 4.15: a.) How different f2 functions change the shape of the LPF; b.) How the shape of the exponential LPF changes with different values of S, the shoulder coefficient. 112

Figure 4.16: Non-Dimensional empirical minimum, average and maximum shape profiles for count 36 Hayward kiwifruit (red) compared with an ellipsoid (cyan, Eq. 4.5) and the new exponential LPF (blue, Eq. 4.8). 113

Figure 4.17: a, b c and d.) Dimensionless empirical minimum, average and maximum shape profiles for count 36 Hayward kiwifruit (red) compared with the updated LPF where $S = 7.0$ (blue, Eq. 4.9); and e.) Cumulative error across all 12 comparisons as a function of S, the shoulder coefficient. 115

Figure 4.18: Calculation technique for numerically approximating fruit volume using the disk technique (Riddle, 1974) with the newly developed LPF for kiwifruit. Image based on Olatunji et al., 2015. 117

Figure 4.19: Efficacy of using the disk method to numerically approximate the volume (blue line) and surface area (orange line) of a kiwifruit shape as a function of degree of numerical discretization resolution. 118

Figure 4.20: Creating a kiwifruit in COMSOL as 8 parametric surfaces; a.) 1 parametric surface, b.) 2 parametric surfaces, c.) 4 parametric surfaces (top half of fruit), d.) whole fruit. 120

Figure 4.21: Creating a kiwifruit in Blender as two parametric surfaces (XYZ Math Surface). 121

Figure 4.22: Weight distributions of picked Hayward kiwifruit from 16 growers across the New Zealand 2016 season. Weight is given as a fraction relative to the average weight of count 36 fruit. 123

Figure 4.23: Combined weight distribution of picked Hayward kiwifruit from all 16 growers across the New Zealand 2016 season. Weight is given as a fraction relative to the average weight of count 36 fruit. 123

Figure 4.24:Comparison of the empirical weight distribution (blue bars and solid blue lines) of picked Hayward kiwifruit over the New Zealand 2016 season with the statistical model (dashed red line): a and b.) over the entire weight distribution; c and d.) within the count 36 weight range. 126

Figure 4.25: Flowchart outlining the Monte-Carlo routine, used initially to build a shape index comprised on randomly selected fruit dimensions. 127

Figure 4.26: Results from building the unconstrained shape index, demonstrating that square distributions of randomly selected fruit dimensions did not result in a square weight distribution due to the non-linear relationship between the fruit dimensions and weight. 128

Figure 4.27: Flowchart outlining the updated Monte-Carlo routine, where an empirical or model distribution is used as an input to reject randomly sized fruit that lie significantly beyond a specified weight target. 130

Figure 4.28: Results from building the shape index with the updated, empirically constrained method (Figure 4.27). To demonstrate that a comparable shape index can be built from the same input distribution despite the high degree of randomisation and repetition, the shape index is build 3 times. 131

Figure 4.29: The processes involved with filling modular bulk boxes with kiwifruit: a.) fruit are picked and placed into large bins, then delivered by truck to a packing house; b.) fruit are sorted automatically by a grader, which sorts fruit into their various weight categories, including count 36; c.) fruit within the count 36 size range are automatically deposited from the grading line and into a modular bulk box; d.) after boxes are filled, they are stacked into pallets and taken to a forced-air pre-cooler. 135

Figure 4.30: Model geometry of the chute, created with the same footprint as the inner dimensions of the box under study, inside of which a multitude of digital kiwifruit are to stack. 138

Figure 4.31: Demonstration of the sequential placement process of digital kiwifruit above the chute, where according to Eqs. (4.18), (4.19) and (4.20), fruit are automatically grouped into aisles of 9. Note: for illustrative purposes, shape variation has been removed. Colours were randomly chosen to better distinguish individual fruits and did not have a physical meaning. 140

Figure 4.32: Result of creating N = 150 digital kiwifruit with randomised shape, creation location and creation angle: a.) birds-eye view and b.) perspective view. 141

Figure 4.33: Rigid body dynamics simulation loop, consisting of collision detection, collision resolution and time integration segments. Figure based on Coutinho, 2013. 145

Figure 4.34: Body forces acting on 𝕂n during stacking: a.) gravity force; b.) gravity and collision force with the walls; c.) gravity and collision forces between fruits. Figure based on Coutinho, 2013. 146

Figure 4.35: Diagram of how collision detection and collision resolutions are solved in the DEM engine. Figure based on Coutinho, 2013. 147

Figure 4.36: Results of DEM simulation, where N = 150 digital kiwifruit were stacked into a box over 250 seconds of simulated time. a - d.) perspective view; e - h). front view. 150

Figure 4.37: Exploration of the stacking model to alternative packing scenarios: a.) a smaller package, with a footprint of 272x192mm; b.) a larger package, with a footprint of 472x392mm; c.) a standard modular bulk package (372x292mm), filled with N = 150 complex shapes (animal faces) to demonstrate the applicability of the model to alternative shapes. 151

Figure 4.38: Identification and elimination of overfilling: any fruit with even a single vertex above the inner height of the box (BZ = 187mm) is marked for elimination (red fruits in c and g). 154

Figure 4.39: Inception of the polyliner geometry: a cuboid with 10% larger dimensions as the inner dimensions of the box. 156

Figure 4.40: Application of the ‘Subdivide Surface’ object modifier, which divides the surface mesh into a larger number of smaller faces. 157

Figure 4.41: Application of the ‘Shrinkwrap’ object modifier, which brings the vertexes of one object (polyliner) to the nearest vertex of a target object (bulk kiwifruit shape). 158

Figure 4.42:Application of the ‘Smooth’ operator, which creates a more uniform distribution of vertexes 160

Figure 4.43: Impact of the Shrinkwrap Modifier offset, affecting the degree of direct fruit contact with the bulk motion of the airflow: a.) a 1mm penetration depth; b.) no gap, and; c.) a 1 mm gap. 161

Figure 4.44: Demonstration of the flexibility of the polyliner creation process. The same code was executed on a.) a randomly stacked box of fruit; b.) a manually stacked, ordered stack of fruit; c.) a random stack of cubes (edge length of 0.04m), and; d.) a random stack of animal faces (radius of 0.03m). 163

Figure 4.45: Illustration of procedure developed to measure the centroid position of individual fruits from CT scan information: a.) CT scan of kiwifruit stacked in a box; b.) application of the non-dimensionalised Euclidean Distance transform to the CT scan information; c.) temporary elimination of all fruit voxels with a relative distance <0.5: original CT scan information in transparent yellow; new objects in opaque red; d.) centroid position of individual fruits, marked as blue dots, derived as the centre of mass of the new opaque red objects. 165

Figure 4.46: Demonstration of different relative distance thresholds: a.) example of the threshold being too low (0.3), failing to completely separate individual fruits, forming a ‘voxel bridge’ in many scenarios; b.) example of the threshold being too high (0.8), completely eliminating all voxels from individual fruits in some cases. 166

Figure 4.47: Comparing ordered stacks of kiwifruit: a.) empirically determined (through CT scanning) 3D render of manually stacked box; b.) 3D render of manually constructed computational model of an ordered stack; c and d.) flattened 2D relative density maps of the 3D renders. 168

Figure 4.48: Cumulative distributions of the height of the geometrical centre of individual kiwifruits for: a CT scanned box (red circles), and the manually created computational geometry (solid black line). Dashed lines represent the first derivative of the cumulative height curve, ΔH, peaks indicating the position of a new layer of fruit: red dashed line = CT scanned box, black dashed line = computational geometry. 171

Figure 4.49: Comparing random stacks of kiwifruit: a. and b.) empirically determined (through CT scanning) 3D renders of real boxes of fruit; e. – g.) 3D renders of computationally generated random stacks of fruit through DEM. 174

Figure 4.50: Comparing select random stacks of kiwifruit: a.) empirically determined (through CT scanning) 3D render of a real box of fruit; b.) 3D render of a computationally generated random stack of fruit. c. and d.) flattened 2D relative density maps of the 3D renders. 175

Figure 4.51: Cumulative distributions of the height of the geometrical centre of individual kiwifruits for: the CT scanned boxes (red squares and black circles); and the 5 computationally generated random stacks (solid lines of varying colours). 175

Figure 4.52: First derivative of the cumulative height curves, ΔH, peaks indicating the position of a new layer of fruit: a.) ΔH for the CT scanned boxes; b.) ΔH for the computationally generated randomly stacked boxes. 176

Figure 5.1: Model geometry of 100 kiwifruit stacked manually into 4 orderly layers in Blender within the inner dimensions of a modular bulk package: a.) bottom layer, 30 fruit; b.) 2nd layer, 20 fruit; c.) 3rd layer, 30 fruit; and d.) top layer, 20 fruit. 182

Figure 5.2: Automated polyliner wrapping of the fruit geometry (Subdivide = 6, Offset = -0.00035 and Smooth = 5). a.) fruit geometry; b.) polyliner and fruit; c.) mesh topography of the polyliner. 182

Figure 5.3: Export of fruit and polyliner from Blender as an .stl and then imported into COMSOL (a, b, d and d). Geometries are then converted from surfaces to solid and then joined (d). 183

Figure 5.4: Finalised geometry of fruit and polyliner in COMSOL. a.) top down view (Y-X direction); b.) front view (Z-X direction); and c.) side view (Z-Y direction). 183

Figure 5.5: Results of DNS model investigating the impact of external convection on the fruit-polyliner stack. a.) geometry of the fruit and polyliner; b.) mesh of the geometry (117775 elements); c.) cutplanes for visualisation of results; d). temperature gradients within the stack at 10 hours of cooling for cut plane 1; d.) temperature gradients within the stack at 10 hours of cooling for cut plane 2. 188

Figure 5.6: Overall impact of external convection on cooling rates: a.) volume average fruit temperature cooling curves; b.) impact of external heat transfer coefficient on volume average HCT................. 188

Figure 5.7: Comparative impact of natural convection on cooling rates: a.) volume average fruit temperature cooling curves, with (dotted lines) and without (solid lines) natural convection; b.) impact of external heat transfer coefficient on volume average HCT, with (dashed line, circles) and without (solid line, squares) natural convection.. 192

Figure 5.8: Comparative impact of direct contact between fruit and polyliner on cooling rates: a.) volume average fruit temperature cooling curves, with a 0.5mm gap between fruit and polyliner (dotted lines) and with contact between fruit and the polyliner (solid lines); b.) impact of external heat transfer coefficient on volume average HCT, with a 0.5mm gap (dashed line, circles) and with direct contact (solid line, squares). 193

Figure 5.9: Results of DNS model investigating the impact of direct contact between the fruit and polyliner; a.) geometry of fruit and polyliner with a close-up of the 0.5 mm gap between fruit and polyliner; b.) temperature gradients with contact between fruit and polyliner; c.) temperature gradients with a 0.5mm gap between fruit and polyliner. 193

Figure 5.10: Comparative impact of respiration on cooling rates: a.) volume average fruit temperature cooling curves, with (dotted line) and without (solid line) respiration; b.) impact on HCT with and without respiration. 195

Figure 5.11: Geometry of thermal radiation DNS model, with the normal of emissive surfaces (fruit) as red arrows.. 198

Figure 5.12: Comparative impact of thermal radiation on cooling rates; a.) volume average fruit temperature cooling curves, with (dotted line) and without (solid line) thermal radiation; b) impact on HCT with and without respiration. 198

Figure 5.13: a.) an example model geometry: fruit and polyliner inside of a package; b.) the model geometry divided into a number of zones; c, d and e.) illustrations of the geometry within a variety of zones from different locations throughout the model geometry. 203

Figure 5.14: Intra- and Inter-Zonal heat transfer networks, connecting: a.) adjacent phases within zones (intra-zonal exchanges; Table 5.2), and b.) adjacent zones (inter-zonal exchanges; Table 5.3)......... 206

Figure 5.15: Voxelisation, a process through which a continuous geometric shape is converted into a voxelised grid. a.) the object to be voxelised (a circle); b.) a voxel grid laid over the top of the object; c.) the voxelised object with filled (voxels inside the object, yellow) and empty (voxels outside the object, white) voxels. 212

Figure 5.16: Use of Aitkenhead's (2013) voxeliser on an average sized count 36 Hayward kiwifruit, voxelised to a.) 5mm3; b.) 1mm3; and c.) 0.5mm3 resolutions.. 213

Figure 5.17: Use of Aitkenhead's (2013) voxeliser on a.) a random stack of kiwifruit. The surface meshes (.stl files) of b.) fruit and c.) the polyliner are voxelised separately with a 1mm3 voxel resolution. The voxelised d.) fruit and e.) polyliner are then combined into f.) the finalised voxelised geometry. 215

Figure 5.18: Voxel geometry finalisation process through a combination of matrices. 216

Figure 5.19: The cuboid zoning strategy, where the global geometry is divided into zones through a series of planar cuts. a.) a low resolution zoning strategy; b.) a higher resolution strategy; c.) a skewed zonal strategy, with zones of disparate size and shape. 220

Figure 5.20: Single cuboid-shaped zone taken from the centre of a zonal network to investigate the zonal adjacency. 222

Figure 5.21: Concept of the Zone Builder and the Geometric Procedures: a.) the voxelised fruit, polyliner and packaging geometry is divided into zones, and imported one by one into the Geometric Procedures; b.) a series of computational operations automatically convert the geometrical information into a small set of intra- and inter-zonal properties, ℙii and ℙij, completing the zonal network. 224

Figure 5.22: Geometric Procedure for appropriating volume from each phase inside a zone, by summing voxels from each phase. 227

Figure 5.23: Voxels in a zone converted into a surface with ‘isosurface’ MATLAB function – the total surface area being the sum of the areas of each individual triangular face. 227

Figure 5.24: Geometric Procedure for appropriating the heat and mass transfer surface area between each of the 6 phase-pairs. 229

Figure 5.25: Electrical analogue for conduction heat transfer between a specific phase-pair using lumped properties. Image derived from van der Sman (2003). 230

Figure 5.26: Visualisation of the Average Voxel Distance Calculator, as applied to a hypothetical 2 dimensional zone filled with voxels of fruit and air; a.) a 30×30 mm 2 dimensional zone filled with voxels of fruit (yellow) and air (blue); b.) identification of the surface voxels (dark red); c.) paths from a given voxel to all surface voxels (white arrows) to determine the shortest distance from that position (green arrow); d.) shortest distance from each voxel to the nearest surface; e.) computation of the characteristic distance for the zonal geometry as the mean minimum distance, dmin. 235

Figure 5.27: The AVDC tested on a 1-D slab. a.) the voxel geometry of the slab; b.) identification of surface voxels; dmin given relative to the length of the slab, L, with c.) 10; d.) 50; e.) 100; and f.) 1000 voxels. 237

Figure 5.28: The AVDC tested on a 2-D cylinder. a.) the voxel geometry of the cylinder; b.) identification of surface voxels; dmin given relative to the radius of the cylinder, r, with a c.) 30×30; d.) 100×100; e.) 200×200; and f.) 1000×1000 voxel grid. 238

Figure 5.29: The AVDC tested on a 3-D sphere. a.) the voxel geometry of the sphere; b.) identification of surface voxels; dmin given relative to the radius of the sphere, r, with a c.) 30×30×30; d.) 100×100×100; e.) 200×200×200 voxel grid. 238

Figure 5.30: Automated surface voxel identification: a.) a voxelised cuboid zone from the corner of a package; b.) a 2-D cross section of the zone; c.) the specific phase-pair is isolated; d.) the secondary phase is dilated by one voxel (white voxels); e.) overlap between the dilated phase Zβ and phase Zα are the surface voxels (yellow voxels). 242

Figure 5.31: Repetition of the automated surface voxel identification algorithm for each of the 6 possible phase pairs. 243

Figure 5.32: Application of the AVDC for $dS \rightarrow A, i$ (fruit to polyliner air) for a cross section of a corner zone; a.) path of least resistance from each position; b.) path of least resistance from each position, plotted from shortest to longest, to derive $dS \rightarrow A, i$. 244

Figure 5.33: a.) path of least resistance distances from 11170 randomly selected voxels (a 10% sample size) from the fruit phase of a zone from the corner of a package, with random selection being repeated 100 times; b.) population of percentage error between the fully calculated and randomly sampled dmin for 100 random samples of 10%. 245

Figure 5.34: Relative effective thermal conductivity of fluids (Nusselt number) as a function of the porous media modified Rayleigh number, various models. Image based on Cheng (1978 a), Cheng (1978 b) and Wang and Bejan 1987 250

Figure 5.35: Geometric procedure for appropriating the inter-zonal heat transfer surface area between adjacent zones. 255

Figure 5.36: Electrical analogue for conduction heat transfer between adjacent zones using lumped properties. Image derived from van der Sman (2003) 256

Figure 5.37: a.) original zonal geometry; fruit divided into slices perpendicular to the direction being investigated: b.) left/right direction; c.) forward/back direction; and d.) up/down direction. 257

Figure 5.38: Area of slices in the direction of each of the 6 adjacent zones. 258

Figure 5.39: Linear slice heat flux simulation, where heat is transferred through slices n via connectivity to slices in front and behind it, the rate controlled by the thickness of the slices, dslice, and the heat transfer surface area, Aslice n. 260

Figure 5.40: Example of the linear slice heat transfer geometric procedure. A.) the geometry is divided into slices perpendicular to the left direction (j =←); b.) the area of each slice in the direction-←; c.) predicted temperatures of all slices (solid blue lines) and the volume average temperature of zone i (dashed red line); d.) the derived resistance of zone i to conductive heat transfer through the fruit in the direction-←. 263

Figure 5.41: A scenario where a ‘pinch’ occurs within a zone, where in a given direction there is a region with zero area, limiting heat transfer access through the entire zone; the shielded portion of the zone is shaded. 264

Figure 5.42: Example of how the liner slice heat transfer geometric procedure fails when a ‘pinch’ occurs, resulting in no tendency toward a constant heat transfer resistance. 265

Figure 5.43: The solution to the pinch problem: the shielded portion must be excluded from the simulation in order to derive a representative conductive heat transfer resistance. 266

Figure 5.44: The zone solver, applied to a geometry divided into 100 zones: a.) temperature and time versus solver iterations, and; b.) predicted time-temperature curve. Each line represents an individual zone, and colours represent phases (magenta for fruit, cyan for air and orange for packaging)........ 270

Figure 5.45: The computational structure of this new interpretation of the zonal modelling approach 271

Figure 6.1: Electrical analogue for heat transfer between an object and refrigerated airflow using lumped properties. Image derived from van der Sman (2003). 275

Figure 6.2: Simplified lumped approach (solid lines) versus the finite element approach (circles) for simple objects: a.) spheres; b.) cubes; c.) finite cylinders, and; d) cones. Externally cooled at hext = 10 $W \cdot m^{-2} \cdot K^{-1}$ in all scenarios. Length scales in meters. 280

Figure 6.3: Simplified lumped approach (solid lines) versus the finite element approach (circles) for: a.) flattened ellipsoids; b.) stretched ellipsoids; c.) flattened cuboids, and; d.) stretched cuboids. Externally cooled at hext = 10 $W \cdot m^{-2} \cdot K^{-1}$ in all scenarios. Length scales in millimetres. 281

Figure 6.4: Simplified lumped approach (solid lines) versus the finite element approach (circles) for: a.) a helix; b.) a torus; c.) an average sized count 36 kiwifruit , and; d) an irregular shape, a bust of the Statue of Liberty. Externally cooled at from hext = 2.5 – 40 $W \cdot m^{-2} \cdot K^{-1}$. Length scales in millimetres. 282

Figure 6.5: Statue of Liberty geometry in both modelling approaches: a.) a tetrahedral finite element mesh; b.) a voxelised geometry (0.25 mm^3 voxel size). 283

Figure 6.6: a.) a cube shaped zone taken from the centre of a CT scan of fruit, with a complex intra-zonal fruit geometry (length scales in millimetres); b.) predicted cooling curves of the fruit phase inside of the cuboid zone using the simplified lumped approach (solid lines) and finite element approach (circles) cooled on the fruit-air surface at hext = 2.5 – 40 $W\cdot m^{-2}\cdot K^{-1}$. 284

Figure 6.7: a.) a skewed zone taken from the centre of a CT scan of fruit; b.) an increasingly skewed zone taken from the centre of a CT scan of fruit (length scales in millimetres); predicted cooling curves of the fruit phase inside of the zone for the simplified lumped approach (solid lines) and finite element approach (circles) for the c.) skewed zone, and d.) severely skewed zone. 286

Figure 6.8: Model geometries for each modelling approach: a.) finite element model, meshed into tetrahedral finite elements; b.) zonal model, voxelised into 1 mm^3 cubic voxels. 288

Figure 6.9: Zonal resolutions used in this validation exercise: a.) zonal network A, with 18 zones; b.) zonal network B, 48 zones; c.) zonal network C, 100 zones, and; d.) zonal network D, 180 zones... 289

Figure 6.10: Visualisation of the predicted local temperature profile over 20 hours of cooling at 5 $W\cdot m^{-2}\cdot K^{-1}$: a.) finite element model; zonal model, b.) network A (18 zones); b.) network B (48 zones); c.) network C (100 zones); d.) network D (180 zones). 292

Figure 6.11: Comparison of volume average temperature profile predictions for the finite element model (circles) and zonal approach (lines), over a variety of zonal resolutions and external cooling conditions: a.) 5 $W\cdot m^{-2}\cdot K^{-1}$; b.) 10 $W\cdot m^{-2}\cdot K^{-1}$; c.) 20 $W\cdot m^{-2}\cdot K^{-1}$, and; d.) 40 $W\cdot m^{-2}\cdot K^{-1}$. 294

Figure 6.12: Fruit positions used to compare local temperature predictions and heterogeneity; identical to positions used during experimentation (section 3.3). 295

Figure 6.13:Comparison of local temperature profiles between the zonal and finite element models at 12 temperature positions (Figure 6.12) for external cooling conditions of hext = 5 $W\cdot m^{-2}\cdot K^{-1}$. 297

Figure 6.14: Comparison of overall process heterogeneity (OHI) for the finite element model (circles) and the zonal model (squares, lines) over each cooling condition, hext = 5 – 40 W·m-2·K-1. OHI was computed with a modified process end time of Y = 0.182. 299

Figure 6.15: COMSOL model geometry of a modular bulk package, 100 count 36 kiwifruit and polyliner for the CFD airflow model. 302

Figure 6.16: Geometry of numerical wind tunnel for the CFD airflow model. 303

Figure 6.17: Boundary conditions of the CFD airflow model. 304

Figure 6.18: Convergence of the CFD airflow simulation: a.) probe location at the centre of the inlet to the left vent; b.) the measured velocity at the probe over GREMS solver iterations. 305

Figure 6.19: Cut planes through model geometry to visualise predicted airflow pattern (Figure 6.20). 306

Figure 6.20: Predicted airflow fields at two positions (Figure 6.19) through a single modular bulk package of polylined kiwifruit using CFD at ΔPpallet of: a.) 118 Pa; b.) 65 Pa; c.) 32 Pa, and; d.) 15 Pa. 307

Figure 6.21: Geometric procedure for determining the 'central position' of the bulk air phase: a.) a zone on the corner of the geometry with a bulk air phase; b.) a cutplane of the bulk air phase with the distance transform applied, the largest relative distance from all surfaces being the 'centre' of the phase...... 308

Figure 6.22: a.) list of 'central positions' exported from the zone builder; b.) list imported into COMSOL to generate the velocity at each position, to represent the airflow through each applicable zone. 309

Figure 6.23: Bulk air velocity through each zone, ui, appropriated from the CFD airflow model using positions derived from the 'central position' geometric procedure; blue, red, green and yellow circles represent ΔPpallet = 15, 32, 62 and 118 Pa, respectively. 310

Figure 6.24: Geometric procedure for appropriating the effective characteristic length for use in Reynolds number calculations, Leff, by dividing the volume of the bulk air phase by the surface area of airflow interaction. 313

Figure 6.25: Experimental validation zonal model set-up: a.) model geometry of a modular bulk package filled with 100 count 36 kiwifruit, wrapped in a polyliner; b.) the model geometry voxelised to 1 mm^3; c.) the voxelised model geometry zoned into a zonal network with NX = 5, NY = 5 and NZ = 4 (Ntotal = 100 zones). 314

Figure 6.26: Boundary conditions for the zonal model. 315

Figure 6.27: Preliminary empirical validation of zonal model, comparing simulation results at the local level, for ΔPpallet of a.) 15 Pa and; b.) 32 Pa. Circles are the zonal model, lines empirical data, error bars are the standard deviation. 319

Figure 6.28: Preliminary empirical validation of zonal model, comparing simulation results at the local level, for ΔPpallet of a.) 65 Pa and; b.) 118 Pa. Circles are the zonal model, lines empirical data, error bars are the standard deviation. 320

Figure 6.29: Preliminary empirical validation of zonal model, comparing simulation results at the global level, for ΔPpallet of a.) 15 Pa; b.) 32 Pa; c.) 65 Pa, and; d.) 118 Pa. Solid lines are empirical data where error bars are the 95% confidence interval, and dashed lines are the zonal model. 321

Figure 6.30: Definition of a residual for one temperature position, the total temperature difference between the experiment and model prediction over all times. 322

Figure 6.31: Structure of the optimisation routine designed to derive a more representative airflow correlation. 323

Figure 6.32: Results of the iterative optimisation routine, tracking the chosen coefficients a, b and c and the residual over each iteration. 325

Figure 6.33: Empirical validation of zonal model with the new airflow correlation, comparing simulation results at the global level, for ΔPpallet of a.) 15 Pa; b.) 32 Pa; c.) 65 Pa, and; d.) 118 Pa. Solid lines are empirical data, error bars are the 95% confidence interval, and dashed lines are the zonal model. 326

Figure 6.34: Empirical validation of zonal model with the new airflow correlation, comparing simulation results at the local level, for ΔPpallet of a.) 15 Pa and b.) 32 Pa. Circles are the zonal model, lines empirical data, error bars are the standard deviation. 327

Figure 6.35: Empirical validation of zonal model with the new airflow correlation, comparing simulation results at the local level, for ΔPpallet of a.) 65 Pa and b.) 118 Pa. Circles are the zonal model, lines empirical data, error bars are the standard deviation. 328

Figure 6.36: Zonal resolutions used to validate the flexibility of the zonal approach: a.) 100 zones (NX = 5, NY = 5, NZ = 4); b.) 180 zones (NX = 6, NY = 6, NZ = 5), and; c.) 245 zones (NX = 7, NY = 7, NZ = 5). 330

Figure 6.37: Centroid positions representing each zone and airflow velocities representing the velocity of air through each zone for three zonal resolutions: a.) 100 zones (NX = 5, NY = 5, NZ = 4); b.) 180 zones (NX = 6, NY = 6, NZ = 5) and; c.) 245 zones (NX = 7, NY = 7, NZ = 5). 331

Figure 6.38: Validation of model flexibility, comparing predicted cooling rates of three separate zonal networks across four different airflow rates/pressure drops 332

Figure 7.1: a.) Model geometry of a modular bulk package with 3 vents, the size, shape and position of which are controlled by optimization variables L1, L2 and L3; H1, H2 and H3; and P1, P2 and P3; which are the length, height and position of vent 1 (left), 2 (middle) and 3 (right), respectively; b.) Model geometry of fruit and polyliner, computationally generated with the random stacking model. 339

Figure 7.2: Monte-Carlo optimization routine structure. 340

Figure 7.3: 4 examples of randomly generated package designs, the result of random selection of vent size, shape and position. 341

Figure 7.4: Predicted airflow velocities at ΔPpallet = 15 Pa through 4 randomly generated package designs, using COMSOL. 342

Figure 7.5: a.) Voxelised fruit and polyliner geometry (1mm3 voxel size); b.) the model geometry divided into a zonal network of 100 zones. 343

Figure 7.6: Packaging performance plot, comparing the performance of each randomly generated package design in terms of cooling rate (SECT, Y-axis) and cooling uniformity (OHI, X-axis). The package optimization direction is as indicated by the arrow. 344

Figure 7.7: Design parameter 'total vent opening area' versus a.) SECT, and b.) OHI. 345

Figure 7.8: Design parameter 'individual vent size' versus SECT and OHI. 346

Figure 7.9: Design parameter 'vent position' versus SECT and OHI. 347

Figure 7.10: Notable randomly generated package designs: a.) the 'best' design, having the most improved combined cooling rate and cooling uniformity; b.) the least uniform design, with the highest OHI; c.) the most uniform design, with the smallest OHI; d.) the slowest design, with the longest SECT. 348

Figure 7.11: Hypothetical new package designs with bypass airflow vents: a.) a single central bypass vent, and; b.) two corner bypass vents. 351

Figure 7.12: Results of the random stacking model, applied to the new bypass vent package designs. The internal geometry was automatically generated for each case in just 2.5 minutes. 352

Figure 7.13: a.) the current package design, a modular bulk package, versus; b.) a new, wider and shallower design, dubbed the "Bulk Tray" package. 353

Figure 7.14: Package layer orientation and height for a.) and c.) modular bulk packages; and b.) and d.) Bulk Tray packages........ 354

Figure 7.15: Distribution of a.) bulk fruit weight, and b.) number of kiwifruit inside a box over 50 iterations of the random stacking model. 355

Figure 7.16: Weight of a pallet of Bulk Tray packages for each iteration of the predicted box weight; compared to a modular bulk pallet, 33 simulations showed an improved volumetric efficiency, while only 17 showed a worsened efficiency. 356

Figure A.1: Empirical cooling curve for pallet CP2: 2 vents, 7.5% TOA, 245 Pa pressure drop. a.) Layer B, and b.) Layer D........ 379

Figure A.2: Empirical cooling curve for pallet CP3: 2 vents, 7.5% TOA, 335 Pa pressure drop. a.) Layer B, and b.) Layer D........ 379

Figure A.3: Empirical cooling curve for pallet SV1: 2 vents, 3.4% TOA, 130 Pa pressure drop. a.) Layer B, and b.) Layer D........ 380

Figure A.4: Empirical cooling curve for pallet SV2: 2 vents, 4.5% TOA, 130 Pa pressure drop. a.) Layer B, and b.) Layer D........ 380

Figure A.5: Empirical cooling curve for pallet LV1: 2 vents, 8.9% TOA, 130 Pa pressure drop. a.) Layer B, and b.) Layer D........ 381

Figure A.6: Empirical cooling curve for pallet LV2: 2 vents, 13.1% TOA, 130 Pa pressure drop. a.) Layer B, and b.) Layer D. 381

Figure A.7: Empirical cooling curve for pallet VN1: 3 vents, 7.0% TOA, 130 Pa pressure drop. a.) Layer B, and b.) Layer D........ 382

Figure A.8: Empirical cooling curve for pallet VN1: 1 vents, 7.0% TOA, 130 Pa pressure drop. a.) Layer B, and b.) Layer D........ 382

Figure A.9: Experimental heterogeneity plots for pallets SV1 and SV2. 383

Figure A.10: Experimental heterogeneity plots for pallets LV1 and LV2. 383

Figure A.11: Experimental heterogeneity plots for pallets VN1 and VN2. 384

Figure A.12: Experimental heterogeneity maps for pallets CP1, CP2 and CP3. 385

Figure A.13: Experimental heterogeneity maps for pallets SV1 and SV2........ 385

Figure A.14: Experimental heterogeneity maps for pallets LV1 and LV2. 386

Figure A.15: Experimental heterogeneity maps for pallets VN1 and VN2. 386

Figure A.16: Experimental cumulative distribution of ΔY (solid blue lines) for cooling of pallet CP1, with fitted Skew-Normal distributions (dashed red lines) for a.) layer B, and b.) layer D at 8 cooling stages: Y = 1, 0.875, 0.75, 0.625, 0.5, 0.375, 0.25 and 0.125. D = Kolmogorov-Smirnov test statistic, p = p-value, α = shape, ξ = location and ω = scale. 387

Figure A.17: Experimental cumulative distribution of ΔY (solid blue lines) for cooling of pallet CP2, with fitted Skew-Normal distributions (dashed red lines) for a.) layer B, and b.) layer D at 8 cooling stages: Y = 1, 0.875, 0.75, 0.625, 0.5, 0.375, 0.25 and 0.125. D = Kolmogorov-Smirnov test statistic, p = p-value, α = shape, ξ = location and ω = scale. 388

Figure A.18: Experimental cumulative distribution of ΔY (solid blue lines) for cooling of pallet CP3, with fitted Skew-Normal distributions (dashed red lines) for a.) layer B, and b.) layer D at 8 cooling stages: Y = 1, 0.875, 0.75, 0.625, 0.5, 0.375, 0.25 and 0.125. D = Kolmogorov-Smirnov test statistic, p = p-value, α = shape, ξ = location and ω = scale. 389

Figure A.19: Experimental cumulative distribution of ΔY (solid blue lines) for cooling of pallet SV1, with fitted Skew-Normal distributions (dashed red lines) at 8 cooling stages: Y = 1, 0.875, 0.75, 0.625, 0.5, 0.375, 0.25 and 0.125. D = Kolmogorov-Smirnov test statistic, p = p-value, α = shape, ξ = location and ω = scale. Layer B has been omitted due to a high level of experimental error. 390

Figure A.20: Experimental cumulative distribution of ΔY (solid blue lines) for cooling of pallet SV2, with fitted Skew-Normal distributions (dashed red lines) for a.) layer B, and b.) layer D at 8 cooling stages: Y = 1, 0.875, 0.75, 0.625, 0.5, 0.375, 0.25 and 0.125. D = Kolmogorov-Smirnov test statistic, p = p-value, α = shape, ξ = location and ω = scale. 391

Figure A.21: Experimental cumulative distribution of ΔY (solid blue lines) for cooling of pallet LV1, with fitted Skew-Normal distributions (dashed red lines) for a.) layer B, and b.) layer D at 8 cooling stages: Y = 1, 0.875, 0.75, 0.625, 0.5, 0.375, 0.25 and 0.125. D = Kolmogorov-Smirnov test statistic, p = p-value, α = shape, ξ = location and ω = scale. 392

Figure A.22: Experimental cumulative distribution of ΔY (solid blue lines) for cooling of pallet LV2, with fitted Skew-Normal distributions (dashed red lines) for a.) layer B, and b.) layer D at 8 cooling stages: Y = 1, 0.875, 0.75, 0.625, 0.5, 0.375, 0.25 and 0.125. D = Kolmogorov-Smirnov test statistic, p = p-value, α = shape, ξ = location and ω = scale. 393

Figure A.23: Experimental cumulative distribution of ΔY (solid blue lines) for cooling of pallet VN1, with fitted Skew-Normal distributions (dashed red lines) for a.) layer B, and b.) layer D at 8 cooling stages: Y = 1, 0.875, 0.75, 0.625, 0.5, 0.375, 0.25 and 0.125. D = Kolmogorov-Smirnov test statistic, p = p-value, α = shape, ξ = location and ω = scale. 394

Figure A.24: Experimental cumulative distribution of ΔY (solid blue lines) for cooling of pallet VN2, with fitted Skew-Normal distributions (dashed red lines) for a.) layer B, and b.) layer D at 8 cooling stages: a.) Y = 1, 0.875, 0.75, 0.625, 0.5, 0.375, 0.25 and 0.1674 and b.) Y = 1, 0.875, 0.75, 0.625, 0.5, 0.375, 0.25 and 0.1553. The SECT is not analysed as the VN2 pallet did not reach the SECT. D = Kolmogorov-Smirnov test statistic, p = p-value, α = shape, ξ = location and ω = scale. 395

Figure B.1: Electrical analogue for evaporation moisture transfer between the fruit and air, using lumped properties. Image based on van der Sman (2003). 398

Nomenclature

English Symbols

A – area, m^2

a – translational acceleration (m·s^{-2})

a, b, c – empirical constants

B_X, B_Y, B_Z – planar cut positions for zones

C – specific heat capacity, J·kg^{-1}·°C^{-1}

c – index

C_{ij} – Connectivity Matrix

CP – cumulative proximity

CT_{Number} – CT number

C_{XYZ} – Coordinate Matrix

d_s – equivalent mean particle diameter, m

D – permeance, m·s^{-1}

d – diameter, m

d_c – characteristic distance, m

$\overline{d_{m\imath n}}$ – average voxel distance, m

$d_{\overleftrightarrow{nm}}$ – distance between a voxel and a surface voxel, m

D_X, D_Y, L_k – dimensions of a kiwifruit, m

dX, dY, dZ – dimensions of zones

dx, dy, dz – dimensions of voxels, m

e – coefficient of restitution

e – experiment index

E_{total} – residual between experiment and model, °C·h

F – force, kg·m·s^{-2}

F – Forchheimer coefficient, m^{-1}

F – volume force, N·m^{-3}

$F_{N.C.}$ – natural convection correction factor

G – gravity force, kg·m·s^{-2}

g – acceleration due to gravity, m·s^{-2}

Gr – Grashof number, dimensionless

H – moment of force, kg·m^{2}·s^{-2}

h - heat transfer coefficient, W·m^{-2}·°C^{-1}

H_1, H_2, H_3 – height of package ventilation, m

HI – heterogeneity index, °C or K

I – identity matrix

I – inertia, kg

I – number of elliptical disks

K_ε – intrinsic permeability, m^{2}

K – permeability, m^{2}·s^{-1}

L_{vap} – latent heat of vaporisation, 2260 kJ·kg^{-1}

L – characteristic length, m

L_1, L_2, L_3 – length of package ventilation, m

$\dot{m}$ – moisture flux, kg water·s^{-1}

M – mass, kg

m – index

n – index

$\boldsymbol{n}$ **–** normal vector

N_S – number of kiwifruit in a box

N_{total} – number of zones

Nu – Nusselt number, dimensionless

N_X, N_Y, N_Z – number of zones in the X, Y and Z directions

o – index

OHI – overall heterogeneity index, dimensionless

p_c – contact point

P – pressure, Pa

p – position index

P_1, P_2, P_3 – position of package ventilation, m

Pr – Prandtl number, dimensionless

P_X, P_Y, P_Z – polyliner dimensions, m

$\dot{Q}$ – volumetric flowrate, m^3·s^{-1}

r – random number

R – resistance, m^2·°C·W^{-1}

Ra – Rayleigh number, dimensionless

R_{CO_2} – rate of CO_2 production, mol·kg^{-1}·s^{-1}

Re – Reynolds number, dimensionless

S – fruit shoulder coefficient

Sc – Schmidt number, dimensionless

Sh – Sherwood number, dimensionless

T – temperature, °C

t – time, h

TKE – turbulent kinetic energy, m^{2}·s^{-2}

T_{Owen} – Owen's T function

Tu – turbulence intensity, dimensionless

u - velocity, m·s^{-1}

V – volume, m^{3}

W – weight, kg

X, Y, Z – Cartesian coordinates, m

Y – Fractional Unaccomplished Temperature Change, dimensionless

Greek Symbols

α – rotational acceleration (rad·s^{-2})

α – shape factor

β – thermal expansion coefficient, K^{-1}

δ – collision margin, m

ε – porosity, $m^3 \cdot m^{-3}$

θ_{fruit} – pixel/voxel threshold

θ_{search} – search radius

θ – angle, °

κ – thermal diffusivity, $m^2 \cdot s^{-1}$

λ_b – effective thermal conductivity of the packed bed, $W \cdot m^{-1} \cdot {}^\circ C^{-1}$

λ – thermal conductivity, $W \cdot m^{-1} \cdot {}^\circ C^{-1}$

$\mu_{Material}$ – X-ray absorption coefficient for the material

μ_{surf} – coefficient of friction

μ_{water} – X-ray absorption coefficient for water

μ – fluid viscosity, Pa·s

ξ – location factor

ρ – density, $kg \cdot m^{-3}$

σ_{rad} – Stefan–Boltzmann constant (5.67×10^{-8} $W \cdot m^{-2} \cdot K^{-4}$

σ – standard deviation

τ – characteristic index of process progression, $s \cdot s^{-1}$

υ – kinematic viscosity, $m^2 \cdot s^{-1}$

ω – scale factor

ϵ – emissivity, dimensionless

ϕ – heat flux, W or $J \cdot s^{-1}$

Miscellaneous Symbols

$\leftarrow, \rightarrow, \uparrow, \downarrow, \otimes, \odot$ – zonal adjacency

$\mathbb{B}_C$ – height of chute, m

$\mathbb{B}_X$, $\mathbb{B}_Y$, $\mathbb{B}_Z$ – inner dimensions of a package, m

$\mathbb{K}$ – kiwifruit

$\mathcal{P}_X$, $\mathcal{P}_Y$, $\mathcal{P}_Z$ – polyliner dimensions, m

$\mathbb{P}$ - zonal properties

$\mathbb{p}$ – pixel

$\mathbb{v}$ – voxel

Subscripts

A	A – air phase
cond	$cond$ – conduction
conv	$conv$ – convection
diff	$diff$ – diffusion
eff	eff – effective
evap	$evap$ – evaporation
Exp	Exp – experimental
ext	ext – external
f	f – final
i	i – initial
i	i – zone i, index

ii	ii – intra-zonal
ij	ij – inter-zonal
int	int – internal
j	j – zone j, index
Mod	Mod – Model
O	O – bulk air phase
P	P – packaging phase
p	p – product (fruit)
rad	rad – radiation
ref	ref – refrigerated fluid (in context, air)
S	S – solid, or fruit, phase
surf	$surf$ – surface
t	t – time
tot	tot – total
Z	Z – phase
Za	Z_α – primary phase
Zb	Z_β – secondary phase

Mathematical Operators

Φ_s – standard normal cumulative distribution

ϕ_s – standard normal distribution

Δ - difference

∇ - partial derivative with respect to all directions in Cartesian space

d – total derivative

Ω – surface (robin boundary conditions)

∂ – partial derivative

Abbreviations

AVDC – Average Voxel Distance Calculator

CFD – Computational Fluid Dynamics

CPRR – Centre for Postharvest and Refrigeration Research

CT – Computed Tomography

DEM – Discrete Element Modelling

DNS – Direct Numerical Simulation

FUTC – Fractional Unaccomplished Temperature Change

HCT – Half-Cooling Time, h

OECT – One Eighths Cooling Time, h

SECT – Seven Eighths Cooling Time, h

SN – Skew-Normal

VSD – Variable Speed Drive