THE DEVELOPMENT OF GENERIC MODELLING SOFTWARE FOR CITRUS PACKING PROCESSES

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Declaration

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and that I have not previously in its entirety or in part submitted it at any university for a degree.

Signature: ....

Date: ....

Summary

This study was initiated in October 2004 when Vizier Systems (Pty) Ltd approached the Department of Industrial Engineering at the University of Stellenbosch with a concept. They proposed that a fruit packing line be represented as a series of unit operations and suggested that the concept could be used to create a generic model that can be used to represent any packing line. After further discussions with Vizier about the concept and their reasons for requiring a generic model, a formal client requirement was formulated. It was decided that the generic modelling concept had to be tested in the citrus industry.

Modelling theory was investigated and a generic modelling methodology was formulated by adapting an existing modelling methodology. The first few steps of the developed methodology led to industry data being gathered and several role-players in the citrus export industry being visited. An analysis of the data enabled the development of the necessary techniques to do distribution estimation and forecasting of the system input, which is fruit. The various processes were grouped into generic groups and detailed capacity calculations were developed for each process.

The fruit parameter estimation techniques and capacity calculations were integrated into a five step modelling procedure. Once the generic model was set up to represent a specific packing line, the modelling procedure provided optimum flow rates, equipment setups and personnel allocations for defined production runs. The modelling procedure was then translated into a computer model. This allowed a complete capacity analysis of a packing line by incrementally varying the characteristics of the fruit input.

The developed generic model was validated by comparing its predictions to the results of two production runs at an existing packing line. It was found that the generic model is able to adequately represent the packing line and that the fruit inputs and outputs can be accurately estimated. The concept proposed by Vizier, that a packing line can be generically modelled as a series of unit operations, was shown to be valid.

Opsomming

Hierdie studie is in Oktober 2004 geïnisieer toe Vizier Systems (Pty) Ltd die Departement van Bedryfsingenieurswese aan die Universiteit van Stellenbosch met 'n konsep genader het. Hulle het aan die hand gedoen dat 'n vrugtepaklyn voorgestel kan word as 'n reeks eenheidsprosesse en dat die konsep gebruik kan word om 'n generiese model te skep om enige vrugtepaklyn te verteenwoordig. Na verdere samesprekings met Vizier oor die konsep en hul redes vir die noodsaaklikheid van 'n generiese model, is 'n formele kliëntebehoefte geformuleer. Daar is besluit dat die generiese modelleringskonsep in die sitrusbedryf getoets gaan word.

Modelleringsteorie is ondersoek en 'n generiese modelleringsmetodologie is geformuleer deur 'n bestaande modelleringsmetodologie aan te pas. Die stappe van die ontwikkelde metodologie het gelei tot die insameling van data vanuit die industrie en verskeie rolspelers in die sitrus-uitvoerindustrie is besoek. 'n Analise van die data het die ontwikkeling van die tegnieke moontlik gemaak wat nodig was om verspreidingsberamings en voorspelling van die stelselinset – die vrugte – te doen. Die onderskeie prosesse is gegroepeer in generiese groepe en gedetailleerde kapasiteitsberekeninge is vir elke proses ontwikkel.

Die vrugparameter beramingstegnieke en kapasiteitsberekeninge is geïntegreer in 'n vyf-stap-modelleringsprosedure. Nadat die generiese model opgestel is om 'n spesifieke paklyn voor te stel, het die modelleringsprosedure optimum vloeitempo's, toerustingopstellings en personeeltoedelings vir die spesifieke produksielopie gegee. Die modelleringsprosedure is toe herlei tot 'n rekenaarmodel. Dit het 'n volledige kapasiteitsanalise van die paklyn moontlik gemaak, deur die eienskappe van die vruginset inkrementeel te varieer.

Die ontwikkelde generiese model is gestaaf deur sy voorspellings te vergelyk met die resultate van twee produksielopies van 'n bestaande paklyn. Daar is bevind dat die generiese model in staat is om die paklyn voldoende voor te stel en dat dit die vruginsette en -uitsette akkuraat kon beraam. Die geldigheid van die konsep wat voorgestel is deur Vizier, naamlik dat 'n paklyn generies gemodelleer kan word as 'n reeks eenheidsprosesse, is bevestig.

Dedicated to Prof. Willie

1953 - 2006

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LIST OF SYMBOLS

α	First Beta distribution parameter
β	Second Beta distribution parameter
γ_1	Skewness of distribution
δ	Maximum successful pickup proportion
ε	Weight of annual values used in fruit statistic estimation
ε_C	ε when estimating crop size
ε_G	ε when estimating fruit grade
ε_S	ε when estimating fruit size
θ	Number of graders
μ	Mean of distribution
ρ_A	Packing density – Area
ρ_{AKV}	Packing density – Adjusted Kepler Value
ρ_C	Packing density – On rollers or brushes
ρ_D	Packing density – In dip tank
ρ_{Kepler}	Packing density – Kepler Constant (Hale, 1998:1)
ρ_N	Packing density – Experiments by Nermoen (2006:24)
ρ_{RCP}	Packing density – Random close packing (Nermoen, 2006:24)
ρ_{RLP}	Packing density – Random loose packing (Nermoen, 2006:24)
σ	Standard deviation of distribution
σ^2	Variance of distribution
τ	Time delay
ψ	Number of grading tables
ω	Fruit mass
d	Fruit diameter
d_c	Fruit diameter carton standard
d_d	Fruit diameter calculated from data
$f(t)$	System input function
p	p-value, indicates statistical significance
r	Fruit radius
$x(t)$	System input at time t
x_{ij}	Assignment of fruit input i to table j
$y(t)$	System state at time t
$z(t)$	System output at time t
A	Surface area
B_S	Number of spray brushes
B_T	Total number of brushes
C_i	Number of cartons for carton type i
C_{ij}	Possible flow combinations for fruit input i and table j
C_P	Number of cartons to be packed
CR_i	Carton output rate for station i
CR_{Max}	Maximum carton rate
E_i	Error of output i
$FMF(d)$	Fruit mass function

F_S	Total number of fruit under spray brushes
F_T	Total number of fruit in a process/table
F_{Ti}	Total number of fruit in packing tables part *i*
F_U	Number of unwrapped fruit per carton
F_W	Number of wrapped fruit per carton
G_E	Type of grading table
G_H	Number of hands available for fruit removal
G_N	Number of grading tables
G_{RG}	Required number of graders
G_{Ri}	Required number of graders at table *i*
G_{RT}	Required number of tables
G_S	Number of grading stations per side
G_T	Double or single sided grading table
GR_{Max}	Maximum grading rate
GR_R	Fruit removal rate per grader
I	Number of process inputs
I_i	Process input *i* of I
L_D	Distance between rollers
L_U	Length of process unit
L_W	Length of brushes/rollers or Width of unit/table
M	Total fruit mass of production run
N_C	Number of container in production run
N_L	Number of lines/lanes
O	Number of process outputs
O_i	Process output number *i* of O
P_C	Assumption correction proportion for area covered by fruit
P_{Ei}	Proportion expected for output *i*
P_F	Proportion of fruit
P_{Gi}	Proportion of fruit of Grade *i*
P_i	Proportion of fruit to grading table *i*
P_{Li}	Proportion range – lower value for output *i*
P_{Ri}	Proportion required for output *i*
P_P	Number of parts of a packing table
P_{Ui}	Proportion range – upper value for output *i*
PC	Parts per container
PS	Number of packing/pallet building stations
PS_i	Number of packing stations at packing table part *i*
PS_{Min}	Minimum number of packers required
R	Fruit throughput rate
R_{GC}	Maximum input rate for conveyor grading table
R_{GR}	Maximum input rate for roller grading table
R_{GT}	Maximum input rate for grading table type
R_i	Specified input rate for fruit input *i*
R_{ij}	Maximum allowable feed rate for fruit input *i* for table *j*

R_{Max}	Maximum allowable or possible R for specific process
R_{Min}	Minimum allowable R for specific process
R_R	Required operating rate R
R_S	Fruit surface area rate per second
S_F	Fruit speed
S_i	Minimum allowable speed of grading table i
S_{Max}	Maximum possible or allowable speed
S_{Min}	Minimum allowable speed
S_P	Maximum pocket speed
SE_i	Estimated value of fruit statistic for year i
ST_i	True value fruit statistic for year i
T_A	Time Allowable
T_{AS}	Time Allowable Spray
T_{AT}	Time Allowable Total
T_B	Brushing time
T_C	Time to pack/stack a carton
T_D	Fruit input time duration
T_G	Time to manually remove one fruit
T_{Max}	Maximum time in unit
T_{Min}	Minimum packing time
T_N	Time to start next carton/pallet
T_O	Time to do other pallet building tasks
T_{Pi}	Time to stack a pallet of carton type i
T_R	Time Required
T_{RS}	Time Required Spray
T_{RT}	Time required in total brushing unit
T_S	Spray time
T_T	Maximum throughput time
T_U	Time to pack an unwrapped fruit
T_W	Time to pack and wrap a fruit
TR_{Max}	Maximum tipping rate
TR_R	Required tipping rate
U_S	Process unit set up – Series or Direct
V_A	Average fruit volume
V_C	Container volume
V_P	Physical fruit volume
V_{Ti}	Volume of packing table part i
Z	Allocated packing table capacity

Glossary

Fruit colour – Citrus fruit colour is divided into eight colour classes; these can be seen in Appendix A. During a production run some fruit may be removed because of insufficient colour.

Fruit quality – Citrus fruit are divided into five quality grades. Grades 1 and 2 fruit are usually packed into cartons and exported. Grade 3 fruit are crated and sold locally and Grade 4 fruit is juiced. Grade 5 fruit is also referred to as waste.

Fruit size/count – Citrus fruit are divided into ten size categories and for each the number of fruit in a carton is referred to as the Count of the size category. Typical Counts are 36, 40, 48, 56, 64, 72, 88, 105, 125 and 144.

Generic model – A generic model is an imitation of a class of realities that can be adapted to represent any specific reality of its class. The development of this definition is described in Section 2.2 on p.13.

Generic modelling – Generic modelling is the process of developing an imitation of a class of realities that can be adapted to represent any specific reality of its class. See *Generic Model*.

Generic modelling methodology – A modelling methodology used to create *generic models*. Developed from the modelling methodology of Hangos and Cameron (2001:25).

GHC – Goede Hoop Citrus is the largest citrus packing house in South Africa and is located in Citrusdal in the Western Cape. There are three separate packing lines at the site.

Grader – A person grading fruit at a *grading table*.

Grading table – A table with a conveyor belt or moving rollers where *graders* manually remove unacceptable fruit from the main flow of fruit.

Packer – A person packing fruit at a *packing table*.

Packing table – A packing table accumulates fruit for packing personnel (*packers*) to pack the fruit into cartons. Fruit at a packing table will only be of a single *grade* and *size/count*.

Packing house – A packing house includes at least one *packing line*, but usually has many other supporting facilities such as storage, degreening and a workshop, among others.

Packing line – A packing line is a continuous process that transforms picked fruit into manageable, standard units of packaging and usually includes processes such as washing, grading and packaging, among others.

Pallet – A pallet is a flat wooden structure on which cartons of fruit are stacked for export. However, when referring to a pallet in this document the intended meaning is "a pallet of fruit", unless used as "empty pallet".

Producer – this refers to farmers who grow, harvest and deliver fruit to packing houses to be packed for export or the local market.

Production run – A production run occurs when crates of fruit, from one or more producers, are emptied into a packing line and prepared, graded and packed in the packing line.

Statistical range – when referring to a statistical range of 95%, two-tailed statistical significance has been calculated with 2.5% and 97.5% probability levels.

CHAPTER 1
PROBLEM STATEMENT

1.1 INTRODUCTION

Since the deregulation of the South African deciduous and citrus fruit export industries in 1996/1997, fruit export has undergone substantial changes. Where marketing was previously controlled by a few entities, suddenly literally hundreds of marketers started exporting; this resulted in a sharp decline in revenue for all parties concerned. An additional result of deregulation was that producers with higher quality products now received larger rewards than under the pooling system that was in place during regulation of the industry (Vink, 2003:9).

Issues such as food safety, traceability and regulated agricultural practices were unheard of before 1995, but these are now sources of great concern to all role-players in the fruit export industry as most developed markets require these regulations (Citrus Growers Association, 2005:2). During recent years the strong Rand has put pressure on the viability of fruit exports and a global oversupply of fruit has caused lower prices for fruit over the last few years (Capespan (Pty) Ltd, 2005:4). These four issues have placed increasing pressure on export practices and enhanced the need for cost-saving techniques throughout the export chain.

The number of major role-players in the physical fruit export supply chain of South Africa is very extensive and consists of thousands of producers (farmers), 850 packing houses (not including single farm grape packing houses), 315 cold stores, freight transportation networks (road and rail), four FPT (Fresh Produce Terminals) and two SAFT (South African Fruit Terminals) terminals and multiple shipping companies (Ortmann, 2005:49, 45). The supporting network of the physical supply chain is also very extensive and includes numerous privately owned consulting firms, of which Vizier Systems Pty (Ltd) (referred to later in the study) is one, as well as small and large private marketing companies such as Capespan. Then there are government structures such as the DTI (Department of Trade and Industry), the CSIR (Council for Scientific and Industrial Research) and PPECB (Perishable Products Export Control Board) that do research to support the industry. The final supporting group consists of producer organisations such as the CGA (Citrus Growers Association) (Ortmann, 2005:xxi).

In 2001 the direct contribution of agriculture to the gross domestic product (GDP) of South Africa, was 2.6% and it was estimated that via strong backward and forward linkages, it contributed 15% to the total GDP (South Africa Directory, 2006). In 2004 South Africa overtook the USA as the world's second largest exporter of citrus fruit (with Spain as the largest) and negotiations added China to South Africa's list of citrus export destinations (Citrus Growers Association, 2005:2). To maintain global competitiveness, it is of major importance to strictly meet the quality standards set by target markets (Citrus Growers Association, 2005:2).

1.2 PROBLEM STATEMENT

Traceability requirements for export fruit have greatly increased (down to orchard level) in the last few years, with more export markets requiring **stricter traceability** each year. The result is that fruit from different producers, destined for these markets must now be packed individually and cannot be grouped together anymore. In some cases it even extends to the point where each orchard of a specific producer has to be packed separately. This, in turn, has greatly increased the variation between consecutive packing runs, which increases the difficulty of planning and quality control. Furthermore, it decreases the duration of production runs, which increases the time spent on setup and leads to decreased efficiency (Bleby, 2006:8; Capespan (Pty) Ltd, 2005:4).

This project was initiated by Vizier Systems (Pty) Ltd, a process consulting firm, situated in Somerset West. Vizier specializes in consulting for the fruit industry, specifically packing facilities and it offers a wide range of products, ranging from tracking of fruit to the design of packing houses and packing line equipment. They realized that their clients needed help to more effectively manage their packing lines in order to meet the new management requirements caused by the stricter traceability demands of export markets. They approached the Department of Industrial Engineering at the University of Stellenbosch in October 2004 with a concept of a software package that creates a statistical model of fruit packing facilities. By modelling fruit packing, possible packing line changes can be evaluated, quality control can be improved and more effective planning and scheduling can be achieved. Vizier further envisions using the model as a tool to demonstrate and market their packing equipment, by evaluating equipment and process changes with regard to quality, throughput and cost. The modelling concept is supported by Miller and Ismail ((s.a.):3), who visualise the packing line as various unit processes that are matched together.

After consulting with two of Vizier's engineers (Bernard van Zyl and Francois Ferreira) (personal communication, November, 2004), the client requirements for the project were formulated and are listed below.

The software package must enable the development of a fruit packing model with a sequence of packing processes. Fruit parameters and other data of a single production run must be used to calculate, with a specific confidence level, the expected values of the following:

- Tipping rate to assure correct quality of output.
- Number of graders required at all grading stations.
- Number of packers required at each packing table.
- Number of cartons required for each fruit count/quality.
- Number of pallets required for each count/quality.
- Runtime of a production run.

All these concepts are explained in detail in Chapter 3.

The software is also required to assist with planning and the evaluation of changes to the equipment or processing sequence.

The initial client requirement was for all fruit types and processes to be included in the software model. It was decided that a specific group of processes and fruit be chosen to test and verify the accuracy and usefulness of the proposed model and concept. The procedure of acquiring and processing data used in this study can then be used to expand the model to other fruit types and their relevant processes at a later stage.

It was decided that this study should be constrained to hard citrus fruit and its relevant processes only, as hard citrus fruit accounted for 56% of all fruit exports from South Africa in 2003 (Ortmann, 2005:51). The processes used to prepare, grade and pack hard citrus fruit are more extensive and include most of the processes also used for packing other fruit. When referring to hard citrus or citrus in this document, Navel and Valencia citrus cultivars are included and soft citrus (Easy-peelers) and grapefruit are excluded.

Consequently, the following problem statement was formulated:
Develop a generic model for hard citrus packing lines.

1.3 GOAL AND OBJECTIVES

The problem statement mentioned above has led to the formation of the goal of the study.

1.3.1 Goal

The goal of the study is to generically model hard citrus packing lines.

In order to realise the above-mentioned goal, certain objectives were formulated:

1.3.2 Objectives

1.3.2.1 To investigate modelling theory and to select a suitable generic modelling methodology or to develop one if a suitable one is not found.

1.3.2.2 To implement the generic modelling methodology, in order to develop a generic model of hard citrus packing lines.

1.3.2.3 To translate the developed generic model into a computer model, in order to do capacity- and packing line analysis, to meet the client requirements.

As a first step in conducting the research, relevant concepts were identified and a conceptual framework was compiled (Figure 1.1).

1.4 CONCEPTUAL FRAMEWORK

The conceptual framework gives a graphic representation of the topic of study and the research methodology that will be followed during the study.

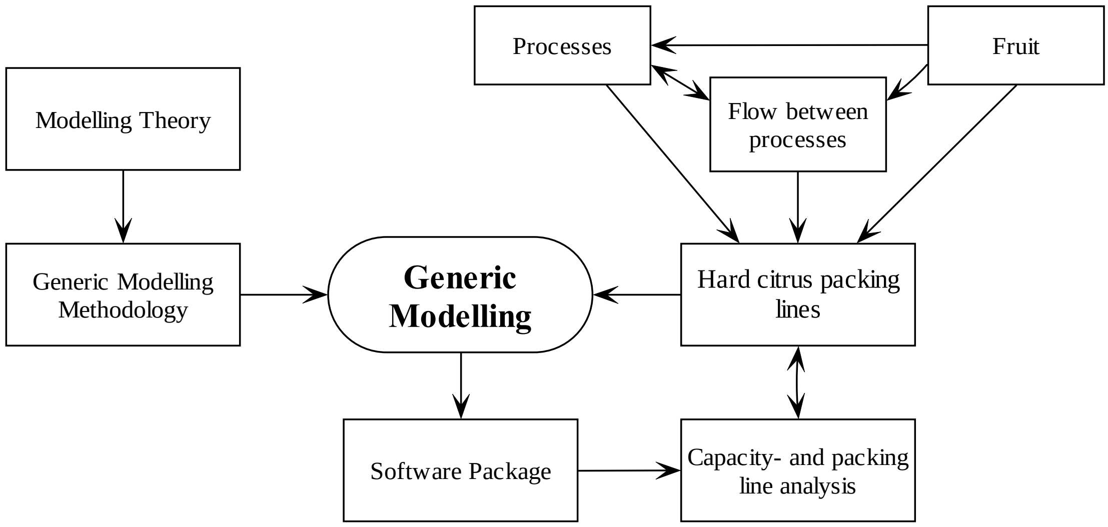


Figure 1.1: Conceptual framework of the study

Modelling theory will be investigated and discussed in order to select or develop a suitable *Generic Modelling Methodology* for this study. This generic modelling methodology will then be used to generically model *hard citrus packing lines*. The different components of citrus packing lines are the different *processes* taking place, the *flow between these processes* and the actual *fruit* that are processed. Data on these aspects will be collected and discussed, with special attention to the influence of fruit characteristics on the other two aspects, as well as the dynamic interchange between the *flow between the processes* and the *processes*. Data of these components will be used in the generic modelling of citrus packing lines.

The generic model will then be translated into a software package, which will be used to conduct capacity- and packing line analysis on hard citrus packing lines. Throughout this process the software package will be verified and validated against run data from a specific citrus packing line. If any irregularities are found, the generic model will be reworked. This iterative process will continue until the generic model and the subsequent software package are acceptable. Meyer (1984:69) and Severance (2001:1) agree that perfection is frequently unattainable for models as there will almost always remain some margin of error. The iterative process will therefore be a quest for zero defect as a model will never be a perfectly accurate representation of the real-world, but might approximate it so closely that the error becomes negligible.

1.4.1 Conceptual definitions

The main concepts are defined as follows:

1.4.1.1 Modelling theory

According to Hangos and Cameron (2001:4), a model is an imitation of reality and attempts to capture features of a system or process. *Modelling theory* is the fundamental ideas used to create these models.

1.4.1.2 Generic modelling methodology

The term *generic model* is defined in Section 2.2 (p.12) and refers to an imitation of a group of realities. Adding the term *generic* therefore modifies the definition of a model to not only imitate a single reality, but a group of realities. A generic model is developed using a *generic modelling methodology*, which is described in Section 2.3 on p.13.

1.4.1.3 Generic modelling

The developed generic modelling methodology was performed on the defined group of citrus packing lines to develop a generic model. *Generic modelling* is therefore the process that has taken place. The data and process analysis of citrus packing lines were used during the modelling process. The process includes validation and verification.

1.4.2 Operational definitions

The operational concepts of the study are defined as follows:

1.4.2.1 Hard citrus packing lines

For the purpose of this study, *hard citrus packing lines* refer to all hard citrus packing lines in South Africa only, since the logical order of packing is different in other countries where other standards and market requirements apply (Miller, Wardowski & Grierson, 2001:2, Figure 1). Hard citrus refers to Valencia and Navel citrus cultivars, only. A packing line is a continuous process that transforms picked fruit into manageable, standard units of packaging (Harris, 1988, chap. 4.1) and has three primary controlling features, namely the processes in the packing line, the flow of fruit between these processes and the fruit that are being transformed.

Packing line processes were analysed by conducting industry visits, interviews and reviewing available literature. Fruit data was collected for five producers, at three sites, spanning three years. A total of seventy nine production runs were collected as well as annual production summaries. The data was collected to evaluate the various fruit characteristics and the results of these investigations were used to understand the dynamics and the flow between the processes.

1.4.2.2 Software package, capacity- and packing line analysis

The developed generic model was translated into a *software package*. This computerized model is a direct output of the generic modelling process. *Capacity- and packing line analysis* was used to compare the model to an existing packing line.

1.5 RESEARCH DESIGN AND METHODOLOGY

Research design refers to the type of study being conducted, whether it is an empirical or a non-empirical study.

In this study the research design comprises of both empirical and non-empirical designs. The *non-empirical* part of the study refers to objective 1.3.2.1, namely the investigation into modelling theory in order to select or develop a generic modelling methodology. Here generic modelling methodology is the unit of analysis. This specific type of non-empirical study is further classified by Mouton (2001:176) as a *Theory-building or model-building study*. The data could be numeric and textual, it is hybrid and there is medium to low control over the data. A further classification of this type of non-empirical design is *Mathematical model-building*. Typical applications of this type of non-empirical design are in theoretical and conceptual studies that aim to develop new models and theories or refine existing models and theories, which is the case in this study (Mouton, 2001:177).

The *strengths* of this type of non-empirical research design lies therein that quality theories and models allow the development of predictive claims under certain conditions, it brings conceptual consistency to a field of science and it simplifies our comprehension of the world. It is, however, *limited* in that theories are ineffective if they make incredible claims on reality, or if they make statements that are not testable and vague, or that are conceptually inconsistent, contradictory and confusing (Mouton, 2001:177).

The main *sources of error* in formal theory construction are associated with over-abstract formulations, so far removed from reality that they cannot be validated empirically. In model-building it is related to the assumptions that are made during model specification, the quality of the empirical data, and the correct application of statistical and mathematical procedures (Mouton, 2001:177).

The empirical part of this study refers to objective 1.3.2.2., namely to implement the generic modelling methodology in order to develop a generic model of hard citrus packing lines, as well as objective 1.3.2.3, namely to translate the developed generic model into a computer model, in order to do capacity- and packing line analysis. In this case citrus packing lines are the units of analysis. Here the data is mostly numeric and hybrid and there is medium control over the data. Mouton (2001:163) classifies this specific type of empirical study as *Statistical modelling and computer simulation studies*. These are defined as studies that aim to develop and validate accurate representations or models of the real world. In statistical modelling, a specification of a model is constructed through a process of abstraction from what are theorised to be the processes in the real world. By means of a statistical technique (e.g. regression analysis or statistical inference), the model is used to generate expected values that are compared with actual data. A simulation model can be "run" to produce output, while a statistical analysis programme is required to generate output for a statistical model (Mouton, 2001:163).

The strengths of this type of empirical design are its ability to model large-scale phenomena and to simplify relationships in order to explain and predict with more accuracy. The limitations, however, are that the quality of the data or complexity of phenomena do not always allow full specification of a model. The main *sources of error* are low quality of the data, under-specification of the model and the implausibility of modelling assumptions (Mouton, 2001:163).

The research methodology has been briefly discussed in Section 1.4 (p.4), the Conceptual Framework. Figure 1.1 gives a graphic presentation of the research methodology to be followed. Detailed descriptions of the literature review, the selection of packing houses for the data collection and the selection of production runs, as well as the process of data collection and data analysis and interpretation will be given in Chapters 2, 3 and 4 respectively.

1.6 ASSUMPTIONS AND LIMITATIONS

This study is restricted to hard citrus fruit (Valencia and Navel cultivars) and its relevant processes only. Furthermore, this study does not include operational aspects of packing lines. These, such as ensuring that equipment is working properly and that personnel are adequately trained, fall outside the scope of this study. While the model will attempt to guide the user within the effective ranges of equipment capacities, it is assumed, at various stages of the study, that equipment operates at designed levels and that personnel performs within expected behavioural limits.

It should also be noted that many aspects influence fruit quality, but that these will not be investigated individually as general fruit quality is determined before fruit arrive at the packing line. The packing line is therefore constrained by the fruit quality, but nothing can be done to change the given fruit quality. When fruit quality is very low containers of fruit may be pre-sorted to remove low quality fruit before the fruit enter the packing line.

1.7 RESEARCH LAYOUT

In this chapter the problem statement, the goal and the objectives of the study, as well as the conceptual framework, the research design and the assumptions and limitations of the study have been presented.

In **Chapter 2** modelling theory and the general development of mathematical models and their implementation are described with reference to literature from Hangos and Cameron (2001). This is then refined into a *generic modelling methodology*, which will be used in this study.

The information and literature required for the practical application of the generic modelling methodology, in the citrus packing line industry, is discussed in **Chapter 3**. The first two steps of the generic modelling methodology of Chapter 2 are also presented. As part of the second step, the various processes and variable types are grouped into generic groups.

In **Chapter 4** the dynamics and variability of hard citrus fruit during packing are discussed. Fruit data gathered in the citrus industry is presented. The application of the data, to develop various fruit statistic distributions and a forecasting tool to define the packing line input, is also discussed. The evaluation of the process data is the third step of the generic modelling methodology.

Chapter 5 contains detailed analysis and modelling of every process found in the typical citrus packing line. The model construction is the fourth step of the generic modelling methodology. The analysis is presented in the context of the generic process groups described in Chapter 3.

The development of the modelling procedure, which is the fifth step of the generic modelling methodology, and its translation into a software tool are discussed in **Chapter 6**.

The developed computer model was verified and used to represent an existing packing line. The model was validated by comparing it with captured industry data. The results of these tests and the validity of the modelling concept are discussed in **Chapter 7**. The verification and validation of the model are the last two steps of the generic modelling methodology. Thorough testing was also done on a theoretical packing line.

Chapter 8 contains the conclusions of the study as well as recommendations for future development and innovations.

CHAPTER 2
MODELLING

In this chapter the concepts of a model and a system are introduced and the theory on mathematical modelling is presented. A definition is developed for generic mathematical modelling and the seven step modelling procedure developed by Hangos and Cameron (2001:24-30) is applied to the definition of a generic model to develop a generic modelling methodology.

2.1 GENERAL MODELLING THEORY

All reviewed literature on modelling is initiated by defining the term *model*. To conform to this practice a few definitions will now be presented and discussed. Hangos and Cameron (2001:4) and Jacoby and Kowalik (1980:2) define a model as an imitation of reality and state that models attempt to capture certain features of a system or process for a specific use. The South African Concise Oxford Dictionary defines a model as follows: *"a simplified description, especially a mathematical one, of a system or process, to assist calculations and predictions."* (The Dictionary Unit for South African English, 2002:747)

McLone (1976:1) and Meyer (1984:1) define a mathematical model as a representation or description of some part of the real world in mathematical terms. This is done to comprehend the significant properties or to predict events or behaviour of the modelled subject. Mathematical models can consist of various elements, such as variables, constants, mathematical expressions (in the form of equations or inequalities), logical statements and data (Meyer, 1984:2).

Therefore, a mathematical model, defined for the purposes of this study, is an *imitation of reality, in mathematical terms, to assist in calculations and predictions.*

Hangos and Cameron (2001:4) start the model development process by translating a real world problem into an equivalent mathematical problem and solving it by creating a mathematical model. It is required that certain characteristics of the actual system be represented by the model. Those characteristics could include:

- The correct response direction of the outputs as the inputs change;
- A valid structure which correctly represents the connection between the inputs, outputs and internal variables;
- The correct short- and/or long-term behaviour of the model.

2.1.1 Mathematical model classification

Mathematical models are classified by Jacoby and Kowalik (1980:12) and Hangos and Cameron (2001:10) according to the following criteria:

- Time-related behaviour – dynamic or steady-state
- Model data – stochastic or deterministic
- Dependent variables – lumped or distributed parameter
- Equations – linear or non-linear

- Variables – continuous or discrete (or hybrid)
- Solution technique – mechanistic or empirical

These six classes are extremes of fundamental concepts and a model can contain elements from all extremes.

The first classification represents the state of the model over time. The state of *dynamic* processes is time dependant. *Steady-state* processes remain constant over time and are independent of time. The classification can usually be made by looking at the inputs and outputs of the process. Where the inputs and outputs are equal, the process is at steady-state. The opposite applies for dynamic processes. Whether the dynamic changes are significant enough to be included in the model, will depend on the process being analysed (Hangos & Cameron, 2001:21). Jacoby and Kowalik (1980:12) further define two types of dynamic models; *instantaneous dynamic* and *memory dynamic*. An instantaneous dynamic model exists where the behaviour of the model at any given moment is dependant on time only, while the behaviour of a memory dynamic model is dependant on the internal state as well.

The second classification is between stochastic and deterministic models. Deterministic models are based on cause-effect analysis (Hangos & Cameron, 2001:11) and elements are specified to a level at which model behaviour and operation can be determined. Stochastic models contain elements that are uncertain, probabilistic in nature or which have natural random variances that are best described by probability distributions (Jacoby & Kowalik 1980:13).

The third classification is lumped or distributed parameter models. A distributed model is one where one or more independent variables, denoting degrees of freedom, are involved as opposed to a lumped model in which the variables and relationships are dependent on average or representative values of variables (Jacoby & Kowalik, 1980:14)

Hangos and Cameron (2001:10) add linear and non-linear as the fourth classification. The superposition principle, which declares that two or more sets of linear equations can be added together, applies to linear models. The fifth classification is between continuous and discrete models. Models are classified as continuous if all data, parameters and relationships are continuous. Models representing material flow are usually continuous (Jacoby & Kowalik, 1980:13).

The last classification is the mechanistic or empirical class. Mechanistic models are based on system mechanisms such as mass, heat and momentum transfer. They can be termed "white box" models since the mechanisms are evident in the model description. Empirical models, on the other hand, are based on input-output data, trials or experiments. These are typically used where principles and mechanisms are not well understood. Empirical models are termed "black box" models, as little is known about the real mechanisms of the process. It is common for models to contain both mechanistic and empirical parts that form what is termed "grey box" models (Hangos & Cameron, 2001:10,23-24).

Leigh (1980:1) adds another categorization of mathematical models, namely according to its purpose. The two categories are, firstly, models that assist with plant design and operation, and secondly, models that assist with control system design and operation. Design and operation models are usually detailed, physically based and often non-dynamic, while control system models are usually dynamic.

2.1.2 System theory

Severance (2001:1) bases the system on a set of cause-effect relationships that can be decomposed into sub-systems and applied over a restricted application domain. The system is then simplified as a "black box", as illustrated in Figure 2.1.

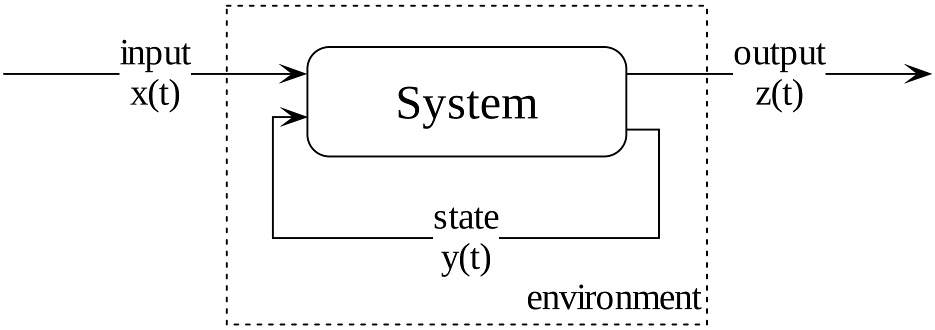


Figure 2.1: System as a "black box" (Severance, 2001:2)

It is evident, from Figure 2.1, that a system is an entity completely isolated from its *environment*, excluding the entry of *inputs* and exit of *outputs*. The *input* $x(t)$ is a combination of environmental inputs, such as noise, and process inputs. In a dynamic system, the "next" system *state* $y(T)$, is typically a function of the *input* and the current system *state* $y(t)$. The *output* $z(t)$ is usually a combination of the *input* and system *state*, but in simple systems it may be dependant on the *input* only (Severance, 2001:2-3).

Hangos and Cameron (2001:20-21) summarize a system as part of the real world with well defined boundaries. Inputs are influenced by its surroundings or environment and outputs have an influence on its surroundings. The model is an approximation of the system and the closer the behaviour of the model to the behaviour of the real-world system, the more valuable the model will be.

2.1.2.1 System dead-time

Dead-time occurs when a system or process takes in an input function $f(t)$ and gives out the same function, delayed in time by τ time units, but otherwise unaltered. System dead-time is rarely constant and can be a function of the input or system state (Leigh, 1980:11-12). Figure 2.2 illustrates the delayed input-output relationship of system dead-time.

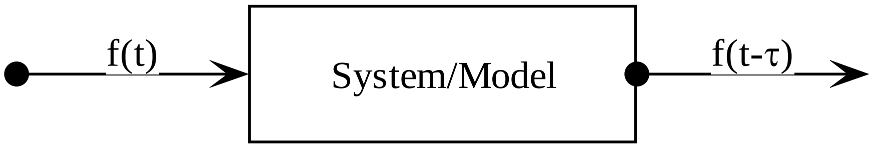


Figure 2.2: System dead-time (Leigh, 1980:11)

As Leigh (1980:11) states that dead-time is found in processes where products flow from one place to another, it is expected that this will be evident to some extent in the fruit packing industry as fruit flow through the system.

2.1.3 Sources of error

According to Hangos and Cameron (2001:6) the development of mathematical models *"...is far more than simply the generation of a set of equations"*; precise problem definition, assumptions, validation and verification also play a major role.

Mouton (2001:177) warns that, during the development of the model, the main sources of error are:

- Incorrect assumptions that are made in specifying the model
- Poor quality of the data against which the model will be fitted
- The incorrect use of statistical and mathematical procedures

Further difficulties of mathematical modelling may arise when the system that is to be modelled is inadequately understood. If this is the case, defining the mathematical relationships of the system may not be possible and, even if the relationships can be mathematically defined, they may not amount to a solvable problem (Jacoby & Kowalik, 1980:7).

Great care should therefore be taken to ensure that gathered data is accurate and that the nature of the data is properly understood. An intense study of the subject at hand will also be required and modelling assumptions will need to be tested.

2.2 GENERIC MODELLING

During initial research of similar studies and literature review, various references were found that made use of the term *generic modelling*. Unfortunately, all of these referred only to very specific studies in specific fields and did not discuss or present a generic modelling theory or methodology. Jacoby and Kowalik (1980:ix) also came across this problem and state that modelling experience is mainly contained in documents of particular modelling projects and that there is no book that covers all the steps of mathematical model building or that provides guidance and tools for this process. Even definitions of generic modelling in reviewed studies are given in the specific context of the specific study and cannot be universally applied to generic modelling. The problem with this is that *generic* is defined as the opposite of *specific* (Marckwardt, Cassidy & McMillan, 1995:526). One can therefore not jump the gun and start generic modelling by looking only at a specific problem. The theory and logic behind generic modelling must first be thought through without any reference to the specific problem that is to be solved.

As no clear definition of a generic model was found, a definition was developed from the meaning of the two separate words.

The concept of a model was defined earlier in this chapter (see Section 2.1 on p.9) as *"an imitation of reality"* (Hangos & Cameron, 2001:4).

The term *Generic* is an adjective when used in the phrase *Generic Model*. Below are definitions from the Webster Comprehensive Dictionary and the South African Concise Oxford Dictionary, when used in this way:

"Pertaining to a genus or a class of related things: contrasted with specific or varietal."
(Marckwardt *et al.*, 1995:526)

"characteristic of or relating to a class or group; not specific" (The Dictionary Unit for South African English, 2002:480)

In the phrase *generic model*, the *class* or *group* (from definitions of *generic* above), refer to the *realities* which the adjective describes, i.e. *group of realities*. Using the definition of a model (Hangos & Cameron, 2001:4) it follows that a *generic model* can be defined as an *imitation of a class of realities that can be adapted to represent any specific reality of its class*.

The definition above can now be used to define *generic modelling* as the *process of developing an imitation of a class of realities that can be adapted to any specific reality of its class*. Now that modelling theory and generic modelling have been described and defined, a methodology to perform generic modelling will be developed.

2.3 SEVEN STEP MODELLING PROCEDURE

During initial research, the *Seven Step Modelling Procedure,* developed by Hangos and Cameron (2001:24) was identified to be a useful modelling methodology for this study. This modelling procedure was chosen because it comes from a chemical background where even the smallest effect must be included as there will be a risk for error if it is excluded. Although the procedure includes physical and chemical modelling concepts, some of which are not applicable to this study, the modelling principles discussed have laid the foundation for complex multiscale modelling (Cameron, 2004:8). This procedure will now be used in similar fashion to lay the groundwork for a generic modelling methodology.

It is commented by Hangos and Cameron (2001:24) that *"model development is inherently iterative in its nature"*. The steps are therefore repeated until the model resembles the real world with an acceptable level of accurate behaviour. Figure 2.3 shows the seven step procedure, as well as the possible "backward" leaps of the iterative modelling process.

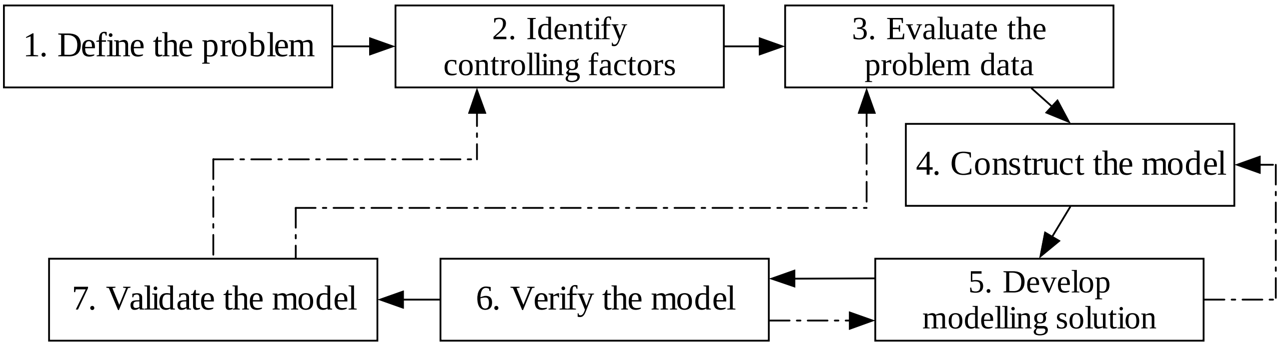


Figure 2.3: Systematic model building steps (Hangos & Cameron, 2001:25)

Hangos and Cameron (2001:24) developed the *seven step modelling procedure* to facilitate the development of conventional process models. As generic modelling is a form of modelling, the *seven step modelling procedure* can be applied to the development of generic models by slightly adapting it. The following section explores the theoretical application of each of the seven steps as developed by Hangos and Cameron (2001:26-30). Each step is then applied to the definition of generic modelling and a methodology for generic modelling is developed. Jacoby and Kowalik (1980:23) add a step for the development of a computerized model between the development of the modelling procedure (Step 5 in Figure 2.3) and verification of the model (Step 6 in Figure 2.3) steps. Development of a computerized model was added to the original *seven step modelling procedure* as part of the afore-mentioned steps.

2.3.1 Step 1 – Define the problem

Hangos and Cameron (2001:24) state that the definition of the problem consists of two elements, namely the *specification of the process system to be modelled* and the *modelling goal*. The definition of these two concepts is discussed below for conventional and generic modelling.

2.3.1.1 Problem definition in conventional modelling

The *process system specification* should contain a description of the specific process and its physical boundaries, as well as initial assumptions that can be made. According to Hangos and Cameron (2001:21) the modelling goal specifies the intended use of the model and has a major impact on the level of detail and the mathematical form of the model to be built.

Further information such as inputs and outputs, type of spatial distribution, necessary range and accuracy and time characteristics (see Section 2.1.1 on p.9) should also be included in the problem definition (Hangos & Cameron, 2001:26).

2.3.1.2 Problem definition in generic modelling

Having defined the *generic model* as an *adaptable imitation of a class of realities*, it follows that the generic model can imitate several specific realities. It follows that there will be a set of realities for which the imitations will be accurate or applicable. The function of the *problem definition* when creating a generic model is to define the set of realities to be modelled.

Hangos and Cameron (2001:21) require that the problem definition include the *specification of the process system to be modelled* and the *modelling goal* in conventional modelling.

For modelling, the *process system specification* should contain a description of the specific process and its physical boundaries, as well as initial assumptions that can be made (Hangos & Cameron, 2001:21). For generic modelling purposes, the *process system specification* refers to the class of reality that has been selected to be represented by the generic model. It should contain a description of the general process and its physical boundaries, as well as initial assumptions that can be made that apply to *all realities of the defined class.*

The *modelling goal* should specify the intended use of the model in generic modelling. It should also contain, as with conventional modelling, inputs and outputs, type of distribution, etc. (see Section 2.3.1.1 on p.14), but only characteristics that are applicable to the whole range of models (realities). Mathematical principles, which apply to every reality in the set of realities being modelled, should be included in the modelling goal. This will lay the generic foundation on which similar, yet different, models can be built.

2.3.2 Step 2 – Identify controlling factors

Controlling factors or mechanisms refer to the physical and chemical processes and phenomena that take place in the system.

2.3.2.1 Controlling factors in conventional modelling

According to Hangos and Cameron (2001:26), the most important and common controlling factors are:

- Chemical reactions
- Diffusion of mass
- Forced or free convection or radiation heat transfer
- Evaporation
- Turbulent mixing
- Heat or mass transfer through a boundary layer
- Fluid flow

Most of the factors mentioned above apply mainly to chemical processes. In most practical scenarios the controlling factor "*mass transfer through a boundary layer*" will exist, as this refers to the movement of objects or material into and out of the system being modelled.

As shown in Figure 2.3, there is a possible "backward" leap from Step 7, *validation of the model*, to this step. This will occur when process characteristics have been incorrectly included or not fully examined (Hangos & Cameron, 2001:26). These errors will only become apparent during the validation step and will result in reworking the model from this step onward.

2.3.2.2 Controlling factors in generic modelling

All physical and chemical processes and phenomena that can take place in any instance of the class of realities, as defined in Step 1, need to be included. Where the process or phenomena is dependant on a certain characteristic of a reality, the effect of this characteristic should be investigated and included as a variable parameter. The direct result of variable parameters is that a class of similar processes can be generically modelled, instead of modelling each one separately.

2.3.3 Step 3 – Evaluate the problem data

When the problem data is evaluated, the same principles apply to conventional and generic modelling. As mentioned earlier (see Section 2.1.1 on p.9), it is seldom possible to "white box" model a real-world system. There is usually process data or parameter estimation required that form part of the "black" part of a "grey box" model. Process data must be gathered and parameters defined. The uncertainty and precision of the data and estimated parameters also require special consideration (Hangos & Cameron, 2001:28). This can be achieved by including the confidence of the accuracy of the data as a statistical parameter. As also mentioned earlier (see Section 2.1.3 on p.12), inaccurate data is one of the main sources of error during model building (Mouton, 2001:177).

2.3.4 Step 4 – Construct the model

Model construction refers to the development of a set or sets of model equations.

2.3.4.1 Model construction in conventional modelling

Hangos and Cameron (2001:30) describe this development in eight sub-steps:

1. Identify regions where mass, energy or momentum accumulates, known as balance volumes.
2. Define characterizing variables associated with the inputs, outputs and internal states of the system.
3. Establish balance equations for conservation of mass, energy and momentum.
4. Specify rate expressions for transfer of heat mass and momentum between balance volumes.
5. Specify physical and chemical properties and their relation to balance volumes.
6. Specify relationship between physical volumes and balance volumes.
7. Specify equipment and control constraints.
8. Document modelling assumptions for previous steps.

2.3.4.2 Model construction in generic modelling

Very few model equations will be fixed for all real-world systems being modelled. One would expect that there would exist at least one variable parameter, which would have a varying effect on the outcome of each derived model equation.

For example, in warehousing, each warehouse has a different number of forklifts available (see Section 2.3.4.1, Sub-step 7: equipment constraint on p.16) on site. By keeping the number of forklifts variable one can use the generic model to answer what-if questions or determine the optimal number of forklifts.

Another example would be where liquid is heated in a tank. If the size of the tank and the energy input are variable parameters, various real-world tanks can be modelled.

It is proposed that the eight sub-steps (see Section 2.3.4.1 on p.16) be followed loosely, keeping in mind that specific concepts must be generalised for the defined class of realities.

2.3.5 Step 5 – Develop a modelling procedure

A modelling procedure must be found and implemented for the mathematical form of the model. All input, output and control variables defined in Steps 1 to 4 must be satisfied (Hangos & Cameron, 2001:29). The result of the developed modelling procedure must also satisfy the requirements of the modelling goal. This will apply to both conventional and generic modelling. If the implementation of the modelling procedure into a computerized model is required, it will be included in this step. It is expected that several iterations will be required to verify the model successfully (see Figure 2.3).

2.3.6 Step 6 – Verify the model

Verification is performed by comparing the model behaviour against expected behaviour using test data. The test data should include typical, boundary (minimum and maximum) and unexpected values. Ways must be explored to prove the model inaccurate instead of merely confirming correct behaviour (Bekker, 2004:14). If incorrect behaviour is found, Steps 4 and 5 must be repeated to ensure that the model is correct and that all variables are satisfied (Hangos & Cameron, 2001:29). The same applies for generic modelling, but test data must also be applied to variable parameters to test typical, boundary and unexpected realities.

Verification can also refer to testing the behaviour of a computerized model. This will include debugging of code and checking the logic for inaccuracies (Hangos & Cameron, 2001:29).

2.3.7 Step 7 – Validate the model

Validation ensures that the right model has been built (Bekker, 2004:15) and is done by testing the model against independent observations or assumptions (Hangos and Cameron, 2001:29).

2.3.7.1 Validation during conventional modelling

According to Hangos and Cameron (2001:29), there are several ways to achieve validation, including:

- Experimental verification of the simplifying assumptions
- Comparison of the model behaviour against the actual process behaviour
- Development of analytical models for simplified cases and comparison of the behaviour
- Comparison with other models using a common problem
- Comparing the model directly with process data
- Sensitivity studies to identify key parameters and inputs

If it is found that the model is unsuitable or inaccurate, the process must be repeated from Step 2 onward (Hangos & Cameron, 2001:29).

2.3.7.2 Validation during generic modelling

Testing the behaviour of a generic model against all possible realities in the class of realities would be very time consuming. Not requiring testing for all realities is also one of the main reasons for developing a generic model. Instead, the behaviour of the model should be tested against one or more specific cases. Testing typical, as well as "extreme realities" would provide for confidence in the validation. If inaccurate behaviour is found, the process must be repeated from Step 2 onward, as with conventional modelling.

If all the steps of the developed methodology have been followed strictly, the validated generic model should be valid for every instance of the selected class of realities.

This chapter explored the modelling methodology required to develop a generic model. The generic modelling methodology was developed from an existing methodology developed by Hangos and Cameron (2001:29). In the subsequent chapters, the developed generic modelling theory and methodology are put to the test by using them to develop a generic hard citrus packing model.

In the next chapter, Steps 1 and 2 are carried out. It also includes an introduction to the citrus packing industry. This is followed by Step 3 in Chapter 4, in which the process data is presented.

CHAPTER 3
PACKING HOUSE MODELLING

In this chapter background information on the typical citrus packing line is presented to grant the reader a basic understanding of the processes involved before they are modelled in the consecutive steps of the developed generic modelling methodology. The chapter further describes the implementation of the first two steps of the generic modelling methodology that was described in the previous chapter from the existing seven step modelling procedure of Hangos and Cameron (2001:29).

3.1 INTRODUCTION TO FRUIT PACKING

In this section an introduction to the fruit packing industry is given. This is done, before the formal modelling problem definition, to provide familiarity with the processes and operations that take place in and around a citrus packing line.

3.1.1 The packing house and packing line

A citrus packing house is a combination of facilities, machinery, equipment, personnel and procedures which convert harvested fruit into acceptable market-ready packages (Wagner & Sauls, (s.a.)a:3). The packing line is a critical part of the packing house and involves a series of processes; usually tipping, trash elimination, pre-sizing, cleaning, pre-grading, fungicidal treatment, waxing, grading, sizing, marking, packaging and palletizing (Miller & Ismail, (s.a.):3; Harris, 1988:chap.5.2).

Wagner and Sauls ((s.a.)a:3) and Harris (1988:chap.5.2) both state that no two packing lines are identical in size, process order, layout or efficiency, but that all are similar. Miller and Ismail ((s.a.):3) visualise the packing line as various standard unit processes that are matched together or combined.

A reason why packing lines in different regions vary is that they serve different market needs (Miller & Ismail, (s.a.):2). In Florida, USA, the packing of second grade citrus is of minor importance. Furthermore, most of their citrus is distributed locally, as opposed to the Southern African citrus crop, which is weeks away from its markets (mostly in the northern hemisphere e.g. Europe, Japan, USA, etc.). Therefore a different approach needs to be adopted here (Ortmann, 2005:31). It is also common practice in South Africa to pack two export grades and crate or bag a third for the local market. This was observed during visits to four major packing houses in South Africa (personal observation, 2005).

The working area of the packing house is typically divided into three sections: pre-packing line (unloading, degreening, temporary storage), packing line and post-packing line (assembly and loading of packed fruit) (Wagner & Sauls, (s.a.)a:3-4). All operations at and around the packing house are centred on the processes taking place in the packing line.

3.1.2 Packing line processes

A well-designed packing line should allow maintenance or enhancement of the quality of the incoming product while providing flexibility for marketing needs (Miller & Ismail, (s.a.):3). The packing of citrus fruit starts with an initial intake stage where crates or trailers are emptied into the line. The fruit flow is regulated into a constant flow of fruit. During the following packing line processes, the flow of fruit is graded several times according to the size, colour and quality of the fruit, while several product enhancing or recording processes take place at various stages throughout the packing line.

A flow diagram of the typical processes found in a South African citrus packing line is shown below. The diagram is an amalgamation of descriptions and similar diagrams from several sources, as well as personal observations (Goede Hoop Citrus, 2005; Grierson & Wardowski, 1977:137; Miller *et al.*, 2001:2; Outspan, 1998, chap.3:4 & personal observation, 2005). The processes involved are briefly discussed after the figure is presented. Each process and most of its variations are discussed in more detail in Chapter 5, where the generic modelling of the processes is also described. To give an indication of how the various fruit flows divide throughout the packing line, the various grades of fruit are shown.

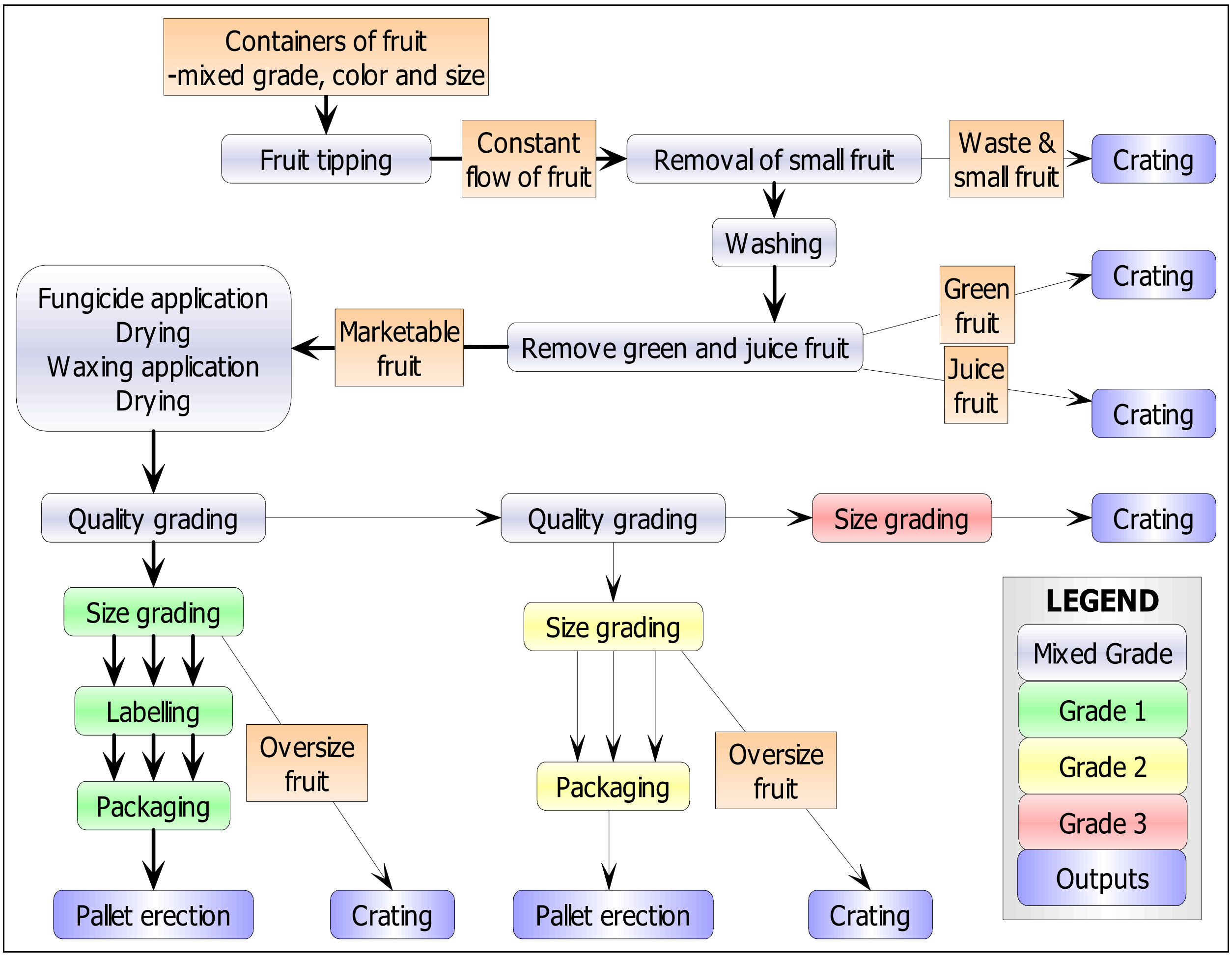


Figure 3.1: Process flowchart of typical citrus packing line

3.1.2.1 Fruit tipping

Crates or trailers of fruit are transported to the tipping machines. The containers are then tipped into the packing line one by one (personal observation, 2005). An in-depth analysis of fruit tipping is presented in Section 5.2 on p.67.

3.1.2.2 Removal of small fruit

Small fruit are usually removed mechanically at this early stage of the packing line and then crated. According to G. Verster from Goede Hoop Citrus (GHC) (personal communication, 28 September, 2005), this is done because the fruit have almost no marketability. An in-depth analysis of the small fruit removal units is presented in Section 5.4.2.2 on p.83.

3.1.2.3 Washing

The fruit are washed when they move across static rotating brushes and often a high pressure water spray system is used to improve the washing process. This process removes all foreign materials such as dirt, scales and insects from the fruit surface. An in-depth analysis of the washing process is presented in Section 5.3.1 on p.70.

3.1.2.4 Pre-grading – removal of green and juice fruit

Fruit that have not coloured sufficiently, or that have no marketable value, are removed from the main flow of fruit by hand. The green fruit might be treated for colour improvement before being crated. The crates of green fruit are stored in controlled cold storage that improves colour. Unmarketable fruit are sent to the juice factory (G. Verster, GHC, personal communication, 28 September, 2005). An in-depth analysis of removal of unsuitable fruit is presented in Section 5.4.2.1 on p.79. For more on the fruit colour classification, see Section 3.1.3.3 on p.24.

3.1.2.5 Fungicide, waxing and drying

Fungicide, usually diluted in water, is applied to the fruit. The fruit are dried using brushes, a drying tunnel or both. Fruit that are to be used for making juice may not contain fungicide residues and therefore need to be removed from the main fruit flow before this process is reached (Miller *et al.*, 2001:2). Wax is applied to the fruit as the natural wax has been brushed and washed off during the washing process. The wax layer is then dried in a drying tunnel. An in-depth analysis of these processes is presented in Section 5.3.1 to 5.3.3 on pp.70-77.

3.1.2.6 Quality grading

Manual quality grading is commonly done in two stages. Firstly, Grade 2 and 3 fruit are removed (primary grading) so that the Grade 1 fruit remain. Then the Grade 3 fruit are removed from the Grade 2 and 3 mix (secondary grading) at separate grading tables. At some citrus packing facilities, manual grading has been replaced by optical grading systems that do quality, size and colour grading (personal observation, 2005). An in-depth analysis of manual and optical grading systems is presented in Section 5.4.2.1 and 5.4.2.3 on pp.79 and 83. For more on the fruit quality classifications, see Section 3.1.3.1 on p.23.

3.1.2.7 Size grading

Where quality grading is done manually, size grading of Grade 1, 2 and 3 fruit is done mechanically. Oversized fruit are removed at this stage and are then crated. If optical or electronic grading is used, size, quality and colour grading can be done simultaneously (personal observation, 2005). An in-depth analysis of size grading systems is presented in Section 5.4.2.2 and 5.4.2.3 on p.83 and 84. For more information on the fruit size classifications, see Section 3.1.3.2 on p.23.

3.1.2.8 Labelling

Fruit might need to be labelled depending on the target market. Only Grade 1 fruit are usually labelled (Capespan (Pty) Ltd Citrus Business Unit, 2005:52). An in-depth analysis of labelling units is presented in Section 5.3.4 on p.77.

3.1.2.9 Packaging

Fruit are packed into cartons by hand according to packing patterns determined by fruit size. Each carton contains an exact number of fruit of a certain size and grade. In some cases, each fruit of every second layer is wrapped in wax paper. Carton packaging is commonly used in South Africa as cartons are later stacked into easily manageable pallet units (Ortmann, 2005:11). An in-depth analysis of packaging is presented in Section 5.6.1 on p.85.

3.1.2.10 Crating

The following fruit are removed from the main stream of fruit at various stages:

- Undersized fruit
- Oversized fruit
- Green fruit
- Low quality fruit
- Grade 3 fruit

The undesirable fruit roll off a conveyor belt and straight into large crates (personal observation, 2005). An analysis of crating is presented in Section 5.6 on p.84.

3.1.2.11 Pallet erection

A number of cartons are stacked onto a wooden pallet according to a certain pattern that is mainly dependant on the carton type being used (Ortmann, 2005:11). An in-depth analysis of pallet erection can be found in Section 5.6.2 on p.88.

3.1.3 Fruit input

Most of the processes described in the previous section are strongly affected by the quality, size or colour of the fruit being processed. For instance, low quality fruit will slow down the packing line as the grading stations, as well as the Grade 2 packing tables will be working at maximum capability, while Grade 1 packing tables will be almost idle. Packing lines are typically designed for 70% to 80% of the fruit being Grade 1 (G. Verster, GHC, personal communication, 28 September, 2005).

Controlling the three fruit characteristics of quality, size and colour, is a major issue for most producers. Each of the three characteristics will now be discussed, as well as aspects of the total fruit volume. In Chapter 4, industry data that enables better understanding of these characteristics and their statistical variance is presented.

3.1.3.1 Fruit quality

Fruit quality cannot be improved after the fruit have been harvested. It can, however, be worsened by inappropriate handling (Harris, 1998, chap.3.1&3.3). Before fruit are harvested, quality is determined by the conditions under which the crop is grown, the horticultural practices used, the fruit variety and the time of the year it was planted. Thus the ultimate market quality of the produce is determined by the producer from the moment he selects the crop, the variety and the production system (Harris, 1998, chap.3.1).

Before fruit are harvested, the quality could be negatively affected by various types of insects, weather conditions such as hail and wind and fruit formation disorders, among others. Harvesting under cold or wet conditions causes oleo, which is only visible after a few days. After harvesting, the quality is primarily worsened by bad handling techniques and faulty equipment (Harris, 1988, chap.3.1).

Fruit quality is typically divided into five categories. The best grade is primarily sent to elite export markets, the second grade is exported or sold locally, the third grade is sold locally in shops and by hawkers and the worst grade of fruit is used to make juice. Fruit that are completely unusable are referred to as waste and are usually removed from the line and destroyed offsite (G. Verster, GHC, personal communication, 28 September, 2005). It is rare for more than 80% of fruit to be accepted as Grade 1 fruit (Wagner & Sauls, (s.a.)b:6). According to Miller *et al.* (2001:2), over 50% of the fruit may be unacceptable as Grade 1 fruit.

A primary goal of a fruit packing line is to accurately grade fruit, with only a small tolerance for inaccurate grading (4% inaccuracy allowable) (Outspan, 1998, chap.12:13). In Section 4.2 (p.47), the analysis of production run reports and development of a fruit quality distribution are presented. A method to predict the quality of fruit that have not yet been packed is investigated.

3.1.3.2 Fruit size

Fruit size distributions are primarily determined by the fruit variety, but seasonal conditions also play a role. Industry fruit size classification is done by the number of fruit that fits into a certain carton size using a certain fruit packing pattern. The number of fruit in a carton is referred to as the *count*. Typical citrus counts are 144, 125, 105, 88, 72, 64, 56, 48, 40 and 36 for the popular A15C carton (400 x 300 x 270 mm) (Capespan (Pty) Ltd Citrus Business Unit, 2005: 3,50,52). In this study, the fruit size classifications will be referred to as Size 1 to 10, for fruit count 144 to 36. According to Capespan's Packing Guide (2005:53), the permitted difference in diameter between the smallest and largest fruit in a carton is 6mm.

During a typical production run, there is usually a certain size that is most common and up to 45% of the fruit may be of a single count (See Section 4.2.1 on p.47). This peak count varies considerably between production runs and it follows that different equipment setups are required to handle this variation in the peak count.

3.1.3.3 Fruit colour

Fruit colour for citrus fruit is divided into eight colour classes. These classes are defined by colour charts (Appendix A), ranging from orange-red (Chart 1) to solid green (Chart 8). Fruit colour in citrus fruit is improved by cold weather, fruit maturity and other conditions. At the beginning of the citrus season (the beginning of winter), fruit are internally mature, but they look immature externally. This is not acceptable to the buyer. Fruit colour becomes less of a problem at later stages of the season, when sufficient cold weather has been experienced (Wagner & Sauls, (s.a.)a:1; Outspan, 1998, chap.6:2). As fruit are shipped at very low temperatures, fruit colour improves during the voyage up to two colour classes (Outspan, 1998, chap.6:17).

Fruit that are not within the two best colour classes have very little market demand (Outspan, 1998, chap.6:1). Fruit that are deemed unacceptable because of insufficient colour are removed from the main fruit flow early in the packing line processes. Colour is then manipulated by using cold storage or nitrogen gas methods, among others (Outspan, 1998, cap.6:9). When the colour has improved sufficiently, the fruit are sent to the packing line again for treatment, grading and packaging.

According to Outspan's Citrus Production Guidelines (1998, chap.6:9), the most promising method of improving colour is the use of ethylene gas degreening chambers, as their operation is independent of ambient temperature. Ethrel improves the fruit colour with one to two colour classes over a six to eight day period (Outspan, 1998, chap.5:24). For successful degreening, it is essential that fruit colour has broken before fruit are picked, i.e. the fruit colour is not a solid green, but does have patches of orange. Fruit colour Classes 5 and 6 are the most suitable for degreening, while Classes 3 and 4 will experience sufficient colour improvement during the voyage (Outspan, 1998, chap.6:10).

It is important to note that all fruit cannot be degreened, as well-coloured fruit should not be subject to degreening since it could damage fruit quality (Outspan, 1998, chap.6:10). In the packing line the green fruit must therefore be separated from the main fruit flow for degreening.

3.1.3.4 Fruit volumes

The volume of fruit handled each year is determined by several factors. According to Harris (1988: chap.3.1) the conditions under which the crop are grown, the horticultural practices used, the variety of crop grown and when it was planted, all play a role in how big the harvest will be. New orchard developments also contribute to the variability of the volume of fruit.

According to G. Verster from GHC (personal communication, 28 September, 2005), producers send estimates of fruit volumes to the packing house at various stages during each season and contracts are drawn up each year for delivery of estimated volumes and markets that are to be targeted. The packing house therefore has an estimation of the total amount of fruit that will be delivered. Data was gathered that show the deviation from the estimated, contracted figures.

A brief description of important aspects of the typical citrus packing line has been presented in this section. The remainder of the document describes the implementation of the generic modelling methodology described in the previous chapter.

3.2 PROBLEM DEFINITION

Step 1 of the developed generic modelling methodology (see Section 2.3.1 on p.14) requires that a problem definition be generated; this includes the *process system specification* and the *modelling goal*.

3.2.1 Process system specification

The first part of the process system specification requires the definition of the **set of realities to be modelled.** For the purposes of this study, the "set of realities" refers to all variations of citrus fruit packing lines. The primary source of variation is the use of diverse methods to clean, grade and pack fruit. Another source of variation is the different equipment and personnel setups that can be used. All processes that take place in the packing line during normal packing operations, and their possible setups, will therefore need to be analysed.

The boundaries of the process will be determined by defining the system and its inputs and outputs, as seen in Figure 3.2.

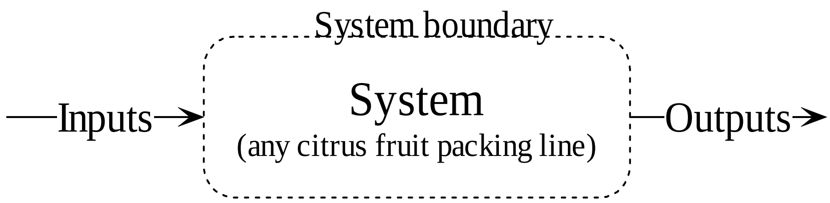


Figure 3.2: System, inputs and outputs and boundary

3.2.1.1 System inputs

According to G. Verster from GHC (personal communication, 28 September, 2005), fruit are delivered to the system by tractor or forklift with fruit in trailers and bins respectively. The fruit may be from local storage or directly from the farms, either way, the only impact the method of delivery has, is the size of the container. It is assumed that the system never waits for containers, as this rarely happens and should ideally never occur as the whole packing line is then delayed.
Other inputs are electricity, water, chemicals and packaging material. Although water and electricity are both critical to the operation of the packing house, it is assumed that both are always available. It

should be noted that large volumes of water are consumed by the fruit preparation processes, as well as for cooling facilities (Harris, 1988, chap.5.3).

Through personal communications with, and observations at GHC, as well as other packing houses (September 2005), it was found that chemical inputs include soap, fungicide, wax and degreening chemicals. These system inputs are process specific and should ideally be in ample supply. It is therefore assumed that the chemical inputs will not run out. Some of the chemical inputs do, however, have an effect on specific processes, but these will be elaborated on in Chapter 5 in which the modelling of the relevant processes is described.

Another system input is packaging material, which is used in various forms. It was found, through personal observations and personal communications in September 2005, that lower grade fruit are usually dumped directly into crates from a conveyor belt, while top grades are hand packed into cartons, which are then palletized. Although packaging material only enters the system at the very end of the packing process and it is not the primary interest of this study, it does contribute substantially to the total packing cost (G. Verster, GHC, personal communication, 28 September, 2005). Basic packaging material consumption will therefore be included to assist with cost calculations. The arrival or availability of packaging material is dependant on the method of delivery and will be included in the modelling of the relevant processes. Packaging material types include sacks and nets, wooden crates, cartons or fibreboard boxes, plastic crates, baskets and pallet boxes (Harris, 1988, chap.4.1).

3.2.1.2 System outputs

Fruit exiting the system can do so in various packages (see previous paragraph) or directly on a conveyor belt (G. Verster, GHC, personal communication, 28 September, 2005). One of the primary reasons for the use of packaging material is that it forms a container for produce and creates a more efficient handling unit which can be easily handled by one person. The packaging should protect the produce at all stages of the marketing process, from the packing house to the consumer (Harris, 1988, chap.4.2).

The fruit therefore leave the system in batches of various sizes or at a "per second" rate in the case of a conveyor. For validation of the model, it is important that all fruit entering the system must also leave the system. This includes undesirable fruit such as green, oversized, undersized and juice fruit, as well as waste (Outspan, 1998, chap.3:4).

Water, usually containing various chemicals and bacterial spores also leaves the system. The treatment and disposal of this water is of considerable importance, but does not fall within the scope of this study.

3.2.1.3 System process

The system that is to be modelled includes all processes that fruit undergo between the input and output stages as described above. All factors that have a significant effect on any of the above-mentioned processes must also be included.

When any fruit packing line is viewed as a single system, as in Figure 3.2, it is easier to see the "big picture". As the inputs and outputs of the system have been defined in the previous paragraphs, the system itself must now be described to complete the initial picture. The nature of this description is still general to allow the inclusion of all possible variations of packing lines.

The processes in any citrus packing line can be divided into three groups. These groups are fruit preparation, grading and packaging (Harris, 1988, chap.5.2). Fruit preparation refers to the processes that enable accurate grading and long shelf life and includes the cleaning, waxing and drying of the fruit.

Fruit are graded according to their colour, quality and size characteristics. These fruit characteristics have been discussed earlier in Sections 3.1.3.1 to 3.1.3.3 (pp.23-24) and industry data is presented in Chapter 4. Grading occurs frequently during the typical packing line as people are normally employed to do this and it is common practice to have a person grade only a single fruit characteristic. Colour or quality grading is usually done by hand, while size grading is done by rollers or other mechanisms (Outspan, 1998, chap.7:1).

During the packaging process, fruit can be packed into cartons (which are then built into pallets), bagged or dumped in crates. The packing method is usually dependant on the grade of fruit being packed. When fruit of the same size are packed into cartons, a specific packing arrangement is employed for the size being packed. Severe problems may arise if the size grading was inaccurate as the fruit may be damaged in transit at a later stage due to cartons being overfilled (Capespan (Pty) Ltd Citrus Business Unit, 2005:52).

While it would have been possible to model these three process groups separately, the correct operation of grading and packaging is strongly dependant on the accuracy of the preparation processes (Miller *et al.*, 2001:2). It therefore makes sense that the system should be modelled as a whole.

3.2.2 Modelling goal

The modelling goal specifies the intended use of the model and has a direct effect on the level of detail which is required (Hangos & Cameron, 2001:21).

3.2.2.1 Intended use of the model

The purpose of the *final model* will be to propose "best"-setup configurations for all processes and to predict where the bottleneck or system constraint will be for each planned production run. It is therefore required that the effect of the variability of production runs be investigated and that all possible setups and their respective process responses be modelled. The model should also validate the concept that a packing line can be modelled as a system of unit operations linked with flows of fruit.

The following specific client requirements were presented in Section 1.1 (p.1) and will be required as outputs of the *final model*.

- Tipping rate that would assure the correct quality of the output.
- Number of graders required at each grading station.
- Number of packers required at each packing table.
- Number of cartons required for each fruit count/quality.
- Number of pallets required for each count/quality.
- Runtime of the production run.

3.2.2.2 Model classification

While visiting role-players in the industry, it was noted that during a production run most processes are in a steady state (fruit input rate is equal to the fruit output rate). Processes that are dynamic are only found in the packaging group (see Section 5.6 on p.84). This dynamic nature occurs as a result of a steady input and an uneven fruit output, which results in a build-up of fruit. The build-up is worked away at the end of the production run. Citrus packing lines cannot be classified according to one of the model classification criteria presented in Section 2.1.1 (p.9), but are hybrid in all aspects as discussed below.

The nature of the model data is not restricted to only being stochastic or deterministic. Most of the processes have clear cause-effect relationships, but the fruit being processed have natural random variances and are therefore stochastic. The model contains a range of independent variables as well as several relationships that depend on representative variables making the model not exclusively of type lumped or distributed parameter. Most equations are linear and linearity was assumed on several occasions in Chapter 4, but some are non-linear and this adds complexity to the model. The number of fruit that is packed in a production run is discrete, but the rate at which it is to be processed is continuous.

And lastly, some parts of the model were solved using industry data, while other parts were developed using physical laws making the model a "grey box" model. The model can therefore not be classified as a specific model type, but rather as a hybrid on all levels. Where industry data was analysed to form the "black" part of the "grey box" model, a 95% two-tailed statistical significance was used. Figure 3.3 shows the 95% two-tailed statistical significance test for the normal distribution. The dark areas on the left and right each represents 2.5% of the total area under the graph.

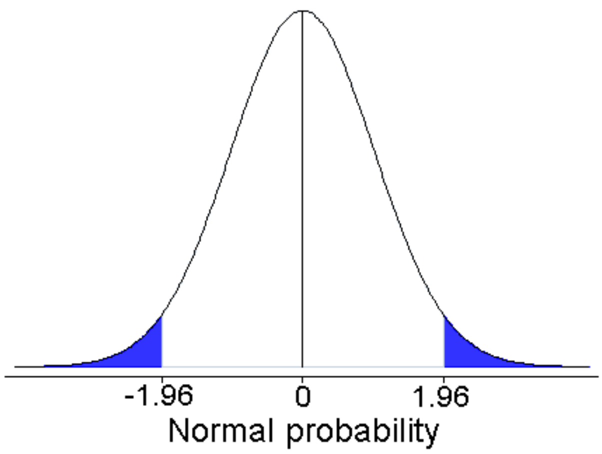


Figure 3.3: Two-tailed statistical significance for normal distribution

This concludes the first step of the generic modelling methodology described in Chapter 2. The next step identifies controlling factors that are relevant to the problem at hand.

3.3 IDENTIFY CONTROLLING FACTORS

When fruit enter a packing line, they typically arrive in a container from which the fruit are dumped into the line. When fruit are transferred between different processes in the system, conveyor belts are typically used. Most of the time only one layer of fruit is found on conveyor belts and rollers. At the end of the line, fruit are packed into cartons. The area and volume that fruit take up will now be investigated. The rate at which fruit enter each production unit must equal the rate at which it leaves, unless the process accumulates fruit and is therefore dynamic in time.

3.3.1 Area covered by fruit on rollers/brushes

The area that fruit occupy is dependant on the size of the fruit, the number of fruit that arrives per second and the speed of the rollers. In processes where static brushes are used, arriving fruit push fruit through the system. In this case the brush unit needs to be filled up at the start of every production run and needs to be cleared manually at the end of the production run.

The following two assumptions were made to enable modelling of these units. The first is that fruit are lined up perfectly and when a fruit enters, another leaves simultaneously. The effect of this assumption is that fewer fruit will fit on the unit in the model than in reality. The second assumption concerns the spaces between fruit, evident in Figure 3.4. It is assumed that these spaces do not exist and that the fruit are tightly packed in a row. The effect of the second assumption is that more fruit will fit on the modelled unit than physically occurs.

When fruit are on rollers, they are lined up next to each other on the rollers (see Figure 3.4). Therefore the fruit diameter only plays a role in one dimension.

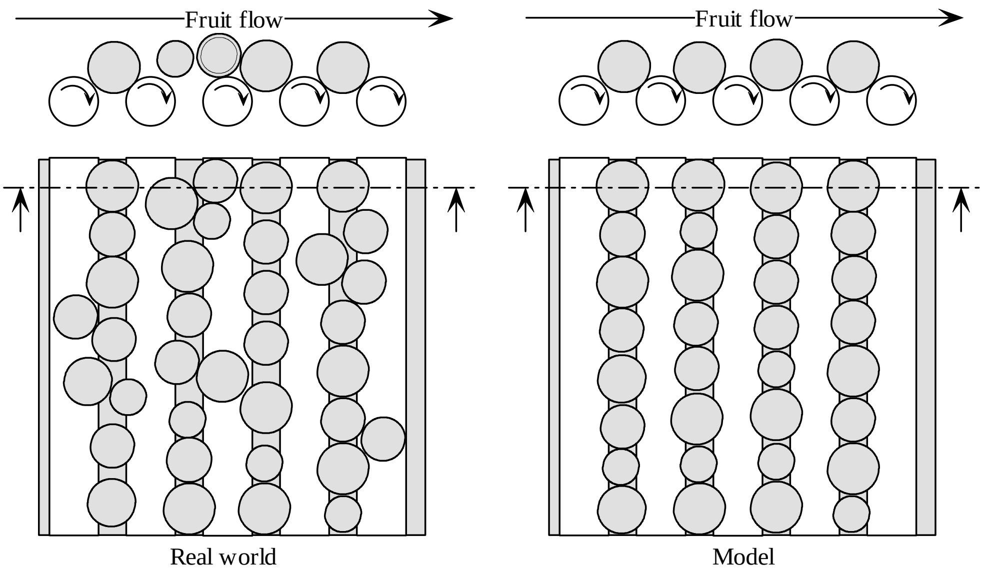


Figure 3.4: Fruit on static brushes/rollers

A test was done to check the validity of the two assumptions and to estimate the combined effect. The number of fruit on or between four brushes was counted twelve times by freeze-framing a video that was taken at GHC in September 2005. The observations, the mean number of fruit (91.8 fruit), the 95% lower and upper expected values of the average, as well as the calculated average of the observations are shown in Figure 3.5.

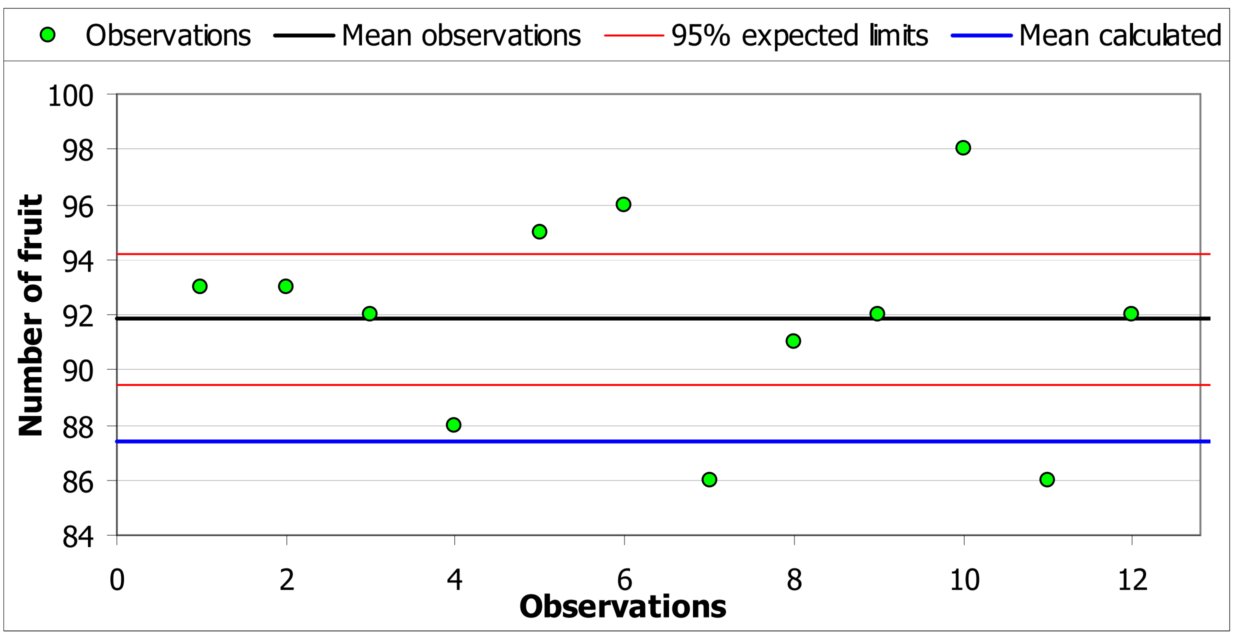


Figure 3.5: Testing assumptions of fruit on rollers/brushes

After capturing data of the relevant packing run, the average fruit size was calculated as 77.8 mm. The brush length (1700 mm) was divided by the average fruit size (77.8 mm) and multiplied by the number of brushes (four). The average number of fruit that is expected to be present on the four brushes was calculated as 87.4 fruit. A paired t-test, with a resultant p-value of 0.0017 (p < 0.05 indicates statistical significance), indicated that the observations and the value calculated from the above assumptions are significantly different. The modelling assumptions therefore need to be corrected with the amount of deviation observed. The calculation was conservative as the calculated mean estimates the capacity of the unit at 95.2% of the true capacity, or between 92.8% and 97.7% if the 95% lower and upper limit of the expected average is used. When models that make use of these modelling assumptions are built, the conservative nature of the estimate of the mean will need to be taken into account. Equation 3-1 shows the values of the correction of the above assumptions.

$$P_C = 0.9518 \pm 0.0238 \quad \textbf{(3-1)}$$

3.3.2 Volume filled by fruit in containers

The volume that fruit take up must be explored as fruit enter and leave the system in containers. Before fruit are packed into cartons, they accumulate at a packing table. An important concept in this calculation is the *average volume per fruit* which consists of two parts, the *physical fruit volume* and *volume lost per fruit*. The *physical fruit volume* is dependant only on the diameter of each fruit, while *volume lost per fruit* represents the empty space between the fruit. The *density* or *pack factor* refers to the *total physical volume* of the fruit, as a percentage of the *total volume* of the container.

Initially, it was thought that the average size (diameter) of the fruit and size variance will play a role in the density. It was however found that both these factors have virtually no effect on the density. This analysis and graphs will be presented after sphere packing theory is introduced.

When identical spheres are *ideally packed*, the *Kepler Constant* represents the maximum density (ρ_{Kepler}) that can be achieved. The *Kepler Constant* is 74.048% of the total volume as seen in Equation 3-2, i.e. if the total volume is 100 cm^3, then 74.048 cm^3 will be *physical fruit volume* and the remaining 25.052 cm^3 will be *lost volume* (Hale, 1998:1).

$$\rho_{Kepler} = \frac{\pi}{\sqrt{18}} \approx 0.74048 \quad \textbf{(3-2)}$$

As the *Kepler Constant* represents the *ideal packing of identical spheres*, it was thought that *different size* fruit being dumped *randomly* into a container (*random sphere packing*) will alter this value. It was expected that the *random sphere packing* (not *ideal packing*) would increase lost space, while size variance and the fact that fruit yield slightly when pressed, should both decrease lost space.

Random sphere packing theory provides many estimates of densities that may be achieved. Recently Nermoen (2006:23) studied random sphere packing theoretically and experimentally. The following paragraph is a brief summary of his findings.

Two density limits are examined; the *Random Close Packing* ***(RCP)*** limit can be obtained by vibrating the sample, while the *Random Loose Packing* ***(RLP)*** limit is the lowest packing density that is still mechanically stable under external load. The values for both are displayed in Equations 3-3 and 3-4. Loose sphere pouring experiments by Nermoen (2006:24) resulted in a density of 0.615 (shown in Equation 3-5 as ρ_N), which is slightly lower than ρ_{RCP}.

Equations 3-3 to 3-5 give an indication of expected values when random filling is used, as is done when fruit are packed and when crates are filled. The sphere packing theory presented above was tested against industry data with interesting results. Data of sixty production runs from GHC of five producers over three years was used to test the above-mentioned relationships.

$$\rho_{RLP} = 0.555 \pm 0.05 \tag{3-3}$$

$$\rho_{RCP} = 0.6355 \pm 0.05 \tag{3-4}$$

$$\rho_N = 0.615 \tag{3-5}$$

A beta distribution was fitted to the size distribution of each production run (see Section 4.2.1 on p.47) and an average size and variance were calculated. The average fruit size ranges from 70.7 mm up to 88.2 mm, while the variance in fruit size ranges between 3.6 mm and 8.7 mm. The average mass per crate was also calculated for each production run. By combining fruit size, average crate mass, typical fruit mass per size and crate size data, supplied by GHC (2005), the packing density was calculated for each production run. The full table of data and calculations can be viewed in Appendix B.

Initial analysis introduced an unexpected factor, namely the effect that the producer has on the packing density. From personal communication with G. Verster in September, 2005, as well as personal observations, it was found that crates are not filled to the top to guard against fruit damage during handling. Typically containers are filled to about ten centimetres from the brim, but this measure varies. It was concluded that the variation from one producer to the next can be attributed to the fact that their employees consistently fill crates to within a certain height from the top. The following graph (Figure 3.6) displays the calculated packing density for five producers over three years.

The producer number, on the graph, is only used for identification and has no numerical value.

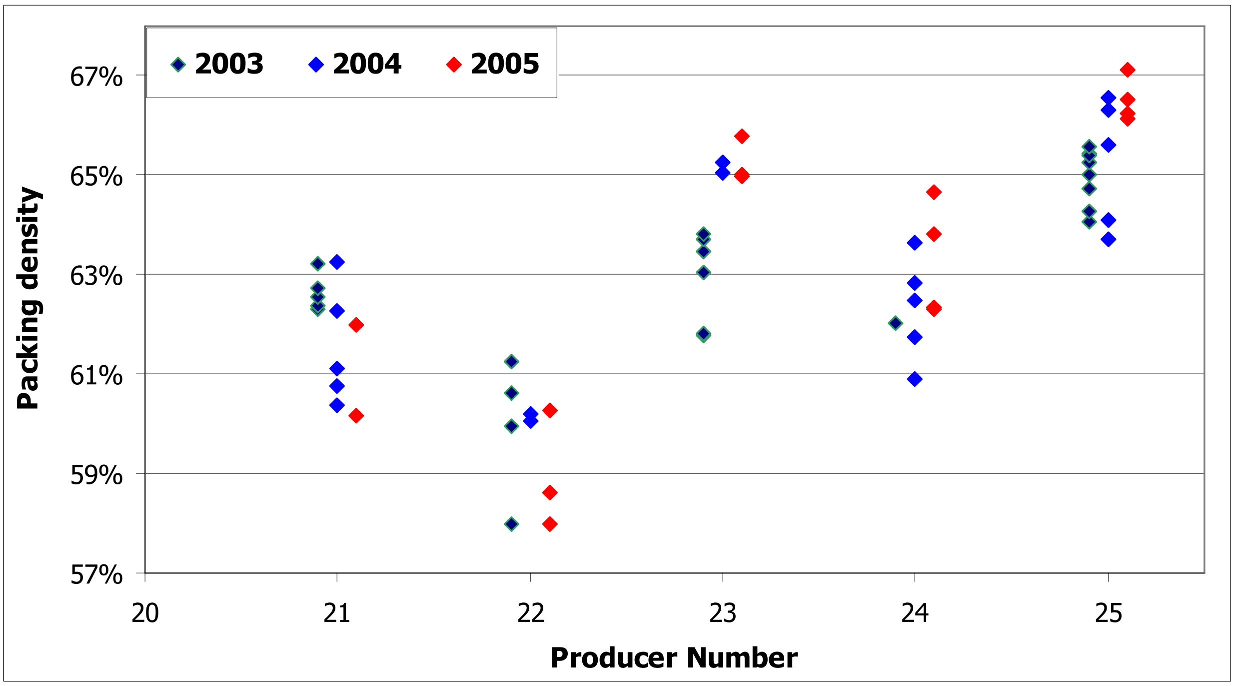


Figure 3.6: Packing density per producer

While producers 21, 23 and 24 have an average of about 63%, producers 22 and 25 deviate from the average with a considerable amount. Producer 22 is seen to "play it safe" by not filling the containers to the norm, while producer 25 would run a risk of damaging the fruit by overfilling.

To calculate the relation of packing density to fruit size and fruit size variance, the effect of the producer was removed by normalizing and keeping the average pack factor constant (see table with calculations in Appendix B for details). Figures 3.7 and 3.8 display the result of these calculations.

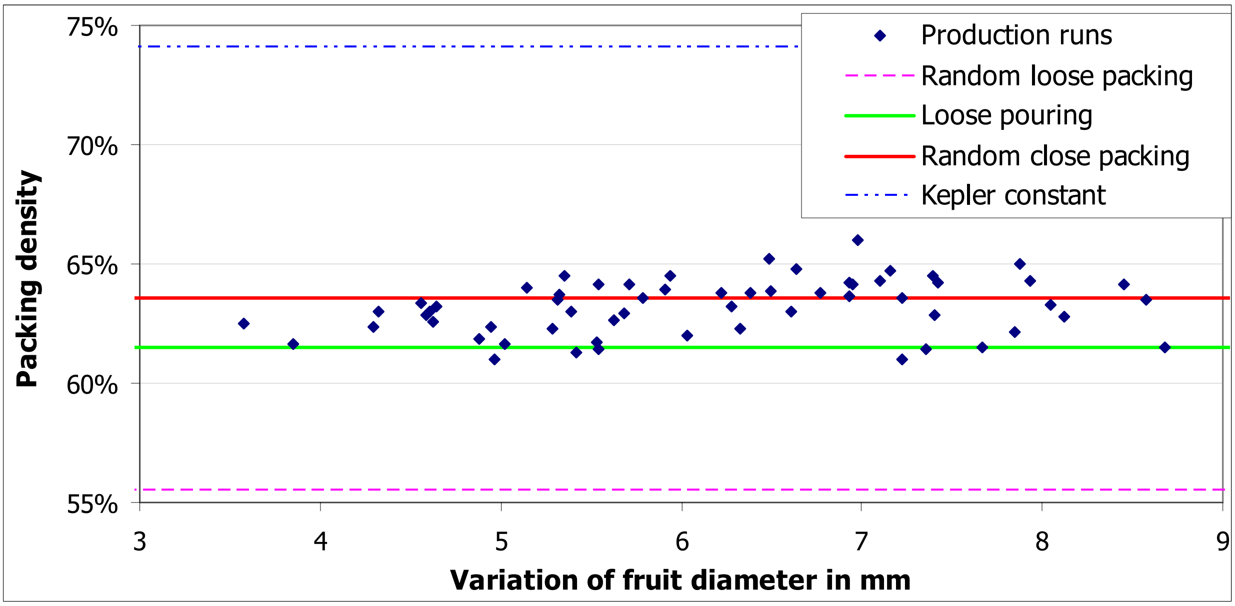


Figure 3.7: Packing density and fruit size variance

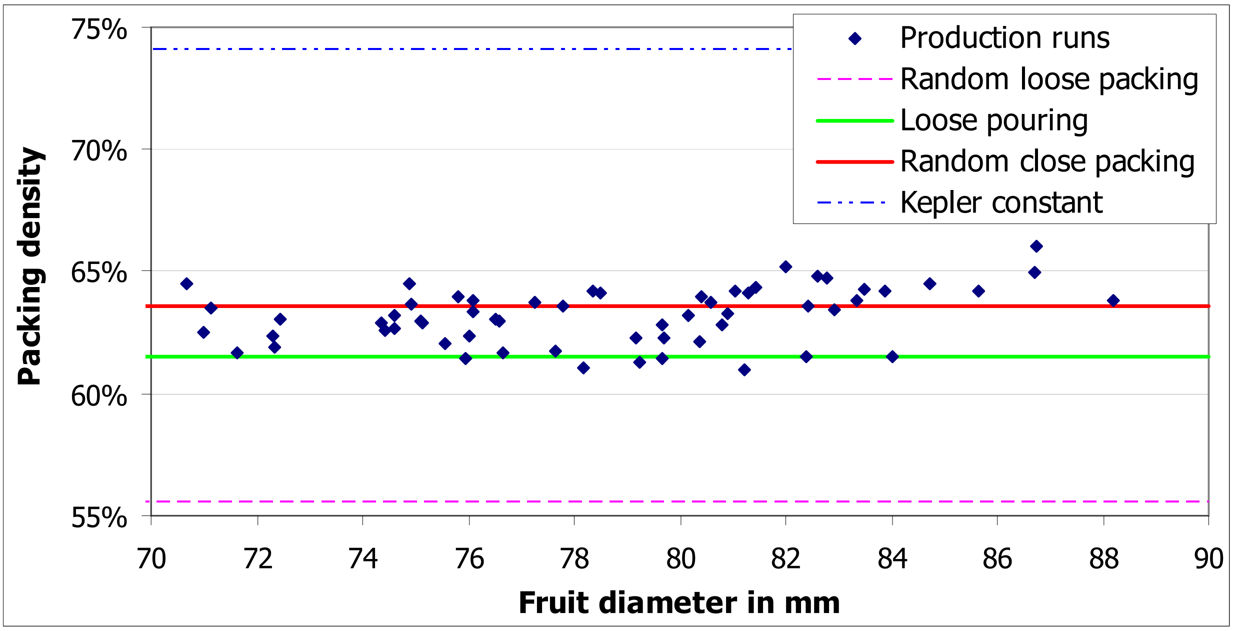


Figure 3.8: Packing density and fruit size

From Figures 3.7 and 3.8, it is clear that samples vary over a range of filling percentages. It is, however, within expected tolerances as indicated by sphere packing theory. It is never less dense than the *Random Loose Packing* density as this would be impossible, but the average density (63.19%) for the production runs falls within the range of the *Random Close Packing* density (63.55% ± 0.5%).

Figure 3.9 shows the mean density and production run densities, with the 95% statistical range for production run observations.

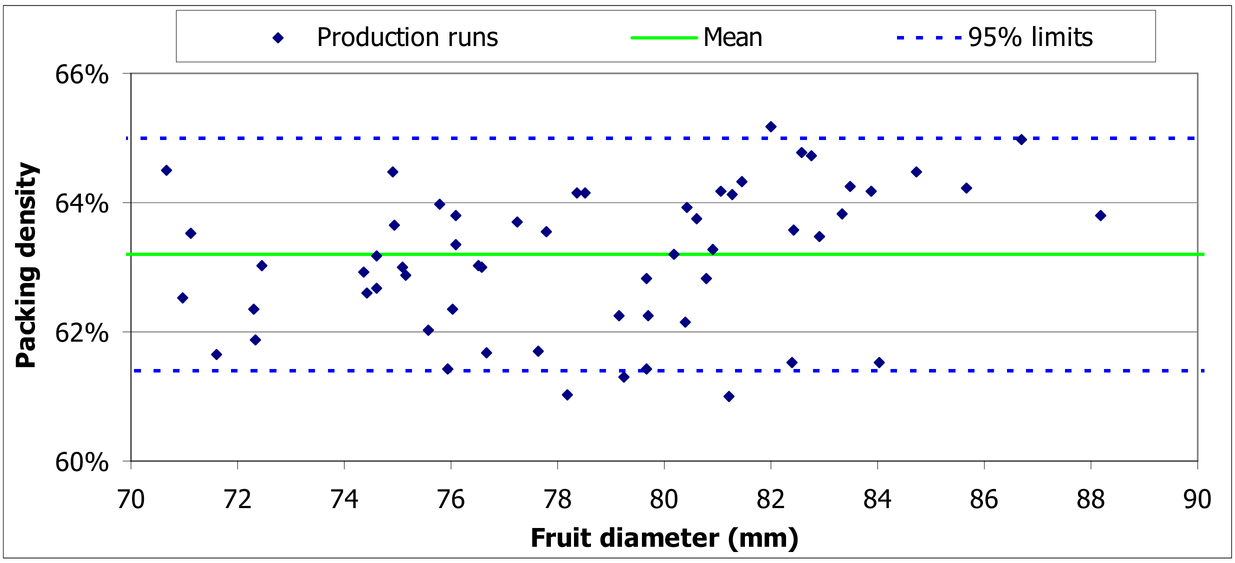


Figure 3.9: Packing density and fruit size – Actual fit

The latter values will be used in Chapter 5 to estimate the number of fruit in a container, and for purposes of this document, will be known as the adjusted Kepler packing densities (ρ_{AKV}), which is:

$$\rho_{AKV} = 0.632 \pm 0.019 \quad \textbf{(3-6)}$$

When lower grade fruit leave the system, they are usually dumped into crates and have possibly been graded by size. The ρ_{AKV} will also assist in calculating the expected number of crates that will be required for each output.

3.3.3 Area covered by fruit on conveyor belts

Conveyor belts are the most common method of transporting fruit between processes. It is rare that a conveyor belt becomes a system constraint as this would constitute a serious design error. However, various conveyor belt widths can only handle a certain volume of fruit, and therefore conveyor capacity must be estimated. The theory on two-dimensional sphere packing is very similar to three dimensional packing presented in the previous section. For this reason, it is assumed that variance of fruit size does not play a role in two-dimensional packing, as was proved for three dimensional packing.

The maximum packing density attainable for equal sized discs packed in two dimensions is 90.7% and each disc then touches six others (Hinrichsen, Feder & Jdssang, 1990:4199). For a disc to be stable, a minimum of three touching discs is required. Using an algorithm specially designed for the purpose, Hinrichsen *et al.* (1990:4208) calculated that discs in two dimensions achieved a packing density of 77.2 ±0.2% of the total area, when random packing is used.

When the experiment above is applied to fruit on conveyor belts, it would enable the calculation of conveying capacity. The use of the theoretical packing density in the fruit industry was not verified as part of this study, but refinement of the packing density will be made possible by allowing the value to be changed in the generic model. For the purposes of this study, the packing density of 77.2% with a 2% margin of error (similar to that of the ρ_{AKV}) will be accepted. The packing density will be noted as:

$$\rho_A = 0.772 \pm 0.020 \qquad \textbf{(3-7)}$$

3.3.4 Generic variable parameters

At this stage, the generic areas of the model need to be identified. The model will be generic with regard to different packing lines, various fruit types and various production runs. These three areas of difference are supported by three groups of variable parameters.

The first group of variables is *hardware specific* and enables the modelling of similar yet different packing lines. These variables are set when a specific reality is represented by the generic model and remains fixed, unless the physical packing line is changed. These variables will also be set when a hypothetical or "test" packing line is represented by the generic model. Where equipment have a range of possible setups (e.g. number of personnel, operating speeds, etc.), the range is included in this group of variables.

The second group of variables represent *industry standards* of the fruit being packed. Processing limits and other parameters that are fruit type specific are set once and remain constant for all realities of this fruit type being modelled. When the industry standards change, these variables will have to be changed and when analysis of a new type of fruit is required, the data has to be created for all applicable processes. This variable group represents controlling factors of desired packing results. For example, Navel oranges need to be washed for a minimum of 20 seconds for adequate cleaning and 30 seconds for particularly dirty fruit (Wagner & Sauls (s.a.)b:2).

The third group of variables represents data of a single production run. Expected fruit quality, size and colour distributions are entered, as well as the number of containers and required outputs. Typical distributions will be part of the second group defined above as these remain fixed per fruit type.

When implemented in Chapter 5, these three variable groups will be known as *User Defined Variables*, *Fruit Info* and *Run Info,* respectively.

3.3.5 Generic process groups

While visiting fruit packing facilities, it became clear that most of the basic elements of the processes used in the packing line are very similar, either for all processes or for groups of processes. In order to eliminate duplication of work, processes with similar inputs and outputs were grouped together.

The processes were grouped into six generic groups which are briefly presented below.

1. Fruit transfer:

   This group represents processes whereby fruit are introduced into the system. Fruit will always be arriving in crates or trailers which will be converted into a continuous flow of fruit.

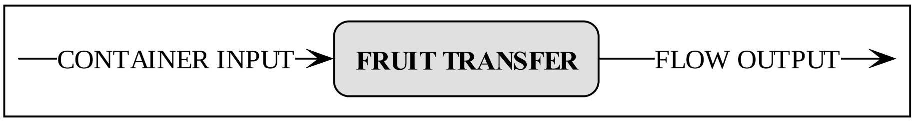


Figure 3.10: Fruit transfer

2. Specific process:

   A specific process that changes or records an element of the fruit. The input and output of these processes are always equal after steady state has been reached.

Figure 3.11: Specific process

3. Flow division:

   Grading (3.1 in Figure 3.16) or random (3.2 in Figure 3.16) flow divisions split fruit flows into two or more flows. Grading is realized by dividing fruit flows according to one or more fruit characteristics and can be achieved by hand, mechanical or optical grading. Random flow divisions are achieved by mechanical conveyor dividers and the fruit flow proportions can be controlled.

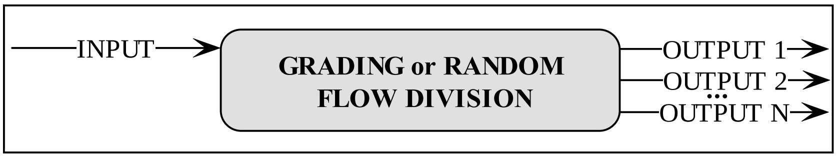


Figure 3.12: Flow division

4. Flow convergence:

   A convergence of two or more flows. The inputs and outputs can be either a flow of fruit or filled cartons. The output will be equal to the sum of the inputs.

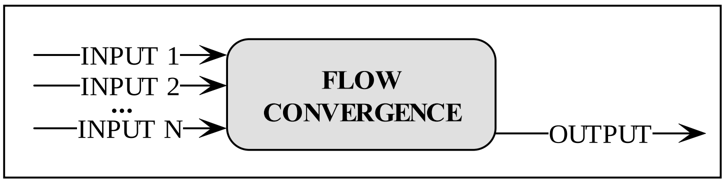


Figure 3.13: Flow convergence

5. Packing or stacking:

   The transfer of continuous flow input (either fruit or filled cartons) to containers (cartons, crates or pallets). Incoming items are built into units containing two or more of the original items.

Figure 3.14: Packing or stacking

6. Flow control:

   Flow control processes where line selections can be made. In Figure 3.15, it can be seen that these processes have multiple inputs (I) and multiple outputs (O). The usual setup is that there are more outputs than inputs ($O>I$), i.e. at least one of the inputs will divide into more than one output. Flow control processes are mostly used to route fruit to packing tables of various sizes.

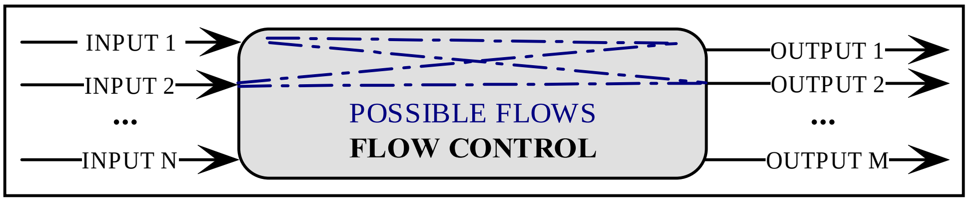


Figure 3.15: Flow control

In Figure 3.16, the use of the above-mentioned process groups is illustrated. The flowchart represents a typical citrus packing line where hand grading is used and it is derived from Figure 3.1.

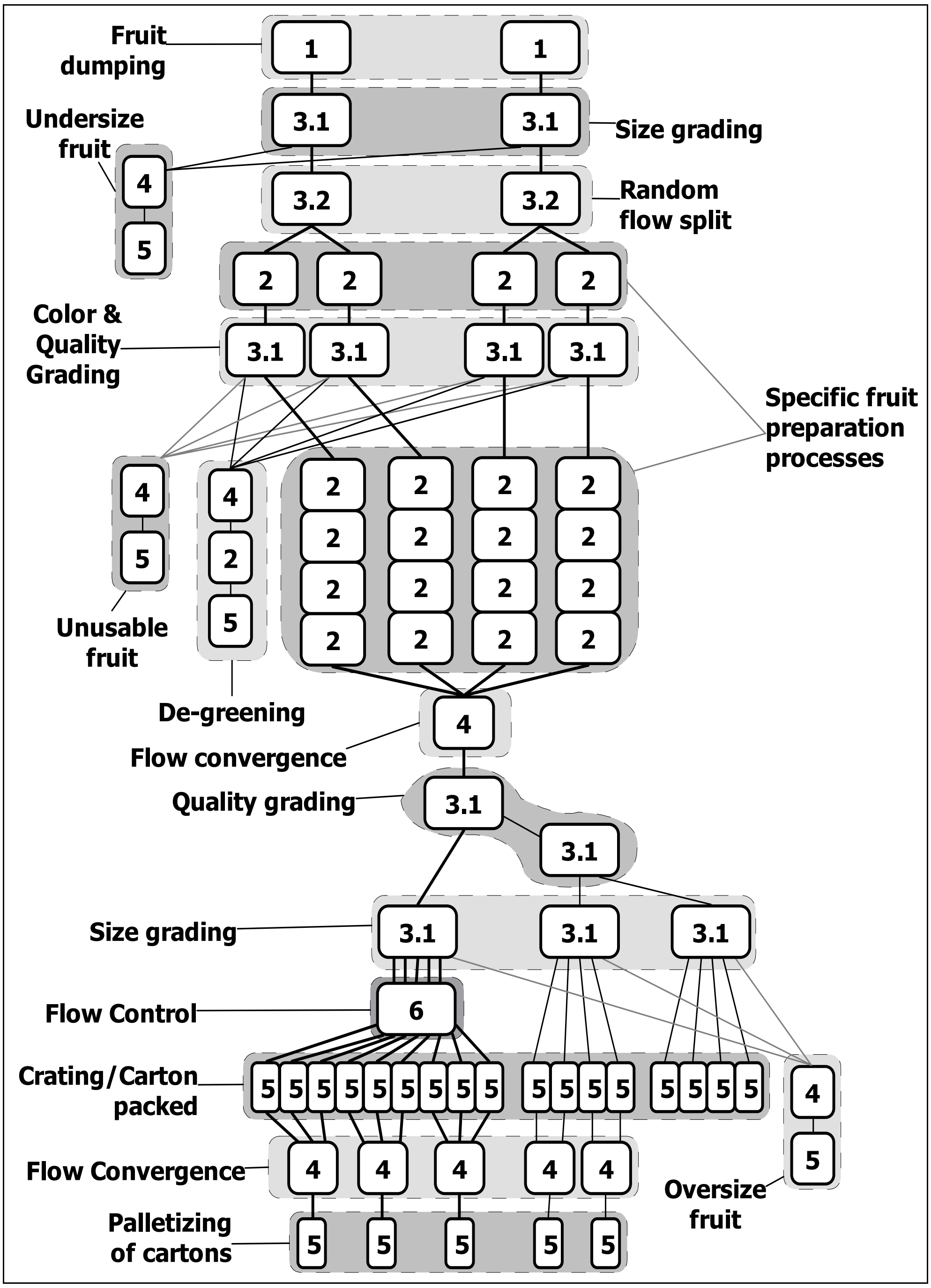


Figure 3.16: Grouping of processes into generic process groups

The numbers in Figure 3.16 represent the six process groups as follows:

1. Fruit transfer from containers
2. Specific processes
3. Flow division (3.1 – grading, 3.2 – random)
4. Flow convergence
5. Packing or stacking into containers
6. Flow control

Each process group, its inputs, outputs and implementation will now be discussed. The detailed mathematical modelling is presented in Chapter 5 in which the model construction is described.

3.3.5.1 Transfer of fruit from containers to continual flow

There are two container types (crates and trailers) that are most often used to transport fruit from the orchard to the packing house. The transfer of fruit from these containers to a constant flow of fruit is modelled by this type of process. The *maximum rate* at which containers can be emptied and *parts per container* are the main parameters required to calculate the *maximum output* for this type of process. See Section 5.2 (p.67) for more information on the detailed calculations.

The input of this process represents the complete system input as this type of process is used to introduce fruit into the packing line. Everything that is known about the fruit in the containers must be part of the input of the model as it will be used to create the output of this process type, which is of course the input for the next process and the rest of the packing line. The following inputs are required:

- The number of containers and their mass, if available
- Fruit size distribution (Beta distribution)
- Fruit colour distribution
- Fruit grade distribution

When a planned production run is modelled, the three distributions can only be estimated. Distribution estimation methods are discussed in Chapter 4, in which the analysis of process data is also presented.

3.3.5.2 Specific processes

Examples of *specific processes* are washing, fungicide application, waxing, drying, labelling and optical data recording of fruit. The input flow of fruit will equal the output flow of fruit if the capacity of the specific process is not exceeded.

This generic group will be used to model processes that are fundamentally different and the capacity calculations will therefore depend on the specific process and its requirements. Several of the processes contain the same basic operating principles, such as static roller and dynamic roller processes.

3.3.5.3 Flow divisions

Processes where flow divisions occur can be grouped into *grading* and *non-grading* processes. Where the flow on a conveyor belt is divided into multiple flows, it is done on a random basis and this is a *non-grading* process. A *grading* process is when fruit are divided into multiple flows based on one or more characteristics of the fruit. *Grading* processes can be grouped into hand, mechanical and optical grading processes. Each output of a *grading* flow division will contain recalculated distributions for the fruit characteristics, as well as a lowered "per second" rate, because some fruit with specific characteristics have been removed and constitute one of the process outputs. For instance, at pre-grading, the main fruit flow is divided into three flows. Green fruit and Grade 4 fruit make up two of the outputs while the main fruit flow now has no green or Grade 4 fruit in it.

It is, of course, logical that the sum of all the outputs must equal the input, even if the capacity is exceeded. For instance, if the grading capacity of a secondary grading table (where Grade 3 fruit are removed manually) is exceeded, it will result in some Grade 3 fruit being packed as Grade 2 fruit.

3.3.5.4 Flow convergence

Flow convergence will occur when two or more conveying lines flow into a single conveying line. The sum of the inputs will equal the output unless the maximum capacity of the output line is exceeded. The input distributions with their relative flow rates will be used to calculate the output.

3.3.5.5 Packing or stacking

The input for this type of process can be fruit or cartons and the output will be cartons and pallets respectively. The number of input units that is packed or stacked into one output unit and the rate at which the packing or stacking can be done determines the maximum capacity for these processes.

Once a container has been filled, there is usually a replacement time that is dependant on the availability of the removal tool (forklift or by hand) and the next container to be filled (empty pallets, cartons, bags and bins) as discussed in the previous paragraph. The replacement time will be included in the modelling of the relevant processes.

3.3.5.6 Flow control

Where there are several input and output flows and different setup possibilities exist, a flow control process will be needed. This type of process is usually found just before fruit packaging and allows different packing table selections to be made. The flow control process takes into account fruit parameters, as well as the capacity of the subsequent processes to determine where each flow should go. This process is always a non-grading process and all input flows that contain fruit must exit through one or more outputs. The conveyor belt widths will also be taken into account.

Consider for example, the case of two inputs of different size fruit and three outputs to packing tables. I_1 (Input 1) fruit can go to either O_1 (Output 1) or O_2 or to both, while I_2 fruit can go to O_2 or O_3 or both. The best solution will depend on the flow quantities of I_1 and I_2. If, for instance, $I_1 > I_2$ then I_1 will divide between O_1 and O_2 while I_2 only connects to O_3.

This chapter started with an introduction to the typical citrus packing line and continued to document the first two steps of the generic modelling methodology described in Chapter 2. In the next chapter, industry data is presented to provide a better understanding of the processes taking place and to explore some elements as "black box" systems. The collection, preparation and analysis of the industry data is the third step of the generic modelling methodology.

CHAPTER 4
FRUIT DATA

In order to model fruit packing, data of packed fruit was gathered from the industry. The complete data capturing procedure that was followed is presented in this chapter. This represents the third step of the generic modelling methodology described in Chapter 2. The fruit data is analysed to view the system as a "black box" (as described in Section 2.1.1 on p.9), where the internal workings of the system are unknown, but where the inputs and outputs are known. The outputs are then used to evaluate what occurs in the system.

During a production run, the quality, size and colour of fruit determine how the flow of fruit will be divided throughout the packing line. These fruit characteristics can vary considerably between two production runs and are the primary drivers for system variability. For these reasons, the above-mentioned fruit characteristics were specifically studied and distributions were fitted. The collected data was also used to create an input estimation method, using typical distributions and annual data.

To determine the number of fruit in an input container, the fruit density (mass/volume, kg/mm^3) must be used in combination with the total fruit mass (kg). Where fruit mass differs with fruit size (volume, mm^3) the relationship between the two must be taken into account.

4.1 SAMPLING AND DATA COLLECTION

To acquire knowledge of common fruit distributions, three citrus packing facilities were visited and data gathered. The three facilities that were visited are; Piketco (Pty) Ltd at Piketberg, Goede Hoop Citrus Ltd at Citrusdal and Namakwaland Citrus (Pty) Ltd at Clanwilliam, all in the Western Cape (see Figure 4.1 for a map of the three areas where the facilities are located). While all three of these facilities are within a 100km radius of each other, each serves a local group of citrus producers. These three facilities were chosen because it is expected that there will be a localized trend in crop size and fruit colour, quality and size. This trend is expected to exist on small scale also, between producers in the same area.

Figure 4.1: Map of the three areas where the three packing facilities are situated

Data, for five large producers over three years (2003, 2004 and 2005), was requested from each of the three facilities, for two hard citrus cultivars (Navel and Valencia). Unfortunately the data that was received, did not match the requested criteria, as data was either not available, it would have taken too much time to gather or the request was not fully understood. The data that was received, did however, enable statistical testing and analysis. Appendix C contains samples of the production reports that were received. Identification data has been removed to ensure the anonymity of the data, as requested.

All data collected, was drawn from databases that were populated as the fruit were processed. The origin of the data is of great importance, as this has a direct effect on the nature and objectiveness of the data. The different origins will now be presented.

4.1.1 Piketco data

Data of five producers for the year 2004 was collected for the two hard citrus cultivars, respectively. For each producer, a season summary was acquired, as well as the largest of the producer's production runs. Data of a total of 42 production runs was received. The selected producers have the largest harvest in the region and the data represents 2 322 tons of fruit.

4.1.2 Goede Hoop Citrus data

Goede Hoop Citrus (GHC) has the largest single citrus packing operation in South Africa on one premise and currently handles 10% of South Africa's export crop (Goede Hoop Citrus Ltd., (s.a.)). For this reason it was important to get a wide range of data from GHC. Five of their largest producers in the region were selected. When a batch of fruit is delivered to the packing house grounds, data is captured by one of three systems, depending on the target markets and packing method. The three systems are for contract- , pool- and USA-contract packing, respectively.

When contract packing takes place, only a single producer's fruit is packed in a production run. The data collected during contract packing is very descriptive of the actual fruit parameters. When pool packing is done, several producers pool their fruit together to make up a production run. To maintain accuracy in the payment of the various producers, 2% of each producer's fruit is randomly selected and graded before production. The result of this test is used to allocate the payments for fruit as different sizes and grades of fruit receive different prices. The results of the 2%-tests, as well as the final pool, were made available for this study.

For the American market, only the very best quality fruit are acceptable. These fruit are packed as a "super"-grade, i.e. the best of Grade 1. For the purpose of the data analysis, the "super"-grade and the remaining Grade 1 fruit were added together.

Each of the three methods of packing therefore has different statistical origins. For this reason, data of 21 control production runs, from 17 different producers, was also made available for comparison. For the five main producers, data was gathered for one or both of the two cultivars (Navels and/or Valencias, depending on delivery over three years) for three seasons namely, 2003, 2004 and 2005. In total, data of 29 780 tons of fruit was obtained from GHC.

4.1.3 Namakwa Citrus data

At Namakwa Citrus, the packing results of five producers were made available for the 2005 season for Navel fruit only. A single production run was captured for one of the producers, two runs for three of the producers and three runs for the largest of the producers. The data collected represents 990 tons of fruit in a total of ten production runs.

In the case of Piketco and Namakwa Citrus, only limited data was made available. For each production run and season summary, the input is described by the total number of crates and their mass, while the output is described with regard to quality and size distributions, but no colour distributions.

4.1.4 Weather of the selected fruit producing areas

The three citrus packing facilities are geographically close to each other, but with a mountain range between Piketberg and the other two facilities. Weather conditions can have various effects on fruit and are therefore discussed here. With regards to temperature, the average minimum temperature is of more importance than the maximum, as fruit colour development is strongly reliant on low temperatures (Outspan, 1998, chap.6:2). Rainfall has a direct effect on the development of fruit size, as more rain increases fruit size (United States Department of Agriculture, 2001:30). However, excessive periods of rain can cause diseases, such as brown rot and moulds, which decrease fruit quality (Texas A & M University, (s.a.)).

Winds stronger than 6.7 m/s for more than one hour cause fruit damage in the form of physical scars. Excessive wind also reduces the crop yield and reduces fruit growth rates. Fruit are most susceptible to wind damage during the first 12 weeks after petal fall, which is in October in South Africa (CITT groups Australia, 2006:2-3).

For these reasons, data was requested from the South African Weather Service (personal communication, 13 March, 2006) concerning the temperatures, rainfall and wind on each side of the mountain. Unfortunately temperature averages and wind speeds were not available for the Citrusdal area. Figure 4.2 shows the temperature averages for Piketberg and Clanwilliam.

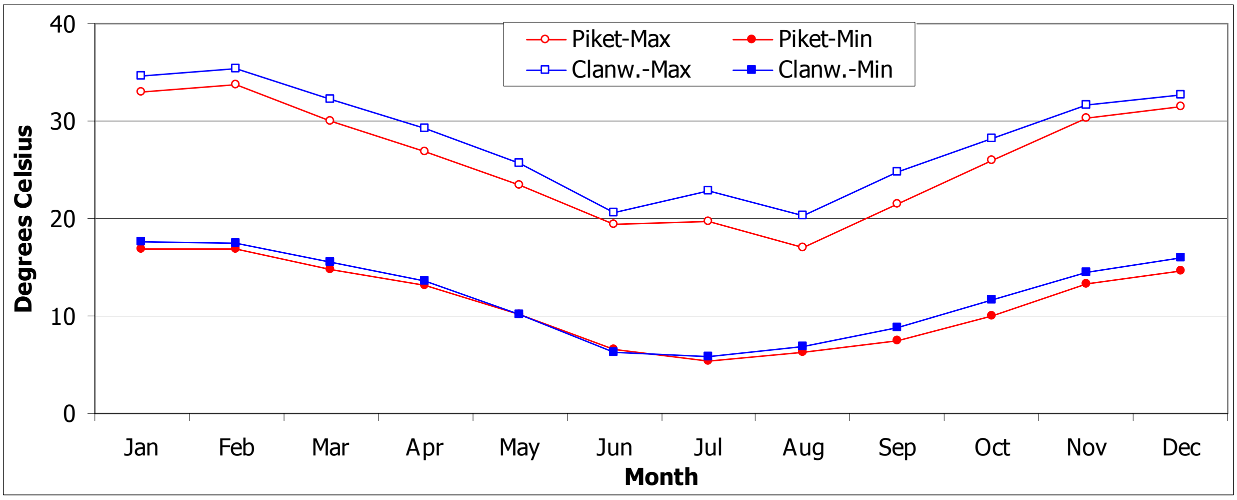


Figure 4.2: Daily max/min temperature average per month 2003 – 2005 (South African Weather Service, personal communication, 13 March, 2006)

It can be seen in Figure 4.2 that the minimum temperatures of Piketberg and Clanwilliam are strongly correlated, with Clanwilliam being marginally higher. As low temperatures are of primary concern for fruit colour development, and only a small minimum temperature difference can be observed, it is not expected to have a noticeable effect.

Figure 4.3 shows that Piketberg has the most rain all year round, followed by Clanwilliam and Citrusdal receiving the least rain.

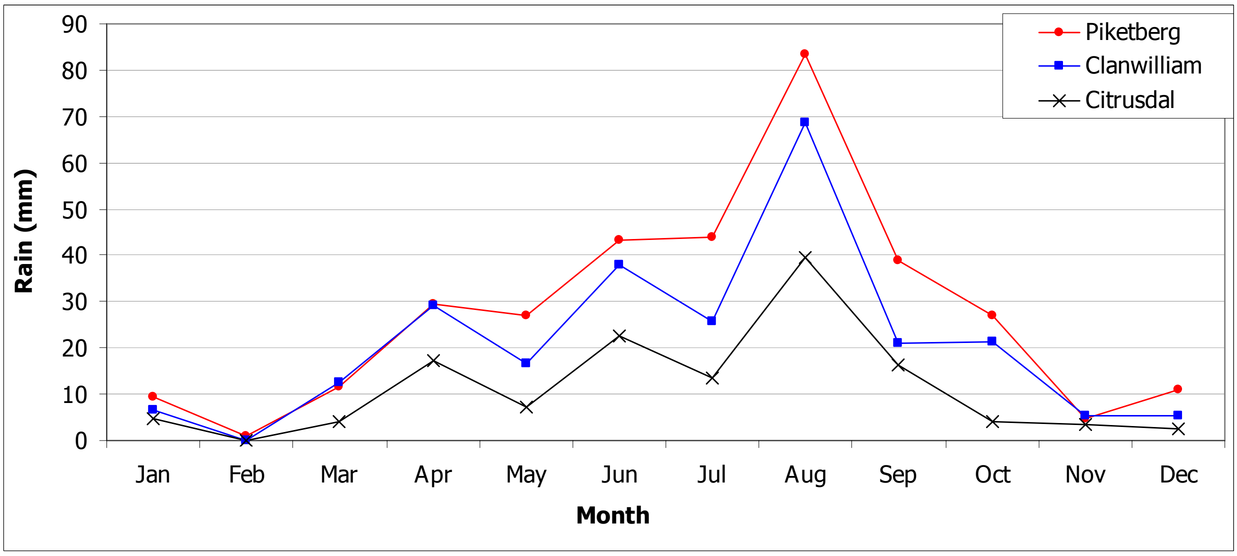


Figure 4.3: Monthly average rainfall for 2003 – 2005 (South African Weather Service, personal communication, 13 March, 2006)

As rain increases fruit size, but causes prospects of diseases, one would expect that fruit from Piketberg would be larger, but possibly of lower quality, while fruit from Citrusdal would be slightly smaller and of better quality. The size and quality of fruit from Clanwilliam are expected to fall in between that of the fruit from Piketberg and Citrusdal.

Figure 4.4 shows the average wind speed per month for Piketberg and Clanwilliam measured at 14h00 each day.

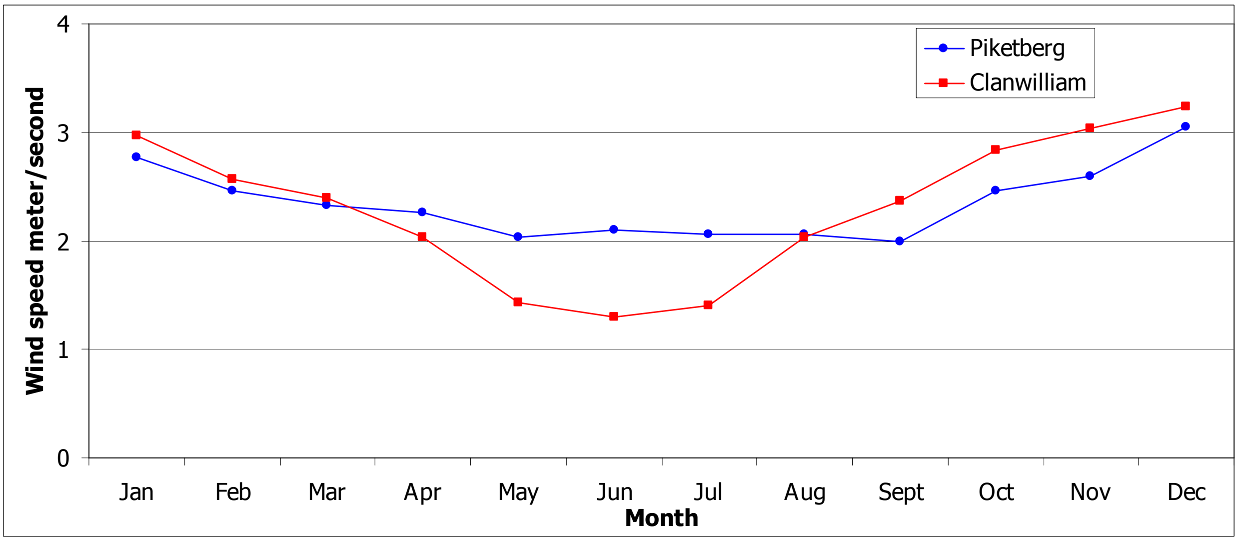


Figure 4.4: Monthly average wind speed for 2003 – 2005 at 14h00 (South African Weather Service, personal communication, 13 March, 2006)

The average wind speed of Clanwilliam drops considerably during the winter months, but is slightly higher than that of Piketberg during the rest of the year, including the three months after petal fall. The fact that the data received represents monthly averages does not enable direct comparison to the "6.7m/s for one hour required for damage"-rule. However, if it is assumed that a higher monthly average indicates higher maximum wind speeds, then it follows that the quality of Clanwilliam's fruit will be slightly lower than that of Piketberg.

The effect of the various weather conditions are summarized in Table 4.1 and discussed afterward.

Table 4.1: Effect of weather conditions on fruit

Weather condition	Fruit size	Fruit quality	Fruit colour
Strong wind	Smaller	Lower (October only)	
Heavy rain	Larger	Lower	
Low temperatures			Better

When the data was analysed the effect of the rainfall on fruit size and quality appeared to be valid. GHC had the smallest fruit and also the least amount of rain, with an average fruit diameter of 80mm, while that of the others were larger at 81.5mm and 85.5mm for Piketco and Clanwilliam. The average of Piketco's data indicates that the stronger wind also negatively influenced fruit size as Piketco had more rain through the year, but the wind in the winter months negatively influenced the fruit size. GHC also had the best quality fruit, with 55% of the fruit being of Grade 1. Piketco, on the other hand, had 50% Grade 1 fruit and Clanwilliam 45%.

4.1.5 Effect of market requirements

In several production runs, of which data was received, it was found that large and small fruit were not packed for the first or sometimes even the second grade, but that they were reduced to third grade or even sent to be juiced (Grade 4). This is done because of the low demand for these fruit, as large fruit often have low sugar levels and it is too much trouble to peel small fruit.

The effect of this is that the quality distributions are influenced by the size distribution. The size distribution however, has no such factors influencing it and is accepted as an accurate representation of the fruit sizes of each production.

Grading of fruit according to quality is affected by the requirements of the market for which it is destined. Some markets do not allow a certain type of defect at all, while other markets will accept it. The personnel that do the grading are informed about which defects should be removed.

4.1.6 Capturing and cleaning the data

As most of the data was entered by hand after it was received from the three facilities, the need arose to test for data capturing errors. This was done by having a double capturing system where both the numbers of cartons, as well as the respective fruit mass were entered. Typical carton mass values were calculated and, where the captured number of cartons and mass comparison revealed unexpected values, the validity of the data was checked.

Typical crate mass figures were also used to remove errors in the same way and, where production summaries were available, it was compared to the captured data. Data was entered into a Microsoft® Excel (2002) spreadsheet and the above-mentioned data validation was performed using standard Excel functions.

The various data sets were not immediately comparable after capturing, as the three packing facilities use different software packages to report on their production data. Where one set contained mass values, another had carton figures and another had proportions. Various calculations and modifications were made to allow direct comparison of the data sets. For more details on the various data sets, see Appendix D, which contains the modified, comparable data.

4.2 DATA ANALYSIS

In this section, data of the three fruit characteristics, namely size, quality and colour are analysed and distributions are fitted to the size and quality data.

4.2.1 Size distributions

For the purposes of this study, the interest in fruit size is threefold. Firstly, packing line input and output estimation requires that the number of fruit in each category be estimated. Secondly, the number of crates and the fruit size can be used to estimate the number of fruit to be processed. Lastly, fruit size has an effect on all processes as fruit take up physical space in each process.

The fruit size distribution is a continuous distribution, but each fruit is classified into a discrete size category depending on the size of the specific fruit. This is done for marketing purposes and also to ensure that fruit are not damaged during export. Typically a packing pattern is used that is specific for each fruit count. The first two levels of the packing patterns used for fruit counts 48 and 88, for the A15C carton, are shown in Figure 4.5.

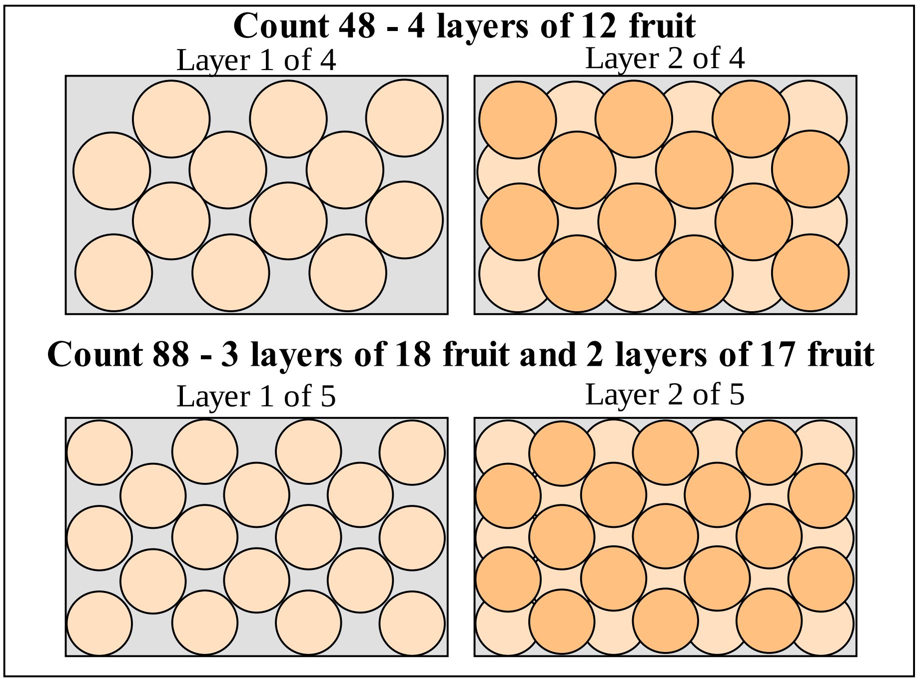


Figure 4.5: Carton packing patterns for fruit counts 48 and 88 for A15C carton

The fruit mass in each size category and for each production run was recalculated as a percentage of the total mass of the production run. An important factor that had to be taken into account before a distribution could be fitted was that each of the industry standard fruit size counts did not cover the same size range. Below is a table of the fruit size counts relevant to the captured data, and the acceptable fruit sizes for each, for the most common A15C carton (Capespan (Pty) Ltd Citrus Business Unit, 2005:52) (see Section 3.1.3.2 on p.23).

Table 4.2: Size ranges for A15C carton

Size category	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Fruit Count/Number of fruit per carton	**144**	**125**	**105**	**88**	**72**	**64**	**56**	**48**	**40**	**36**
Minimum size (mm)	None	62	65	69	73	77	81	86	90	95
Maximum size (mm)	62	65	69	73	77	81	86	90	95	None
Size range (mm)		5	4	5	4	4	4	4	3	

(Capespan (Pty) Ltd Citrus Business Unit, 2005:52)

In a study by Zhang and Robson (2002:1), the normal distribution was fitted on apple size data per tree. The normal distribution fitted only 172 out of 272 trees with a 5% level of significance. It was found that a large percentage of the distributions had significant skewness and/or kurtosis. While the above-mentioned testing was done on a "per tree" basis, the production run data is based on an orchard of trees and the normal distribution was initially chosen to represent the size distribution due to the CLT (sum of distributions).

Normal distributions were proposed and fitted to all 179 production runs for which data was available. The Microsoft Excel™ Solver tool was used to fit normal distributions to the data, by changing the average fruit size and size variance. Solver was programmed to minimise the number of fruit that is inaccurately represented by the distribution. The graphs in Figure 4.6 show two cumulative normal curves fitted to production data.

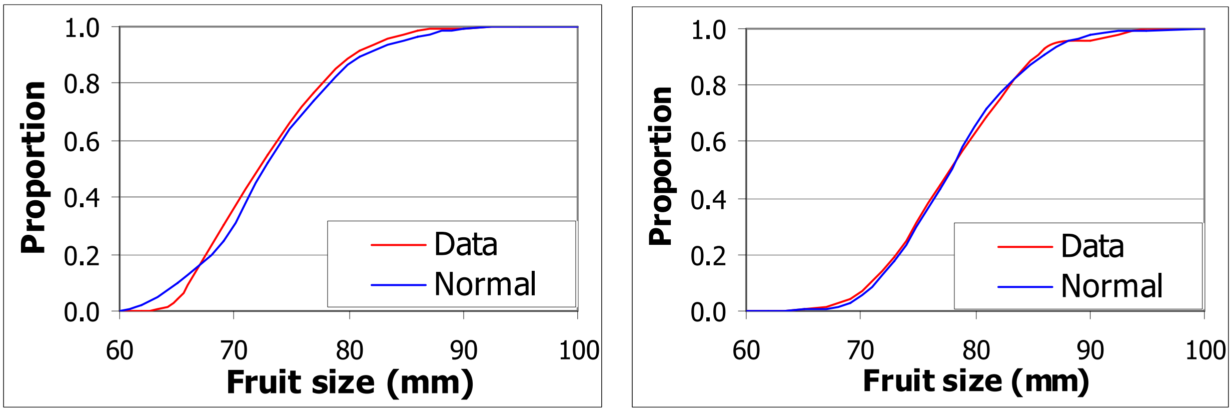


Figure 4.6: Normal distribution fit on fruit size

It was found that, while the graphical analysis showed little difference between the normal fit and the recorded data, several goodness-of-fit tests such as the Kolmogorov-Smirnoff, Chi-square and the Lillifors tests, rejected the hypothesis that the data was normally distributed. The rejections can be accounted to the fact that the sample size was much larger (>100 000) than the tests were designed to assess.

A method was devised to test to what extent the fitted distributions could reproduce the actual data. By determining the summation of the difference between the estimate of the normal distribution and the actual value for each size category (where *fitted normal distribution* is higher than *production data* in Figure 4.7), the number of fruit that would be incorrectly represented, was calculated as a percentage of the total fruit in each production run. The results were rather disappointing as, on average, 11.9% of fruit in each production run would be categorized incorrectly.

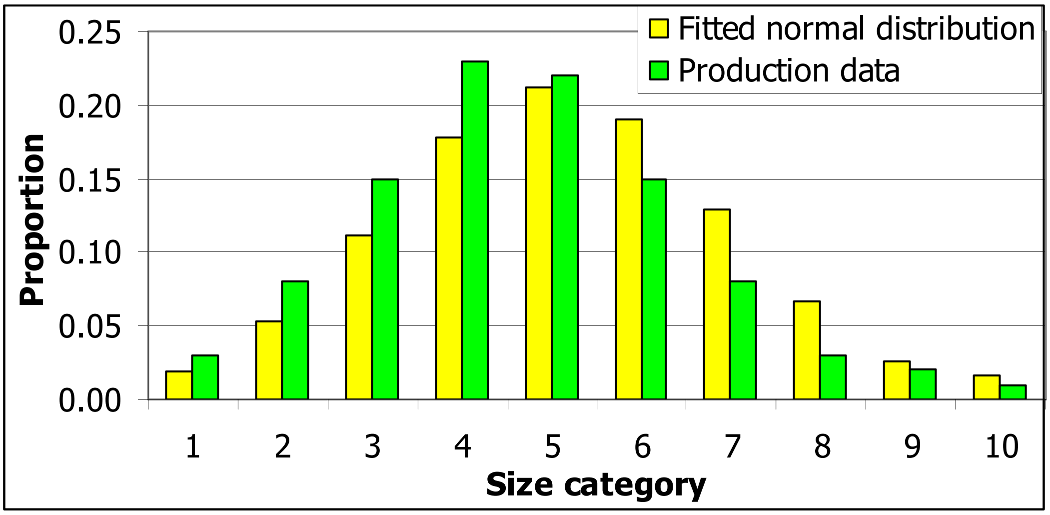


Figure 4.7: Normal distribution fit on actual data in discrete size categories

In the investigation of the reason behind the inappropriate fit, the skewness of the fruit size distributions was also analysed, with interesting results. Skewness refers to **the asymmetrical properties of a distribution.** Negative skewness indicates a distribution with a median lower than the mean (skew to the left) and positive skewness (skew to the right) indicates the opposite (Weisstein, 2003). The following graph shows the skewness that was calculated, plotted against the average fruit size of the fitted normal distributions.

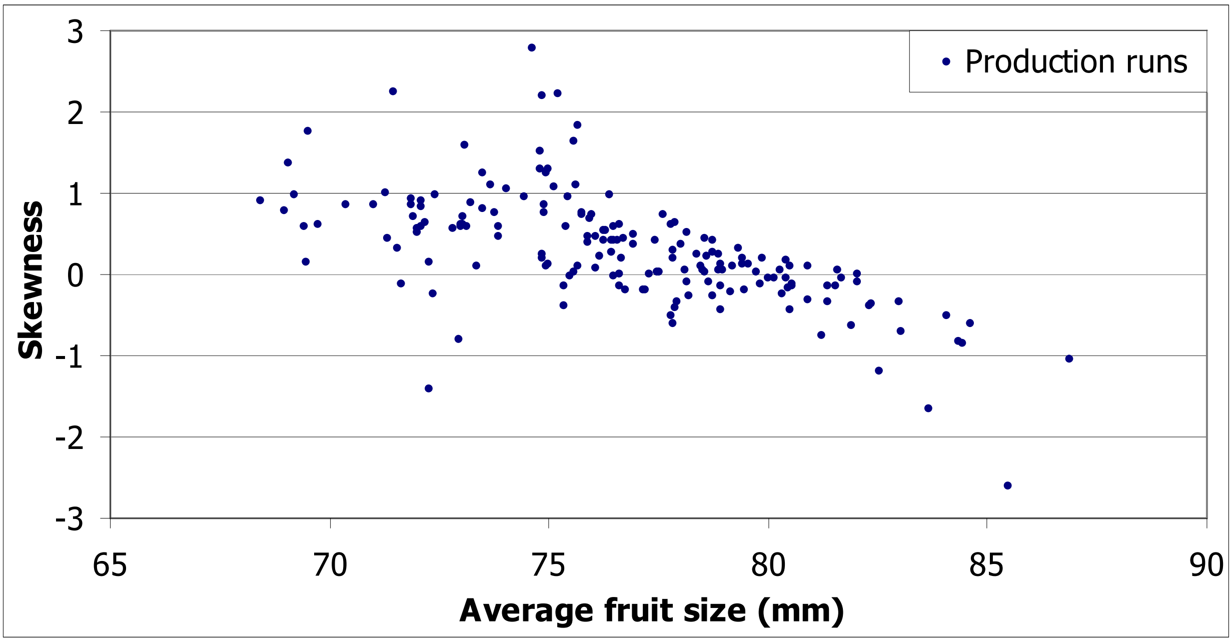


Figure 4.8: Fruit size and skewness

From Figure 4.8 it is clear that the distribution of smaller fruit is skew to the right (positive), while that of large fruit is skew to the left (negative). Figure 4.9 shows this effect clearly. The skewness can be attributed to the natural range of fruit size and a varying peak size. The skewness is therefore directly dependant on the average fruit size. On this basis, and the large error in fitting the normal distribution, the use of the normal distribution is rejected.

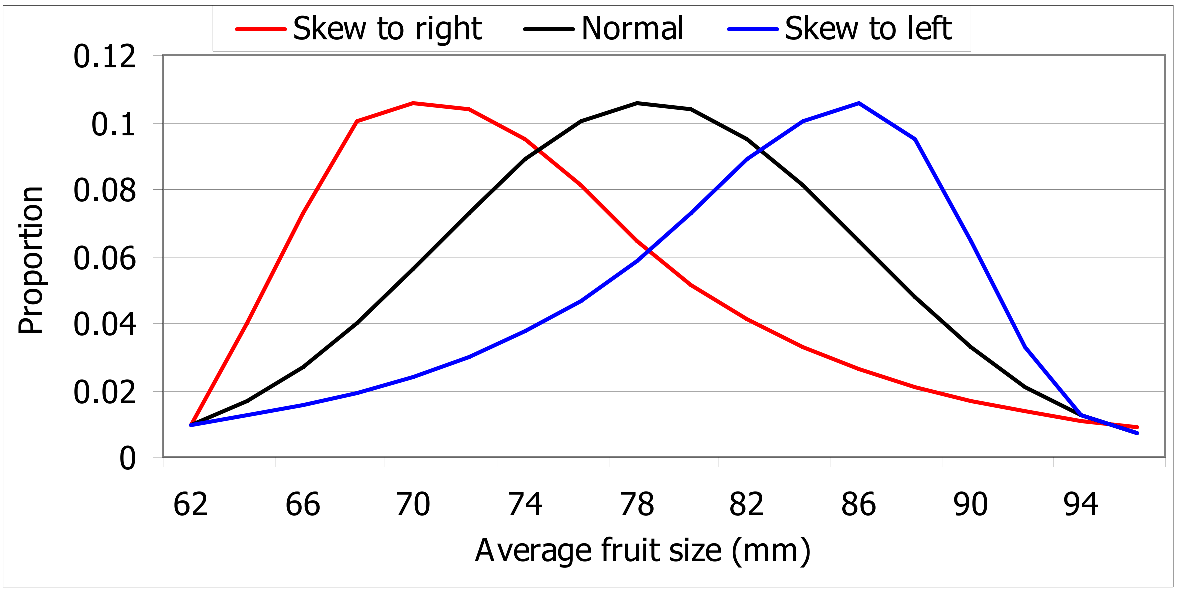


Figure 4.9: Skew-normal distributions

To account for the fact that significant skewness had been found in the distributions of the actual data, fitting the beta distribution was considered. The beta distribution is very flexible in terms of its shape and also allows modelling of finite variables as opposed to e.g. the lognormal and gamma distributions.

The beta distribution has two parameters: α and β. The mean, variance and skewness of the beta distribution in terms of α and β are (Weisstein, 2003):

$$mean = \mu = \frac{\alpha}{\alpha+\beta} \quad \textbf{(4-1)}$$

$$variance = \sigma^2 = \frac{\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)} \quad \textbf{(4-2)}$$

$$skewness = \gamma_1 = \frac{2(\beta-\alpha)\sqrt{1+\alpha+\beta}}{\sqrt{\alpha\beta}(2+\alpha+\beta)} \quad \textbf{(4-3)}$$

The beta distribution was fitted to the fruit size data using the same method used to test for the normal distribution and the result was that only 1.3% of the fruit (1.9 million out of 151 million fruit sampled) would be incorrectly categorised. As the standard beta distribution has a fixed range from zero to one, it is adapted to range from the smallest fruit to the largest fruit. These two parameters were also added to the solver equation, but only a single pair was used for all the data sets, as the smallest and largest fruit are expected to be constant. It was found that the beta distribution fit best with limits set at 55.976 and 97.026 mm (fruit diameter). See Appendix E for detail calculations.

As the average fruit size can be estimated (see Section 4.3, on p.61) before a production run is started, it can be used to estimate the α and β parameters using the "method of moments" (Wikipedia, 2006a). Equations 4-4 and 4-5 use the distribution mean and variance to estimate α and β for the standard beta distribution ($0 < \mu < 1$).

$$\alpha = \mu\left(\frac{\mu(1-\mu)}{\sigma^2} - 1\right) \quad \textbf{(4-4)}$$

$$\beta = (1-\mu)\left(\frac{\mu(1-\mu)}{\sigma^2} - 1\right) \quad \textbf{(4-5)}$$

The variance of the fruit size distribution determines how flat (high variance) or peaked (low variance) the distribution is. To enable the specification of the fitted Beta distribution with only a singe variable, the estimated average fruit size, the relationship between the variance and average of the fitted data was investigated. It seemed that the larger the fruit, the more the variance of fruit size.

Statistica© was used to analyse the relationship between the mean and the variance of the fitted beta distributions (StatSoft, Inc., 2005). The results of regression analysis indicated that the effect of the average fruit size on the variance was statistically significant with a p-value of 0.000. Equation 4-6 was formulated from the results of the regression analysis and the standard deviation of the variance. Figure 4.10 displays the fitted production run values and the 95% statistical range.

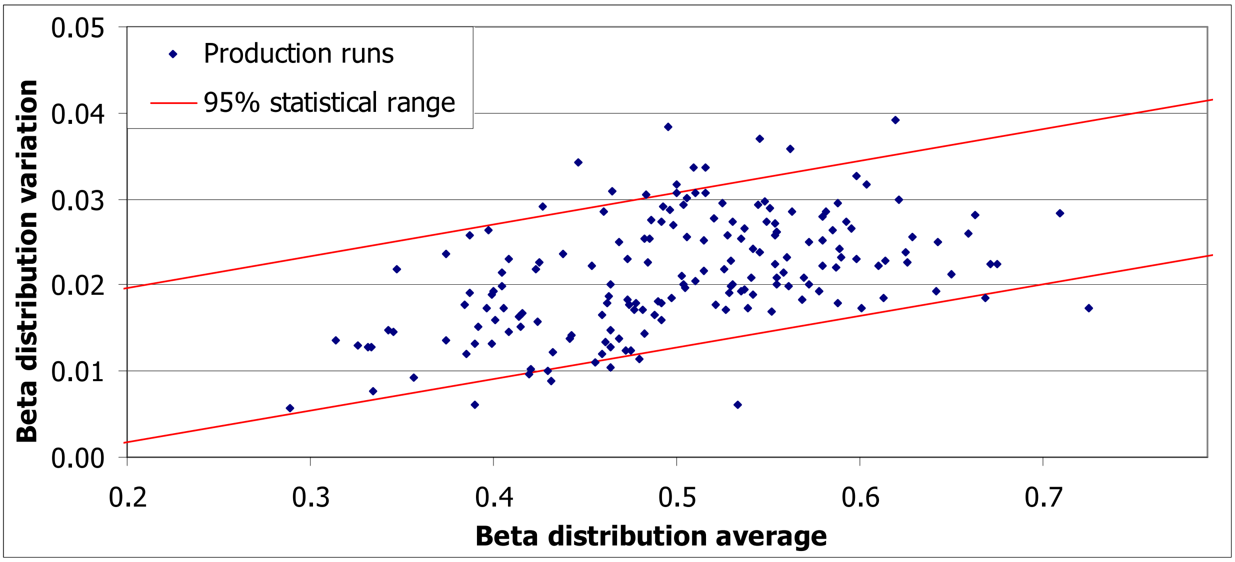


Figure 4.10: Beta distribution relationship between mean and variance

The relationship between the variance and the mean, with a statistical range of 95%, is expressed in the equation below. As 95% of the captured average fruit size values were between 69.2 mm and 84.0 mm, these are the upper and lower limits for which Equation 4-6 is valid. By taking into account the minimum and maximum fruit sizes for the fitted beta distributions (56.0 mm and 97.0 mm) and using interpolation, it follows that Equation 4-6 is only applicable for μ between 0.318 ((69.2 – 97.0)/(56.0 – 97.0)) and 0.677 ((84.0 – 97.0)/(56.0 – 97.0)).

$$\textit{variance} = \sigma^2 = \mathbf{0.0357}\mu + \mathbf{0.0039} \pm \mathbf{0.0119} \qquad \mathbf{0.318} < \mu < \mathbf{0.677} \quad \textbf{(4-6)}$$

Combining the above relationship with Equations 4-1 to 4-3 (previous page), which estimates the α and β parameters using the *method of moments*, will allow α and β to be estimated by specifying only the average fruit size. The two graphs in Figure 4.11 indicate the extreme predicted values of α and β, as well as the parameters of the fitted beta distributions.

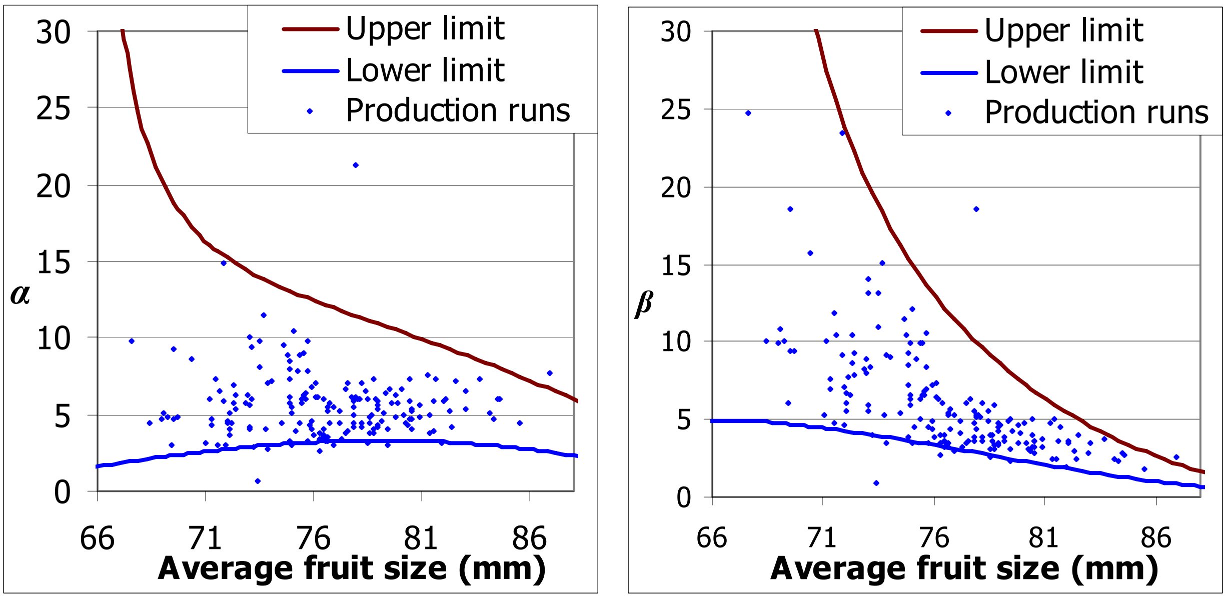


Figure 4.11: Estimation of α and β values using only average fruit size.

Using the estimation of the 95% α and β values, the skewness was calculated. This was achieved by using Equation 4-3, which permits the calculation of the skewness from the two parameters. Figure 4.12 shows the skewness of the beta distributions fitted to the production runs, as well as the skewness of the 95% beta distributions dependant on average fruit size.

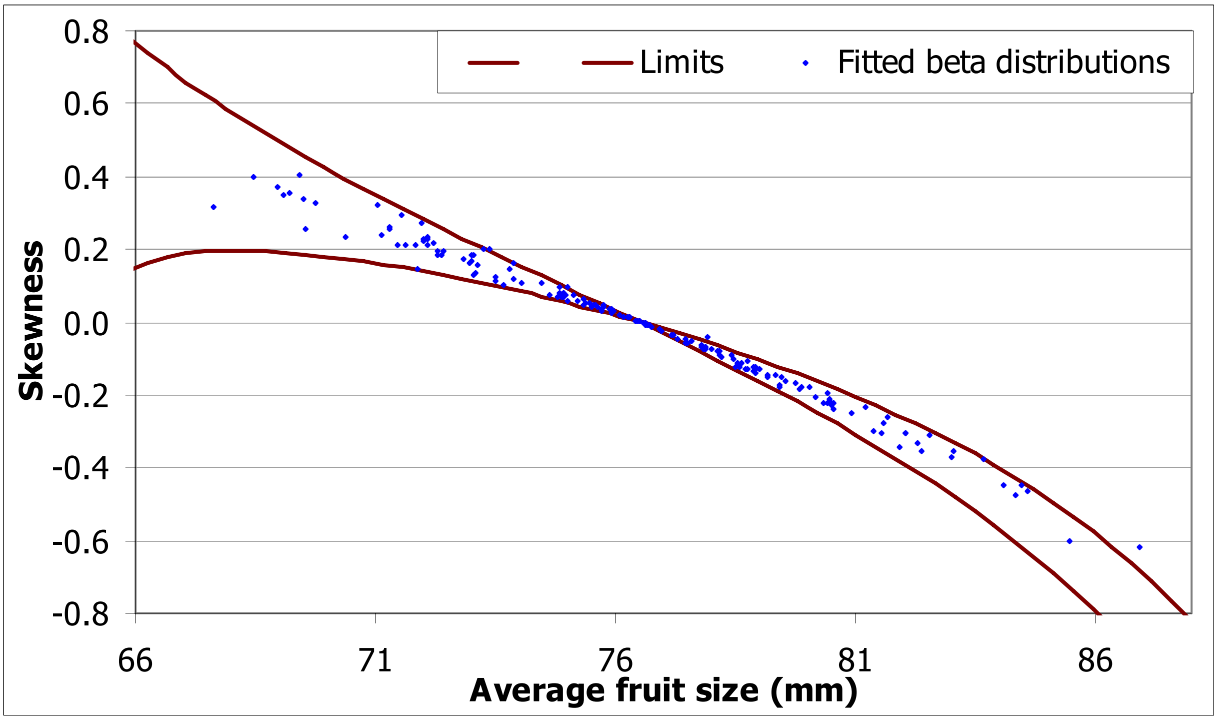


Figure 4.12: Skewness of fitted beta distributions

It was found that, when the fruit size is larger than 76.5mm, the skewness is negative (skew to the left) and positive (skew to the right) where fruit are smaller than 76.5mm. This supports earlier findings where the skewness of the data was calculated (see Figure 4.8).

In Figure 4.13 the proportions in each size category are plotted for the beta distributions of a small, medium and large average fruit size. While the beta distribution is a continuous distribution, it has been divided into the discrete size categories presented in Table 4.2. The distributions have low (peaked) and high (flat) variance as is calculated by Equation 4-6. A large difference in the proportion of fruit in peak counts shows the effect of having a flat or peaked distribution. The skewness that the beta distribution aims to replicate is also clear in Figure 4.13.

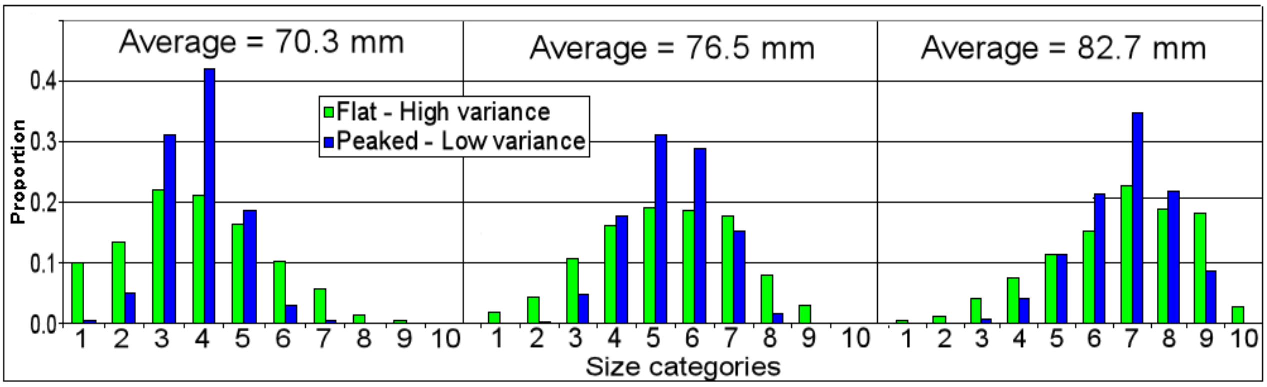


Figure 4.13: Various fruit size beta distributions

To conclude the size distribution analysis, the normal distribution initially seemed acceptable based on visual analysis, but proved to be unacceptable when the error was calculated. The beta distribution, on the other hand, was found acceptable, for the purposes of this study, to represent the fruit size distribution accurately by only estimating the average fruit size. However, as the model will be extended to other fruit types, which have not been analysed here, and it happens that previously graded fruit are packed, the empirical distribution will also be an option when estimating the size distribution input of a production run.

4.2.2 Quality distributions

Citrus fruit quality is traditionally divided into five grades, the first and second grades being packed into cartons, the third grade sold as bulk and the fourth grade used to make juice. The fifth grade is of minor importance with an average proportion of less than 1% (see Figure 4.14) and refers to unusable fruit, such as fruit that have burst. For this reason fruit in Grade 5 will be ignored. Fruit quality is therefore divided into four *discrete* grades.

Figure 4.14 depicts the discrete average fruit grade distribution, as well as the upper and lower limits for the 179 production runs, of which data was captured.

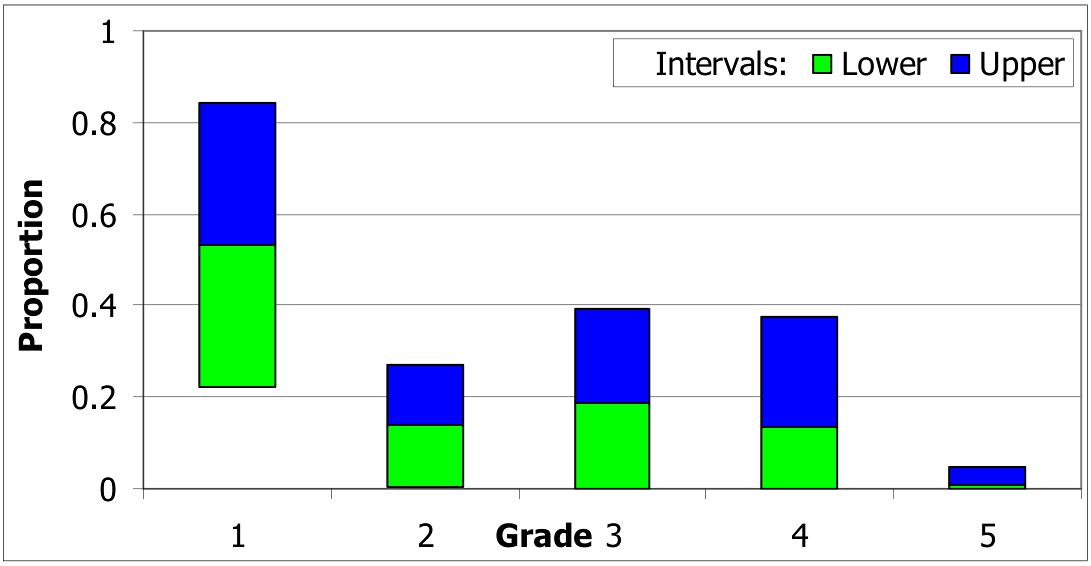


Figure 4.14: Spread of fruit grades of captured data

Fruit quality can be affected by various reasons, but once fruit arrive at the packing house, nothing can be done to improve the quality. The strictness, with which all fruit will be graded, is primarily determined by the target market. For instance, fruit that are acceptable as Grade 1 fruit for one market are not acceptable as Grade 1 to another.

As the data gathered represents actual packing results, it was realised that there might be more factors that have significant influence on the output. The effects of the producer, target market (for six market groups), year of harvest (2003, 2004 and 2005), production area (Clanwilliam, Citrusdal and Piketberg) and fruit variety (Navels and Valencias) were analysed using the method *Main effects ANOVA,* in the *Statsoft's Statistica 7.1* software package (StatSoft, Inc., 2005). The effect on the proportion of Grade 1 fruit was tested, as it is of utmost importance, since fruit in this category obtain the highest prices. The results are presented in Table 4.3.

Table 4.3: Main effects on fruit quality

Effect	***p*-value (< 0.05 indicates significance)**
Data/Market	0.001 334
Producer	0.000 000
Year	0.000 061
Fruit Type	0.000 000
Area*	0.013 716

The effect of the production area could not be established, as there are no degrees of freedom when tested against the "Producer" and "Market" predictors (since these are already grouped into the areas, with no overlapping). The effect of the area was therefore tested separately and the weather analysis earlier in this chapter also gives an indication of the effect of an area. The five parameters *Market*, *Producer*, *Year, Area* and *Fruit type* were found to have strong statistical influences on the quality of fruit.

These effects can be attributed to:

1. *Data/Market:* The grading strictness for different markets has an impact on the proportion of Grade 1 fruit.
2. *Producer:* Each producer uses his own technique to grow fruit. Irrigation, fertilisation and pesticide application practices are not the same for the different producers.
3. *Year:* Various seasonal effects, such as rain, temperature, pests etc. that differ each year.
4. *Fruit Type:* Valencia fruit have a slightly better average quality than Navels.
5. *Area:* The combined effect of the market selections and packing line practices of each packing house, as well the unique weather conditions of each production area as discussed in Section 4.1.4 (p.44).

After various unsuccessful attempts to fit statistical distributions to the quality distribution, it was decided to use an empirical distribution to define fruit quality into the various grades. In the fruit industry, when referring to the fruit quality of a production run, it is typically referred to as a "65% packout" or a "75% packout", referring to the percentage of the fruit in Grade 1. This, and interviews in the industry (G. Verster, GHC. & J. Wepener, Piketco, 27 September 2005), indicated that the proportion of fruit in Grade 1 is of primary importance.

For this reason an empirical distribution was constructed that is only dependant on the proportion of fruit in the first grade. Regression analysis was used to determine the dependency of Grades 2, 3 and 4 on the proportion of Grade 1 fruit. The following set of equations was developed from the regression analysis.

$$P_{G2} = -0.250 \times P_{G1} + 0.267 \pm 0.058 \quad 0.22 < P_{G1} < 0.85 \qquad \textbf{(4-7)}$$

$$P_{G3} = -0.373 \times P_{G1} + 0.422 \pm 0.089 \quad 0.22 < P_{G1} < 0.85 \qquad \textbf{(4-8)}$$

$$P_{G4} = -0.377 \times P_{G1} + 0.311 \pm 0.085 \quad 0.22 < P_{G1} < 0.85 \qquad \textbf{(4-9)}$$

The developed set of equations is only valid for a Grade 1 proportion between 0.22 and 0.85 as this is the range of the captured data. After a proportion is assigned to Grade 1, the upper and lower limits of the expected proportion of Grades 2 to 4 can be calculated. If the last part of each equation is ignored, the expected value is determined, and it is important that the sum of the four $\boldsymbol{P_G}$ expected values will be equal to one. In Figure 4.15 the results of this method are displayed for 60% Grade 1 fruit with 3% uncertainty, i.e. Grade 1 between 57% and 63%. The extreme expected values are used, i.e. with $\boldsymbol{P_{G1}}$ set to 0.57 and 0.63, $\boldsymbol{P_{G2}}$ can be calculated as: **0.183** (-0.250 x *0.570* + 0.267 **+** 0.058) and **0.052** (-0.250 x *0.630* + 0.267 **–** 0.058) as can be seen in the Figure 4.15.

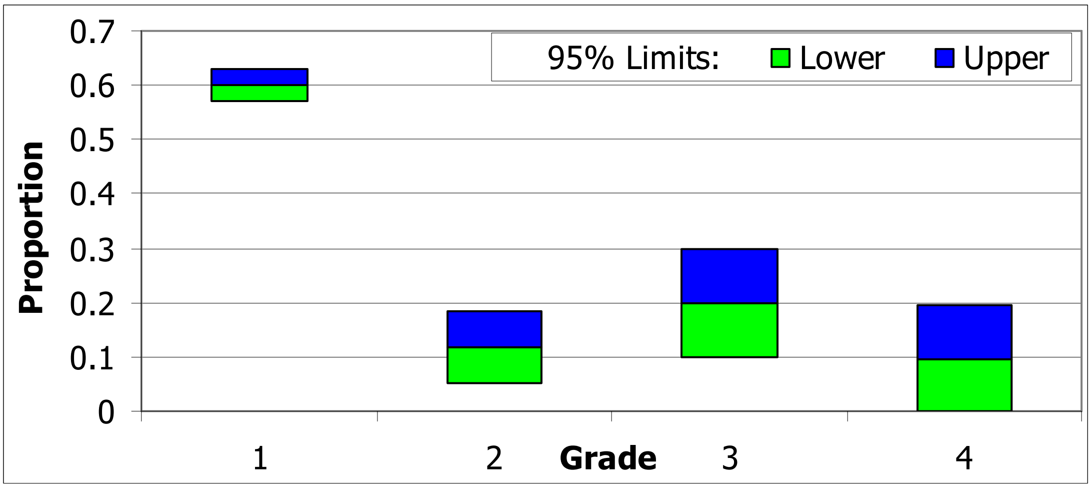


Figure 4.15: Fruit quality distribution estimation

The upper and lower limits of each grade in Figure 4.15 are dependant on the certainty level included in the estimation of the proportion of Grade 1 fruit (3% in example above) and the developed set of equations (Equations 4-7, 4-8 and 4-9).

However, it is expected that the true fruit quality distribution is continuous, such as the one shown in Figure 4.16.

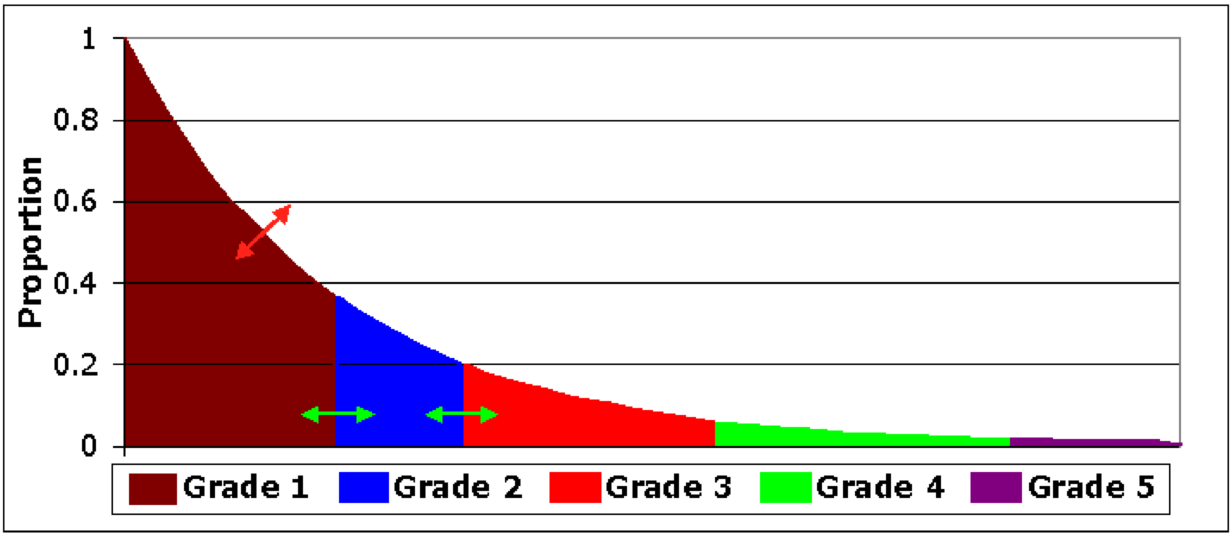


Figure 4.16: Proposed quality distribution

If it is assumed that fruit quality is initially perfect and is then negatively influenced by physical damage, growth problems, insects, etc. through its lifecycle, then the number and size of unacceptable blemishes will decrease fruit quality. In Figure 4.16, the coloured area of each grade indicates the proportion of fruit in that grade. The red, diagonal arrow indicates the variability of the quality distribution as in total more or fewer blemishes are present. Most of the fruit packed for Grade 1 are without blemish and the margin of acceptable blemishes depends on the target market. The green, horizontal arrows indicate the variability of the various target markets. Unfortunately the nature of the gathered data did not allow for analysis of the proposed continuous quality distribution, and it remains a subject in which future research is possible.

4.2.3 Colour distributions

It should be noted, again, that fruit colour is primarily improved by cold weather and that industry standard divides colour distribution into eight categories (see Appendix A). Fruit colour can be improved after harvest by an average of two categories if fruit with insufficient colour are removed from the packing line, degreened and packed at a later stage.

Of the 179 production runs, the removal of fruit with insufficient colour was recorded in only 13 runs. Either green fruit were not removed at all in the rest of the runs, or the data was not captured or provided. The average percentage of fruit that was removed for Navels was 4% (11 production runs) and for Valencias it was 1.25% (two production runs). This was expected as Navels are harvested first in the citrus season, while Valencias are harvested later when lower temperatures are experienced.

The strictness with which green fruit are removed from the packing line also depends on the target market requirements, as is the case with fruit quality and size. Interviews with GHC staff also indicated that, as the season progresses, the fruit colour becomes more and more predictable, and they can more accurately estimate what percentage of fruit will need to be removed (G Verster, GHC, personal communication, 28 September, 2005). For these reasons, the model input for badly coloured fruit will be only a single proportion of acceptable fruit with a range of certainty. For example, if it estimated that between 5% and 10% of the fruit in a particular production run has not coloured sufficiently then between 95% and 90% of the fruit has coloured sufficiently.

4.2.4 Distribution independence

The proportion of Grade 1 fruit is plotted against the average fruit size in Figure 4.17. This was done to test for a possible relationship between size and quality. Such a relationship would significantly increase the complexity of the fruit distributions, but no relationship is apparent in the figure.

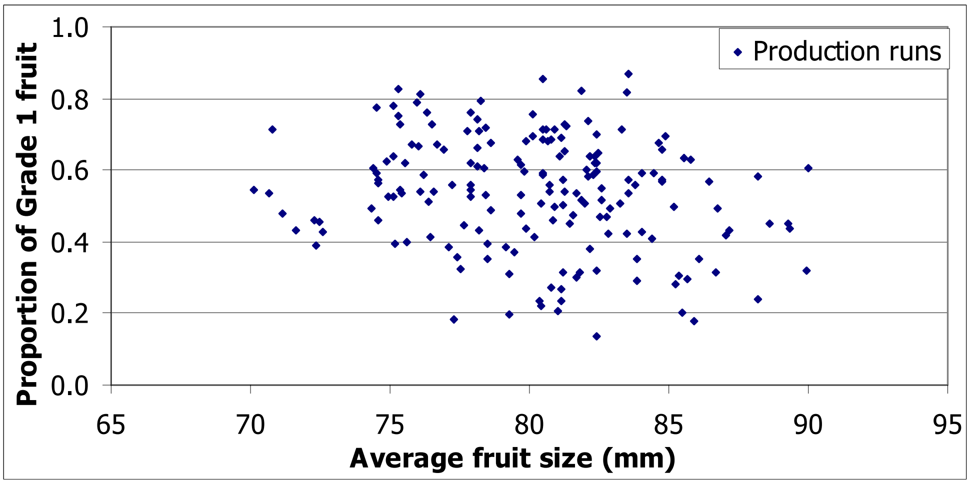


Figure 4.17: Fruit size and quality relationship

The chi-square test for independence was done to verify that the distributions are independent. The test result, a p-value of 0.133 supported independence. The relationships between fruit colour and size, as well as fruit colour and quality, are plotted in Figure 4.18.

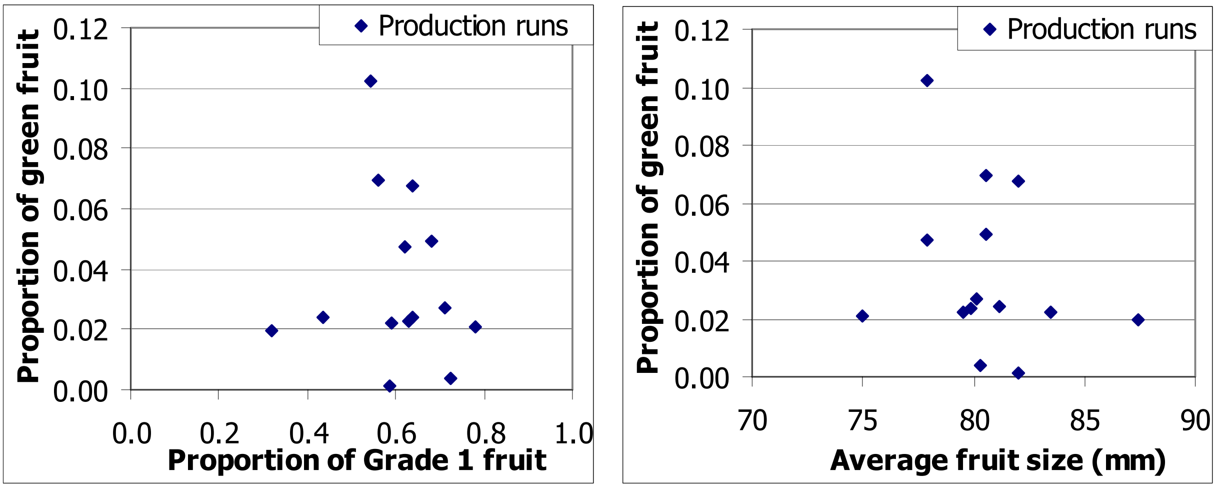


Figure 4.18: Relationships of colour distribution

The chi-square test for independence was repeated for the data displayed in Figure 4.18. The resultant p-values were 0.600 for the quality-colour relationship and 0.744 for the size-colour relationship. Independence is therefore assumed for all the relationships. For the purposes of this study the assumptions simplify the calculations of fruit flow divisions, for instance, when green fruit are removed, it can be accepted that it does not affect the quality and size distributions. Modelling of the packing line processes relies strongly on the assumption that the distributions of the three fruit properties are independent.

4.2.5 Fruit size-mass relationship

To enable the conversion from fruit mass to number of fruit, industry data was analysed to evaluate the size-mass relationship. The double capturing method, used to ensure the accuracy of the data, provided the opportunity to do the calculations needed for the analysis. During initial analysis, it was found that Piketco's data had no variance. On contacting them, it was explained that they did not weigh pallets after packing. They used fixed carton-mass standards to calculate the total mass. Fruit were, however, weighed on arrival at the packing house.

GHC, on the other hand, did weigh the finished pallets, as well as the total mass on arrival. This enabled the comparison of Piketco's fixed standard mass to those of fruit packed at GHC during 2003, 2004 and 2005. The *Multiple Regression* test of the software package Statistica© was used to determine the effect of the year and fruit type on the size-mass relationship (StatSoft, Inc., 2005). No statistically significant relationship was found for either variable, with p-levels of 0.57 and 0.40 respectively (p-level < 0.05 indicates significance).

The relationship of fruit size and mass calculated from the data from Piketco (standard cartons) and GHC is presented in Figure 4.19.

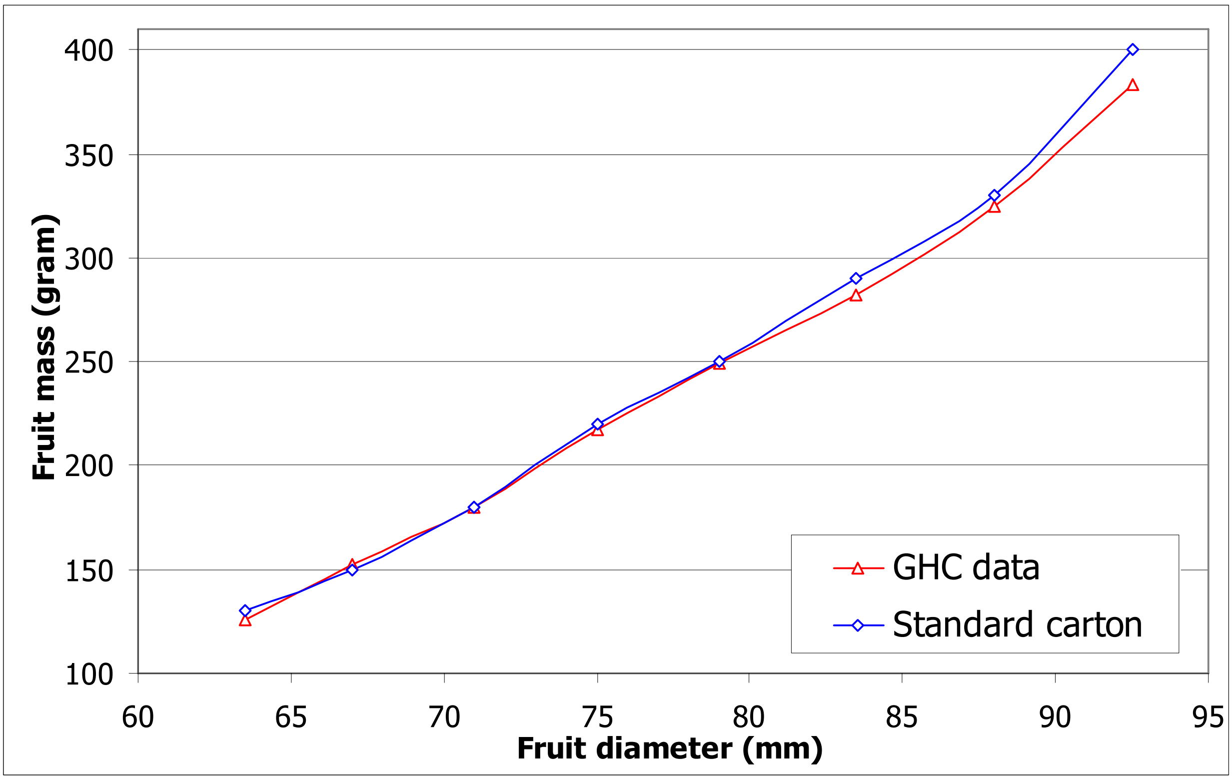


Figure 4.19: Relationship between fruit size and mass

It is clear from Figure 4.19 that there is very little difference between the standard carton mass used by Piketco and the measured mass of GHC for all fruit size categories. The carton standard data of Piketco and the calculated averages from the GHC data, as well as the difference between the two, are shown in Table 4.4.

Table 4.4: Data sets of fruit size (counts) and mass (in grams)

Fruit Count	125	105	88	72	64	56	48	40
Std Carton	130.00	150.00	180.00	220.00	250.00	290.00	330.00	400.00
GHC Data	126.20	152.15	179.80	217.00	249.30	282.25	324.70	383.25
Difference	3.80	2.15	0.20	3.00	0.70	7.75	5.30	16.75

As the relationship under investigation is continuous, linear trends were fitted on the various fruit masses using the Excel Solver tool by minimising the error. This was done to allow conversion from mass to size and vice versa. In the equations below, ω represents fruit mass (in grams) and d the diameter (in millimetres), with subscripts c and d for ***c****arton* standard and GHC ***d****ata* respectively.

$$d_c = 0.117 \times \omega + 49.462 \quad mm \qquad 126.20\,g < \omega < 383.25\,g \qquad \textbf{(4-10)}$$

$$d_d = 0.121 \times \omega + (48.753 \pm 1.547) \ \ mm \qquad 110.2g < \omega < 394.3g \qquad \textbf{(4-11)}$$

The mass intervals, within which the equations are valid, have been determined from the captured data. The Fruit Mass Function (***FMF***) was developed as the inverse of Equation 4-11.

$$\omega \approx FMF(d) = 8.273d - (403.341 \pm 12.800) \ \ gram \qquad 61.7mm < d < 98.65mm \qquad \textbf{(4-12)}$$

The 12.8 gram value in Equation 4-12 is the maximum deviation from the expected value that was found when compared to the actual data. As the deviation occurred during a single production run over the average of 1 192 cartons of Count 56, it was selected as the maximum expected deviation to be used in the ***FMF***. Fruit mass can now be estimated if the fruit diameter is known or estimated, by using the Fruit Mass Function.

4.3 PREDICTION OF FRUIT STATISTICS

Louw and Fourie of Optimal Agricultural Business Systems (2003:2-4) describe a crop forecasting methodology that is employed in Australia and South Africa. The forecast is based on historical production records, estimates of new plantings, fruit set information from technical experts and estimates of crop damage. The resultant prediction is reported to deviate by up to 5% from the actual figures.

Other forecasting methods, described in the literature, are on a nationwide level and do not include the level of detail required for this study. It is not the primary objective of this project to construct an exact statistical method to predict fruit yield, quality, size, etc. However, the usefulness of the model that is to be developed, will greatly improve if the fruit input, which is the main driver of packing line processes, can be accurately described.

Although the initial aim was to obtain data of three years from all three facilities, this could only be realised at a single facility; GHC in Citrusdal. Production run results of five producers over three years (2003 – 2005) were gathered, as well as their total annual summaries. The concept is that, while fruit quality, size, yield and colour vary considerably from season to season, each producer remains in his relative position from year to year. For instance, if one producer had good quality small fruit for the past few years, he will continue to do so. If the whole area has better quality smaller fruit, the quality of his fruit will be even better while remaining smaller than the average. This is the *producer to area* concept that is to be tested. It is expected that it will also apply on an *orchard to producer* scale, although this cannot be tested with the acquired data set and remains a definite possibility for future studies.

The method described by Louw and Fourie (2003:2-3) was used as a foundation for the development of a similar methodology. As three years' data was available, data of two seasons could be used to predict the data of the third season, to test the accuracy of the forecasting method.

The forecasting methodology was developed for average fruit size, proportion of Grade 1 and crop yield statistics. The methodology was not developed for the colour distribution as insufficient data was available. The development of the forecasting method will now be presented as applied to the average fruit size statistic.

The variable ST_i refers to the true value of the statistic in question for year i and SE_i is an estimation of ST_i. ST_i is calculated as a proportion of a local average, for instance, if the average fruit size in an area for two years (years $i-1$ and $i-2$) is 80mm and 84mm, respectively, and a producer in the area delivered fruit with an average diameter of 76mm and 82mm, respectively, the ST_{i-1} and ST_{i-2} would be 0.95 and 0.976 respectively. The producer moved closer to the average size for that area, but his fruit remained smaller. Equation 4-13 shows the expected relationship between SE_i and ST_i. The parameter ε represents the weighted value of the previous two years.

$$ST_i \approx SE_i = \varepsilon ST_{i-1} + (1-\varepsilon) ST_{i-2} \qquad 0 \le \varepsilon \le 1 \qquad \textbf{(4-13)}$$

Using the data collected, a value was assigned to ε. This was done by using data of two years and minimising the absolute error in predicting the statistic of the third year. The resulting ε value was 0.74 for the average fruit size, i.e. when predicting the statistic of year i, year $i-1$ is weighted at 0.74 (74%) and year $i-2$ at 0.26 (26%). Continuing with the example from the previous paragraph, if ST_{i-1} and ST_{i-2} are 0.95 and 0.976 respectively, then Equation 4-13, with an ε value of 0.74, would estimate ST_i as 0.957. Below are the three ε values for fruit size, fruit grade and crop size:

$$\varepsilon_S = 0.739 \qquad \textbf{(4-14)}$$

$$\varepsilon_G = 0.843 \qquad \textbf{(4-15)}$$

$$\varepsilon_C = 0.889 \qquad \textbf{(4-16)}$$

The fact that the values are larger than 0.5 makes sense, as more weight is then assigned to the statistic from the previous year than the year before it. Measurements are often taken during various stages of fruit growth at various locations to allow the estimation of fruit parameters such as fruit size, quality, yield etc. (G Verster, GHC, personal communication, 28 September, 2005). This, and early packing results in each season, can be used to calculate the average seasonal change of each statistic for large areas. If, with a ST_i of 0.957 as in the example above, it was then found that the average size of year i was 82mm, the producer's expected average size would be 78.5mm.

The next step was to add a lower and upper limit to the prediction to accommodate for random changes that occur from year to year. In Figure 4.20 the range limits are presented. By using the 5% deviation relevant to the existing method (Louw & Fourie, 2003:4), it was found that, for the size prediction of Navel fruit, actual values fell within the lower and upper range values.

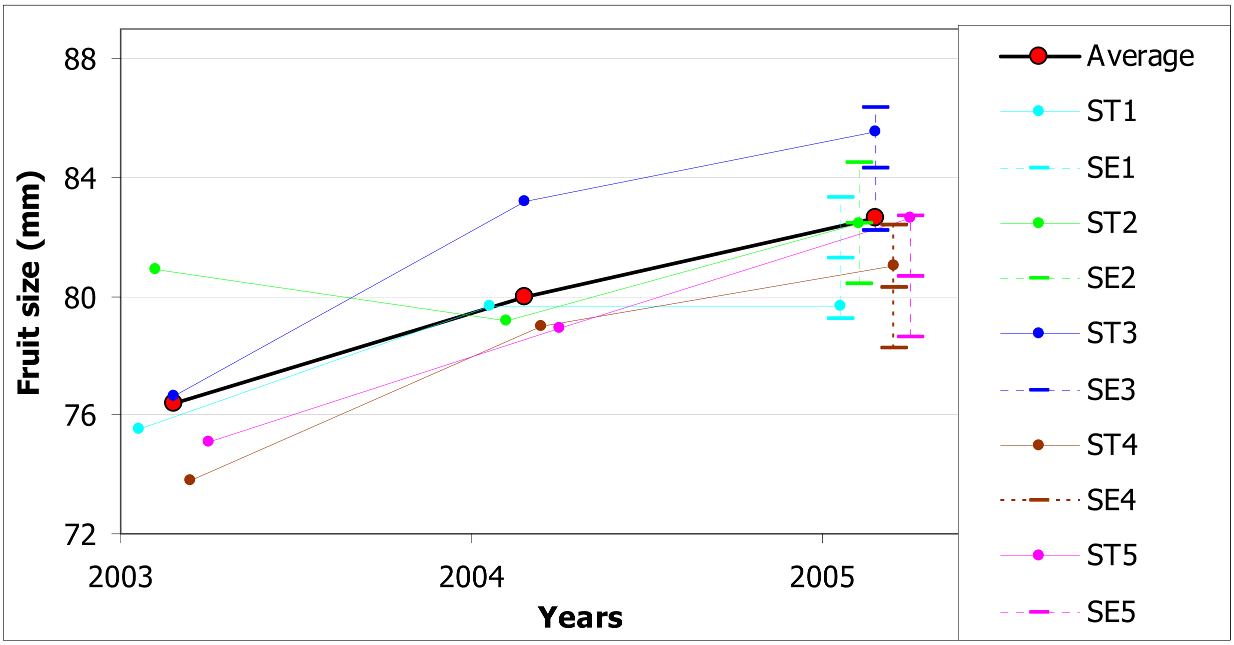


Figure 4.20: Fruit size forecast and actual annual data for five producers

Equation 4-17 was extended to include the random 5% deviation also reported by Louw and Fourie (2003:4):

$$ST_i \approx SE_i = \varepsilon ST_{i-1} + (1-\varepsilon)ST_{i-2} \pm 0.05 \qquad 0 \le \varepsilon \le 1 \qquad \textbf{(4-17)}$$

Even though only historical data was used (no estimates of new plantings were included), the forecasting method was found to be accurate. The method was only tested by using two years' data to do the estimation, but it is expected that if data of more years was used, the estimation would be even more accurate. For detail calculations consult Appendix F.

In this section, the input and output data of the packing line was analysed and distributions were fitted to fruit size and fruit quality. By estimating the average fruit size and the proportion of Grade 1 fruit for a specific production run, the extreme empirical distributions can be calculated. The fruit colour distribution was estimated with a single value from which an empirical distribution is derived. Several modelling assumptions were made and tested and a forecasting methodology reviewed. This formed part of the third step of the generic modelling methodology. In the next chapter, the fourth step, model construction, is described by means of mathematical model building of the parts that make up the complete packing line process.

CHAPTER 5
MODEL CONSTRUCTION

This chapter describes the detailed modelling of the processes typically found in the defined set of realities; the South African hard citrus packing lines. This is the fourth step of the generic modelling methodology described in Chapter 2. The fruit analysis of the previous chapter and the model constructs described in this chapter are used in the next chapter to form a modelling procedure for the generic model.

During the fifth step of the modelling methodology, which is the development of the modelling procedure presented in Chapter 6, it was realised that the capacity of each process will need to be calculated twice; once for maximum throughput and again for a selected throughput. The maximum throughput of all processes is calculated and the slowest rate selected. All processes are then subjected to the selected rate and their actions and required setups recalculated. Originally, only one set of equations was developed for each process, but the model construction (fourth) step was repeated to include the calculation of specific throughputs and applicable setups. In this chapter the first and second iterations of the model construction are presented.

Hangos and Cameron (2001:30) provided the modelling methodology from which the generic modelling methodology was developed. They sub-divided the model construction step into eight sub-steps (see Section 2.3.4.1 on p.16) and it was proposed that these steps be followed loosely (see Section 2.3.4.2 on p.17).

For all the packing line processes, which have been grouped into generic groups in Section 3.3.5 (p.36), balance volumes are calculated (see Section 2.3.4.1, Sub-step 1 on p.16). The second sub-step is the definition of characterizing variables that are associated with the inputs, outputs and internal states of the system (see Section 2.3.4.1, Sub-step 2 on p.16). The next six sub-steps require the establishment of balance equations and rate expressions, among others (see Section 2.3.4.1, Sub-steps 3 to 8 on p.16). These sub-steps were followed for each generic process group in the typical South African hard citrus packing line (see Section 3.3.5 on p.36). Also included, for each generic process group and sub-groups, are calculations that use and estimate the values of the four variable groups (fruit information, user defined, run information, and calculated variables; see Section 3.3.4 on p.35).

5.1 INPUTS, OUTPUTS AND INTERNAL STATES

The system input and output were defined earlier (see Section 3.2.1 on p.25) as containers of fruit. The fruit in the input containers are of mixed colour, quality and size and accurate estimation of these characteristics are required as they are the primary cause for variance in the packing line. The containers of fruit that enter the system are emptied and a continuous flow of fruit results. This flow remains constant throughout the production run until all containers have been emptied.

The granularity of the model refers to the size of the components that make up a system and the level of granularity is dependant on the level of detail required (Wikipedia, 2006b). While it would be possible to model the processing and final destination of every single fruit, such a level of detail is not required as the fruit flow at a constant rate throughout the production run. A representation of a typical conveyor belt, which is transporting fruit, is shown in Figure 5.1.

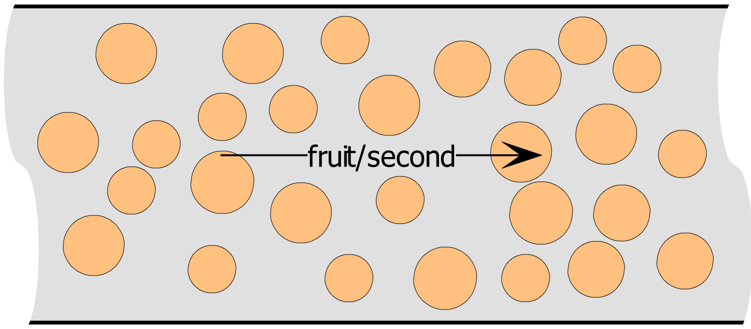


Figure 5.1: Fruit on conveyor belt rate per second

In studying discrete and continuous simulation modelling of bulk conveyor systems, Lebedev (1998:11) defined the continuous conveyor as a *stream of some item* and compared it to a pipe with an incompressible fluid being pumped through. The flow of fruit, in fruit per second, is therefore modelled as a *stream of some item*, rather than each individual fruit being modelled as such a level of detail is not required. The size, quality and colour characteristics of the production run are imposed on the fruit flow.

If one was to look at the *world view* of the model, **input fruit flow(s)** with **characteristics** interact with the various **processes** and the **physical process attributes** to determine the **output fruit flow(s)**. This bears a resemblance to the world-view of Shannon, referred to by Bekker (2004:6), where ***entities*** *having* ***attributes*** *interact with* ***activities and resources*** *under certain* ***conditions*** *creating* ***events*** *that change the* ***state of the system***. However, the resemblance is false as the defined fruit flow rate, in fruit per second, does not represent a singular *entity*, also, *events* do not occur and cannot change the *state of the system* as it is in steady state.

The flow of fruit is divided and manipulated throughout the packing line and various outputs result. The various flows throughout the packing line represent the internal states of the system. Accuracy of the estimation of fruit characteristics is of critical importance to determine, at all stages, what the internal states will be and also what the final outputs will be.

Although some fruit characteristics can be approximated by using statistical distributions, it is common to have inputs of which the distributions have been manipulated, i.e. previously packed fruit dumped with recently picked fruit, thus increasing the proportion of a certain fruit size and making a fitted distribution incorrect. It is common for the distributions of fruit characteristics of the internal states to be different from the original input as fruit flows are divided throughout the system. The flow divisions are usually dependant on at least one of the characteristics of the fruit. Also, although the fruit characteristics have continuous distributions, each fruit is classified into a specific size, quality and colour category. For these reasons, the empirical distributions, described in Chapter 4, will be used to represent fruit characteristics when internal states and outputs are calculated. As the empirical distribution can be calculated from other distributions or directly defined by a user of the model, the beta distribution described in Section 4.2.1 (p.47) can be used and the proportion of fruit in each size category calculated from it. The result is a step function with the number and size of each step fixed.

Throughout the system the input of each process will be equal to the output of the previous process as fruit flows directly from the output to the input. In this way the flow of fruit between the processes is represented by sets of empirical distributions or "internal states". For example, after the process in which the smallest fruit are removed, the applicable classes of the empirical distribution representing the fruit size removed, will be zero. This manipulation of the empirical distributions relies heavily on the assumption of independence between fruit colour, quality and size (see Section 4.2.4 on p.58).

The following table shows an example of the empirical fruit distributions after Grade 4 fruit, as well as small fruit, have been removed. The CPDF (Cumulative Probability Distribution Function) of the three empirical distributions (quality, size and colour) are shown in Table 5.1.

Table 5.1: Table of empirical fruit distributions

Cumulative empirical distributions										
QUALITY	**Grade 1**			**Grade 2**			**Grade 3**		**Grade 4**	
Lower	0.61			0.78			1.00		1.00	
Upper	0.68			0.82			1.00		1.00	
SIZE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Peaked	0.00	0.03	0.06	0.26	0.59	0.86	0.99	1.00	1.00	1.00
Flat	0.00	0.07	0.19	0.36	0.55	0.74	0.91	0.98	1.00	1.00
COLOUR	**Acceptable**					**Not acceptable**				
Lower	0.88					1.00				
Upper	0.92					1.00				
Number of crates	312									

An input/output descriptive set is calculated between each pair of consecutive processes. Such a set contains the following:

- Empirical distributions table, such as Table 5.1 above
- The total number of units (fruit/containers) passing through
- The rate at which units (fruit/containers per second) are leaving the preceding process, which is equal to the rate at which it is entering the next.
- Where containers are filled or emptied, the number of fruit per container is included.

The formulas described in the next couple of sections, require the input variables that were grouped into three groups in Section 3.3.4 (p.35) as *User Defined*, *Fruit Info* and *Run Info* to be defined. When the modelling procedure was developed (see Chapter 6), it was realised that another variable group, namely

Calculated variables, was also required. When a production run is analysed, the maximum fruit flow rate of each process is calculated and the constraining rate is then applied to all processes. The application of the *Calculated* maximum rate results in recalculation of all process equations. The model construction step was reworked to include *Calculated* variables and the subsequent calculations.

Throughout the calculations, the average fruit size plays a major role. Although the average fruit size is specified for the system input, it is recalculated for each process from the empirical distribution for fruit size of that process, which is calculated from the output of the previous process. This is done because the average fruit size will be different if a certain fruit size has been removed from the fruit flow in an earlier process. In the next section the various processes of each generic process group is described in detail and the associated modelled system presented.

5.2 FRUIT TRANSFER FROM CONTAINERS

Crates or trailers of fruit are mechanically emptied into the packing line. Crate emptying equipment range from simple hoist devices to elaborate cot-chain feed units that de-stack, empty and restack the containers (Wagner & Sauls, (s.a.)b:1). The system diagram of the fruit transfer process is shown in Figure 5.2. The fruit transfer process introduces the flow of fruit into the system. Multiple units can introduce fruit simultaneously.

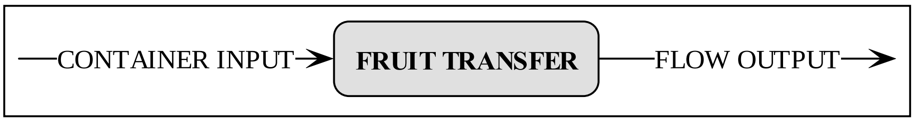


Figure 5.2: System diagram of fruit transfer

The fruit can be dumped into water or onto a soft conveyor belt; these methods are known as wet dumping and dry dumping, respectively. Both have various advantages and disadvantages. Wet dumping holds a risk of contamination with decay-causing organisms and spores in the water, but this risk can be overcome by chlorinating the water. An advantage of wet dumping is that less brushing is required later as dirt is softened by the water (Wagner & Sauls, (s.a.)b:1). Dry dumping on the other hand poses the risk of damaging the fruit and also requires a surge control device, human or mechanical (Wagner & Sauls, (s.a.)b:1), to ensure a uniform throughput, which, according to Miller *et al.* (2001:3), is critical for efficient operation.

Dry or wet dumping makes up the first generic process group (see Section 3.3.5 on p.36) as their properties are so unique that it could not be included in any other group. The two container types that are most often used to transport fruit from the orchard to the packing line are crates and trailers. The emptying of these containers is the primary method by which fruit enter any citrus packing line (G. Verster, GHC, personal communication, 28 September, 2005).

The *maximum rate* at which containers can be emptied and the *number of parts per container* are the main parameters to calculate the *maximum output rate* (fruit per second) for this type of process. While the *maximum tipping rate* is equipment dependant, the *number of parts per container* estimator can be calculated by one of two methods. As some packing houses weigh containers when they arrive at the packing house grounds, which is a process completely separate from the packing line, the *total fruit mass* is typically available. The calculations of the first method, which uses fruit mass, are shown in Table 5.2.

Table 5.2: Calculating parts per container – Method 1

Variable		Value/Origin	Unit
d	Average fruit **d**iameter	*Run Info*	millimetres
FMF	**F**ruit **M**ass **F**unction	$FMF(d)$	gram/fruit
M	Total fruit **M**ass	*Run Info*	kilogram
N_C	**N**umber of ***C**ontainers*	*Run Info*	containers
PC	**P**arts per **C**ontainer	$\dfrac{M \times 1000}{FMF(d) \times N_C}$	fruit/container

Run info

For each production run, the average fruit diameter *(d),* the ***N**umber of **C**ontainers (N_C)* and the *total fruit **M**ass (M)* is required. The ***N**umber of **C**ontainers* represents the number of containers, such as crates or trailers which will be emptied during a production run.

Calculations

If ***M**ass (M)* is divided by the *average fruit mass*, which can be calculated using the ***F**ruit **M**ass **F**unction* (***FMF(d)***, see Section 4.2.5 on p.59), then the *number of **P**arts per **C**ontainer (PC)* can be estimated if the ***N**umber of **C**ontainers (N_C)* is included in the equation.

The second method of calculating the number of ***P**arts per **C**ontainer (PC)* uses an estimation of average fruit volume. The calculations are presented in Table 5.3.

Table 5.3: Calculating parts per container – Method 2

Variable		Value/Origin	Unit
r	Average fruit **r**adius	*Run Info*	millimetres
V_P	***P**hysical* Fruit **V**olume	$\dfrac{4}{3} r^3 \pi$	cubic millimetres/fruit
ρ_{AKV}	**A**djusted **K**epler **V**alues	0.632 ± 0.018	(proportion)
V_A	***A**verage* **V**olume per fruit	$\dfrac{V_P}{\rho_{AKV}}$	cubic millimetres/fruit
V_C	***C**ontainer* **V**olume	*User Defined*	cubic millimetres /container
PC	**P**arts per **C**ontainer	$\dfrac{V_C}{V_A}$	fruit/container

User defined variables

The ***C**ontainer **V**olume (V_C)* parameter represents the "block" of volume that fruit take up in each container. As containers are usually not filled to the top, V_C will be calculated from the inner dimensions of the container and the filling height and its margin of error. For example, with a base of 1150 mm by 1000 mm, 500 mm filling height and 30 mm filling height error, the V_C is calculated at between 0.54 and 0.61 cubic metres. These calculations are not included in the model as some trailers have odd shapes and the user must specify the V_C.

Calculations

The number of ***P**arts per **C**ontainer (PC)* is calculated by dividing the V_C by the ***A**verage Fruit **V**olume (V_A)*. The V_A consists of two parts, ***P**hysical Fruit **V**olume (V_P)*, the volume of a sphere, and *volume lost per fruit* due to fruit being round. The latter can be estimated by using the ***A**djusted **K**epler **V**alues (ρ_{AKV})* described earlier in this document (see Section 3.3.2, Equation 3-5 on p.32).

Two methods for calculating PC have been presented in Tables 5.2 and 5.3. After the PC has been calculated, it can be used to calculate the maximum output for the fruit transfer process as shown in Table 5.4.

Table 5.4: Maximum output for transfer from containers

Variable		Value/Origin	Unit
PC	**P**arts per **C**ontainer	*Method 1/2*	fruit/container
N_C	**N**umber of ***C**ontainers*	*Run Info*	containers
TR_{Max}	***Max**imum* **T**ipping **R**ate	*User Defined*	containers/minute
R_{Max}	***Max**imum* fruit output **R**ate	$\frac{PC \times MR}{60}$	fruit/second
R_R	***R**equired* output **R**ate	*Calculated*	fruit/second
TR_R	***R**equired* **T**ipping **R**ate	$\frac{R_R \times 60}{PC}$	containers/minutes
T_D	Fruit input **T**ime ***D**uration*	$\frac{N_C}{TR_R}$	minutes

User defined variables

The ***Max**imum **T**ipping **R**ate (TR_{Max})* refers to the highest rate at which containers can be emptied into the packing line. The TR_{Max} was timed for equipment at GHC and found to be 2.8 containers per minute (personal observation, 2005).

Calculations

The ***Max**imum fruit output **R**ate (R_{Max})* is the maximum number of fruit that can leave this unit per second. This unit is rarely a system constraint and usually runs at a rate slower than TR_{Max}. When a ***R**equired output **R**ate (R_R)* rate is specified, the relevant ***R**equired **T**ipping **R**ate (TR_R)* and *fruit input **T**ime **D**uration (T_D)* is calculated. As the PC estimation will be a range, with upper and lower values, both TR_R and T_D will also have upper and lower values. The lower (slower) TR_R would be the recommended rate as there is then only a chance of 5% that the R_R will be exceeded.

5.3 SPECIFIC PROCESSES

The next generic process group is *specific processes*. Processes included in this group are washing, fungicide application, waxing, drying, labelling and optical data recording of fruit. One basic characteristic of these processes is that the input flow of fruit will equal the output flow of fruit. However, the success of the process, such as fruit being properly cleaned, is dependant on the rate at which fruit arrive. Figure 5.3 displays the system diagram of specific processes.

Figure 5.3: System diagram of specific processes

This generic group will be used to model processes that are fundamentally different and the capacity calculation will therefore depend on the specific process and its requirements. Processes that are based on the same principles of fruit movement through the unit have been grouped to create the following sub-generic groups for *specific processes*:

- Static brush/roller
- Moving roller
- Dipping
- Singular pocket

Many of the above-mentioned processes are found in the section of the packing line known as the washline.

5.3.1 Static brush processes

Static brush/roller processes are found in the first part of the packing line and include the following processes: high pressure descaling, washing, rinsing, do-nut drying and waxing. Fruit movement through the unit is driven by arriving fruit which push fruit, already in the unit, forward. This movement is assisted by the rotating direction of the brushes and is illustrated in Figure 5.4.

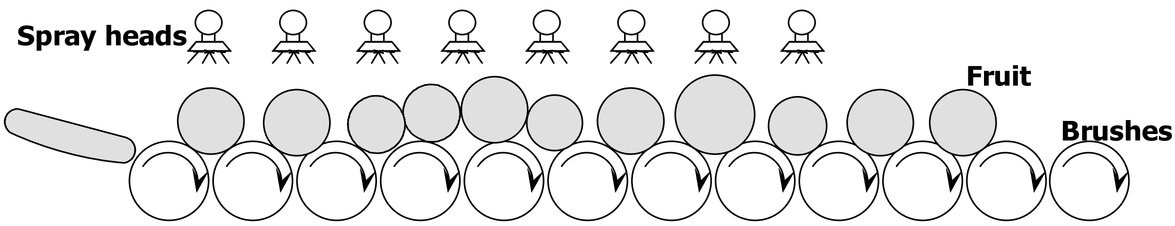


Figure 5.4: Static brush processes – Descaling wash unit

It is clear that the rate at which fruit enter and leave is equal and that the higher the arrival rate, the quicker fruit will be moving through. This could cause the process to be ineffective, because fruit need to spend a certain time in the unit to achieve a specific level of cleanness, dryness or wax. The various durations that fruit need to spend in these units are usually fruit type specific (G. Verster, GHC, personal communication, 28 September, 2005).

Capacity calculations are shown in Table 5.5.

Table 5.5: Capacity calculations for static brush processes

Variable		Value/Origin	Unit
r	Average fruit **r**adius	*Run Info*	millimetres
B_T	***Total*** number of **B**rushes	*User Defined*	brushes
B_S	Number of ***S****pray* **B**rushes	*User Defined*	brushes
L_W	Brush **L**ength (Unit ***W****idth*)	*User Defined*	millimetres
T_{RT}	**T**ime ***R****equired* ***T****otal*	*Fruit Info / Run Info*	seconds
T_{AT}	**T**ime ***A****llowable* ***T****otal*	*Fruit Info*	seconds
T_{RS}	**T**ime ***R****equired* ***S****pray*	*Fruit Info / Run Info*	seconds
T_{AS}	**T**ime ***A****llowable* ***S****pray*	*Fruit Info*	seconds
P_C	**A**ssumption correction	0.952±0.029	[proportion]
F_T	**F**ruit ***T****otal* in unit	$\frac{L}{2r} \times \frac{B_T - 1}{P_C}$	fruit
F_S	**F**ruit under ***S****pray*	$\frac{L}{2r} \times \frac{B_S - 1}{P_C}$	fruit
R_{Min}	Input **R**ate ***Min****imum*	$MAX\left(\frac{F_T}{T_{AT}}, \frac{F_S}{T_{AS}}\right)$	fruit/second
R_{Max}	Input **R**ate ***Max****imum*	$MIN\left(\frac{F_T}{T_{RT}}, \frac{F_S}{T_{RS}}\right)$	fruit/second
R_R	***R****equired* input **R**ate	*Calculated*	fruit/second
T_B	***B****rush* **T**ime	$\frac{R_R}{F_T}$	seconds
T_S	***S****pray* **T**ime	$\frac{R_R}{F_S}$	seconds
R_S	***S****urface* area **R**ate	$4 \times \pi \times r^2 \times R_R$	square millimetres/second

Not all static brush processes have spray application. To include these processes, the spray calculations are excluded when the B_S parameter (*Number of* ***S****pray* ***B****rushes*) is set to zero. The two modelling assumptions of Section 3.3.1 (p.29) are corrected by the *brushing* ***A****ssumption correction* (P_A) parameter. The correction was calculated with lower and upper values, which is included in Table 5.5.

User defined variables

The three *User Defined Variables: **T**otal number of **B**rushes (B_T), number of **S**pray **B**rushes (B_S)* and *brush **L**ength/unit **W**idth (L_W),* are physical attributes of the equipment that can be easily obtained.

Fruit info

The maximum ***A**llowable **T**imes* on ***B**rushes (T_{AT})* and under ***S**prays (T_{AS})* are fruit type specific as fruit can be damaged if brushed or sprayed for too long. The minimum ***R**equired **T**imes (T_{RT}, T_{RS})* represents the fastest speed at which the fruit can move through the unit, while still being sufficiently cleaned. The required time can be over-written by *Run Info* values (see below).

Run info

When fruit are especially dirty or humid conditions are present, ***R**equired washing **T**ime* and ***R**equired drying **T**imes (T_{RT}, T_{RS})* will need to be extended by overwriting the standard *Fruit Info*. For this reason, the *Origin* of these variables is indicated as *Fruit Info / Run Info* in Table 5.5.

Calculations

The ***T**otal number of **F**ruit (F_T)* in the unit and number of ***F**ruit under **S**pray (F_S)* are calculated using the assumptions of Section 3.3.1 on p.29. This is achieved by calculating the number of fruit between each pair of brushes and multiplying this with the number of rollers less one (see Table 5.5). The ***Min**imum* and ***Max**imum input **R**ates (R_{Min}, R_{Max})* are then calculated by dividing the number of fruit in each part (F_T, F_S) by the time fruit should *($T_{\#\#}$)* spend there. Figure 5.5 displays an example of the various feed rates of the total and spray parts, as well as the resultant combination of the two.

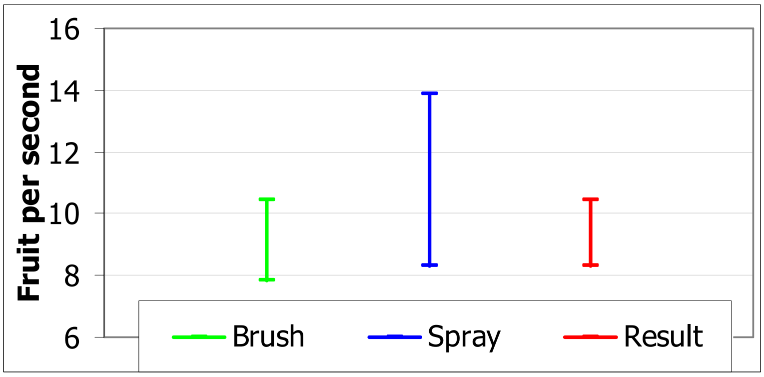


Figure 5.5: Static brush with spray capacity

If a ***R**equired input **R**ate (R_R)* is calculated, the ***T**ime* that fruit will spend on the ***B**rushes (T_B)* and under the ***S**pray (T_S)* can be calculated. The *fruit **S**urface area **R**ate (R_S)* that moves through the unit can also be calculated. The surface area calculation was done to assist in ensuring that wax is applied at the correct rate as the fruit surface area per kilogram decreases with larger sized fruit (Miller *et al.*, 2001:7).

Investigations into packing processes have revealed many sources of recommendations for durations and methods. These recommendations will be added to the generic model as guidelines.

Washing

The washing process removes dirt, sooty mould, scales, spray residues and most of the natural wax of the fruit (Wagner & Sauls, (s.a.)b:2). It is recommended that, where high pressure sprays are used, 12 brushes will provide adequate washing, but where a spray system is not used, 16 brushes must be used with a soap applicator and a clean water rinse (Outspan, 1998, chap.4:3). This recommendation indicates a 33% increase in washing time if high pressure sprays are not used. In tests where only brushes were used, a minimum washing time of between 20 and 30 seconds was found to be appropriate, but with problems such as sooty mould, longer times may be required (Miller *et al.*, 2001:4; Wagner & Sauls, (s.a.)b:2).

High pressure spraying can also be used for descaling, i.e. to remove scale insects. When used in this way, an average of ten seconds is recommended (Outspan, 1998, chap.5:11). However, for cleaning purposes only, fruit should spend a maximum of ten seconds under the spray (Outspan, 1998, chap.4:4).

Waxing

As the washing process removes most of the natural wax of the fruit, the wax is often replaced by artificial application (Wagner & Sauls, (s.a.)b:3). Wax is also applied to reduce shrivelling and improve the appearance of the fruit (Harris, 1988, chap.5.2). Wax units should have between ten and twelve brushes (Outspan, 1998, chap.4:9).

Table 5.6 gives optimum feed rates for various wax unit widths.

Table 5.6: Optimum feed rates

Fruit flow width in centimetres	Kg fruit per minute	Number of Fruit per second	Fruit surface area per second (cm^2/s)
150	400	20.6 to 34.8	5025 to 5606
120	300	15.4 to 25.7	3769 to 4204
90	200	10.3 to 17.1	2513 to 2803
60	100	5.1 to 8.6	1256 to 1401

(Outspan, 1998, chap.5:26)

The third column (fruit per second) displays the range of the number of fruit for the equivalent fruit masses. The equivalent fruit surface area per second is displayed in the fourth column. These were calculated using the ***FMF*** described in Section 4.2.5 on p.59.

5.3.2 Moving roller processes

Moving rollers are primarily found where fruit are picked up from a dip, in air drying units and on grading tables. The application on grading tables is presented later in Section 5.4 (p.77) as grading tables have various other factors that need to be taken into account. Certain types of mechanical sizers, such as the pony sizer, also make use of a simplified form of the calculations in Table 5.7.

Table 5.7: Capacity calculations for moving roller processes

Variable		Value / Origin	Unit
d	Average fruit **d**iameter	*Run Info*	millimetres
L_D	**D**istance between rollers	*User Defined*	millimetres
L_U	Total ***Unit*** **L**ength	*User Defined*	millimetres
L_W	**L**ength *(**W**idth)* of rollers	*User Defined*	millimetres
S_{Max}	***Max**imum* roller **S**peed	*User Defined*	millimetres/second
T_R	**T**ime ***R**equired*	*Fruit Info / Run Info*	seconds
T_A	**T**ime ***A**llowable*	*Fruit Info*	seconds
T_T	Maximum ***T**hroughput* **T**ime	$MAX\left(\frac{L_U}{S_{Max}}, T_R\right)$	seconds
F_T	***T**otal* number of **F**ruit in unit	$\frac{L_W}{d} \times \frac{L_U}{L_D}$	fruit
R_{Max}	Input **R**ate ***Max**imum*	$\frac{F_T}{T_T}$	fruit/second
R_R	***R**equired* input **R**ate	*Calculated*	fruit/second
T_{Max}	***Max**imum* **T**ime in unit	$MIN\left(\frac{F_T}{R_R}, T_A\right)$	seconds
S_{Min}	***Min**imum* **S**peed setting	$\frac{L_U}{T_{Max}}$	millimetres/second

User defined variables

The ***D**istance between rollers* (L_D), *total **U**nit **L**ength* (L_U), ***L**ength of rollers* (L_W) and ***Max**imum roller **S**peed* (S_{Max}) are all physical attributes of the equipment.

Fruit info

During drying processes ***R**equired* and ***A**llowable **T**imes* (T_R, T_A) apply. As fruit are typically dried at high temperatures, they can only spend a limited time in the unit before damage occurs. The minimum drying time can be over-written with a run-specific drying time (see below).

Run info

If cold or humid conditions are present the drying process is hampered and the ***T**ime **R**equired* (T_R) in the unit can be overwritten with a temporary value.

Calculations

The ***T**hroughput **T**ime* (T_T) represents the time it takes for a piece of fruit to move through the unit. This time is to be limited by either the physical ***Max**imum roller **S**peed* (S_{Max}) of the equipment or the minimum ***R**equired **T**ime* (T_R). The ***T**otal number of **F**ruit* (F_T) is the number of fruit present at a moment in time if all the rollers are completely full and is calculated by multiplying the number of fruit per roller and the number of rollers. By dividing F_T by T_T, the ***Max**imum input **R**ate (R_{Max})* can be calculated.

When a ***R**equired input **R**ate (R_R)* is specified the slowest speed setting can be calculated to ensure operating efficiency. First the ***Max**imum **T**ime (T_{Max})* that fruit can spend in the unit is calculated and then the ***Min**imum **S**peed (S_{Min})* setting.

Drying

The drying rate of fresh citrus is influenced by three factors: surface area, humidity ratio difference, and mass transfer coefficient of water into the air stream (Miller *et al.*, 2001:8). Drying of water can be achieved with one of two methods, firstly by evaporation and secondly by mechanically wiping the water away. The mechanical process of wiping water off is much more energy efficient than evaporation (Outspan, 1998, chap.4:6). Where heat is used to accomplish drying, Miller *et al.* (2001:9) recommend a minimum drying time of 2.5 minutes at a maximum air temperature of 60°C.

5.3.3 Dipping processes

During industry visits to GHC (personal observation, 2005), the dipping process was specifically observed to understand the dynamics of the process. When fruit enter the dip-tank, they fall into the solution from a conveyor. Fruit movement through the dip tank is facilitated by a pump, which removes water at the fruit exit point and adds it again at the fruit entry point. Sometimes a device is used to push fruit down to fully immerse it.

Depending on the fruit arrival rate, the fruit might be in the solution in one or two layers. As fruit are less dense than water, the top layer is pushed up when there are two or more layers of fruit present. The maximum number of layers has been included as a ***D**ensity* variable in the capacity calculations in Table 5.8.

Table 5.8: Capacity calculations for dipping processes

Variable		Value/Origin	Unit
r	Average fruit **r**adius	*Run Info*	millimetres
L_W	***W**idth* of dip-tank	*User defined*	millimetres
L_U	**L**ength of dip-tank	*User defined*	millimetres
A	Surface **A**rea	$L_U \times L_W$ / *User defined*	square millimetres
T_R	**T**ime ***R**equired*	*Fruit info / Run info*	seconds
T_A	**T**ime ***A**llowable*	*Fruit info*	seconds
ρ_D	Packing ***D**ensity*	*User defined*	layers
ρ_A	Assumption Correction	0.772±0.020	(proportion)
F_T	***T**otal* number of **F**ruit in unit	$\frac{A}{\pi \times r^2} \times \rho_A \times \rho_D$	fruit

Table 5.8 continued…

Variable		Value/Origin	Unit
R_{Min}	Input **R**ate ***Min****imum*	$\frac{F_T}{T_A}$	fruit/second
R_{Max}	Input **R**ate ***Max****imum*	$\frac{F_T}{T_R}$	fruit/second
R_R	***R****equired* Input **R**ate	Calculated	fruit/second

User defined variables

The ***W****idth* (L_W) and ***L****ength* (L_U) of the dip-tank represent the *surface **A**rea* (A) that can be filled with fruit. These are physical attributes of the dip-tank, but if the dip-tank is of some other shape (not rectangular) then automatic calculation can be replaced by specifying A. The ***D****ensity* (ρ_D) variable represents the acceptable number of layers at which the process is still deemed to be operating correctly. Typical values for the ρ_D parameter are expected to range from one (for a loose single layer) to 2.5 (for more than two layers of fruit if an immersion device is used).

Fruit info

The ***R****equired **T**ime* (T_R) is the fastest that fruit can move through this unit and still receive adequate dip treatment, while the ***A****llowable **T**ime* (T_A) is the longest duration that fruit can spend in the dip-tank before being damaged.

Run info

If treating for a specific disease or problem the ***R****equired **T**ime* (T_R) may need extension – this can be done by over-riding the standard fruit required time.

Calculations

The *maximum number of **F**ruit in the unit* (F_T) represents the maximum number of fruit that can be present in the dip-tank. It is calculated by dividing the total ***A****rea* (A) by the two-dimensional fruit area to determine the number of fruit in one layer, multiplied by the two-dimensional *assumption correction* (ρ_A) proportion (see Section 3.3.3 on p.35) and the ***D****ensity* figure ρ_D for more than one layer. The ***Min****imum* and ***Max****imum input **R**ates* (R_{Min}, R_{Max}) are then calculated as the number of ***F****ruit* (F_T) in the unit divided by the ***R****equired* and ***A****llowable **T**imes* (T_R, T_A), respectively.

The fungicidal treatment, which citrus fruit usually undergo during packing, can be applied over a brush-bed, incorporated in wax or as a dip (Miller *et al.*, 2001:8). According to Outspan's Citrus Production Guidelines (1998, chap.5:14), the dip method is preferred as it provides superior injury penetration when immersing the fruit at least 15 to 30 seconds. Fruit should not spend more than three minutes in the solution. This process is described as essential to post-harvest quality control by Wagner and Sauls ((s.a.)b:4).

5.3.4 Singular pocket processes

When fruit are singled out for data capturing or to be labelled, each fruit takes up one pocket and moves through the process while remaining in the same pocket. When fruit are labelled, each fruit size requires a different label. Labelling units therefore require setup time between production runs (Capespan (Pty) Ltd Citrus Business Unit, 2005:52). These types of processes typically have a number of lines that perform the same operation, e.g. multiple labelling lines. Since each fruit takes up one pocket, the number of lanes and the linear speed are key specifications (Miller *et al.*, 2001:7).

Table 5.9 gives the calculations for the capacity of singular pocket processes.

Table 5.9: Capacity calculations for singular pocket processes

Variable		Value/Origin	Unit
S_P	Maximum ***P**ocket* **S**peed	*User Defined*	pockets/second
N_L	**N**umber of ***L**ines*	*User Defined*	lines
δ	Maximum successful pickup rate	*User Defined*	fruit/cup
R_{Max}	***Max**imum* input **R**ate	$S_P \times N_L \times \delta$	fruit/second

User defined variables

***P**ocket **S**peed (S_P)* refers to the physical maximum speed at which each line can operate, measured in pockets per second. The ***N**umber of **L**ines (N_L)* variable represents the number of lines that are available and the *Maximum **S**uccessful Pickup Rate (δ),* the proportion of cups that are typically filled. An 80% fill of pockets is considered exceptional (Miller *et al.*, 2001:7).

Calculations

The product of the three user defined variables is used to calculate the ***Max**imum input **R**ate (R_{Max})* at which fruit can arrive at the unit.

5.4 FLOW DIVISIONS

Processes where flow divisions occur can be grouped into *grading* and *non-grading* processes. A *non-grading* flow division is where the flow of fruit is divided into multiple flows on a random basis and a *grading* flow division is when fruit are divided into multiple flows based on one or more characteristics of the fruit. *Grading* flow divisions can be grouped into manual, mechanical and optical grading. The system diagram of the flow division group is shown in Figure 5.6.

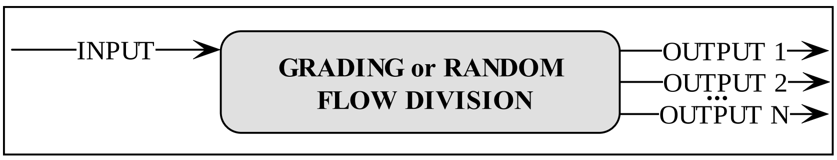


Figure 5.6: System diagram of flow divisions

It is of course logical that the sum of all the outputs must be equal to the input, under normal operation.

5.4.1 Non-grading random flow divisions

In some packing lines a flow of fruit is divided by barriers on conveyor belts. It is assumed that the random flow divisions do not alter the distributions of the fruit. Figure 5.7 displays a typical arrangement where a single flow is divided into three flows.

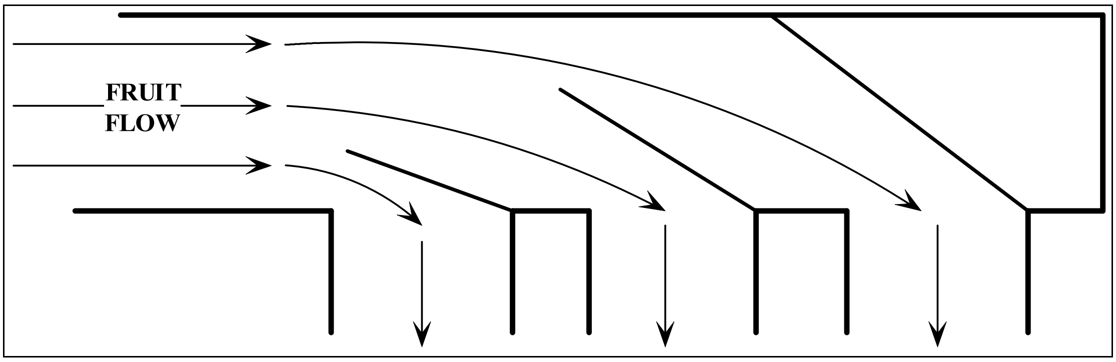


Figure 5.7: Non-grading flow division (series)

It should be noted again at this stage that this is not a study in the correct operation of equipment. It is therefore assumed that the proportions of the divisions can be controlled; however, a level of inaccuracy has been added to model the uncertainty of the proportions. Table 5.10 contains the relevant variables for random flow divisions.

Table 5.10: Random flow divisions

Variable		Value/Origin	Unit
O	Number of **O**utputs	*User Defined*	outputs
P_{Ui} P_{Li}	**P**roportion Range of ***i*** of O ***-upper*** and ***lower*** values	*User Defined*	(proportion)
E_i	**E**rror of *output **i***	*User Defined*	(proportion)
U_S	**S**eries/Direct	*User Defined*	series-1/direct-0
R_R	***Required*** input **R**ate	*Calculated*	fruit/second
P_{Ri}	***Required*** **P**roportion of *Output **i***	*Calculated* $P_{Li} \le P_{Ri} \le P_{Ui}$	(proportion)
P_{Ei}	***Expected*** **P**roportion of *Output **i***	$(P_1)\times\ldots\times(P_i \pm E_i)$ - Series $P_i \pm E_i$ - Direct	(proportion)
R_i	Output **R**ate of *Output **i***	$R_R \times P_{Ei}$	fruit/second

User defined variables

The *Number of **O**utputs (O)* and the possible ***P**roportion Range* (***U**pper* P_{Ui} and ***L**ower* P_{Li} values) of each output need to be specified. The level of ***E**rror (E_i)* of each output must be estimated. The ***S**eries/Direct (U_S)* parameter identifies the nature of the output proportion specifications and has a Boolean value. It gives the option of defining the proportions and errors as final or consecutive (as in Figure 5.7) divisions.

Calculations

Initially this process seems simple, but the effect of the division might significantly influence the rest of the line and calculations therefore are mostly dependant on the requirements of the complete system. Once the capacity of the whole system has been analysed a ***R**equired input* (R_R) **R**ate and ***R**equired* (P_{Ri}) divisions are specified. These are then used to calculate the *output **R**ate* (R_i) of each process output.

For example, if there are four outputs that are fixed and equal with 5% error, the upper and lower proportions will be [0.25 ± 0.05 ; 0.333 ± 0.05 ; 0.5 ± 0.05 ; 1] for series and [0.25 ± 0.05 ; 0.25 ± 0.05; 0.25 ± 0.05 ; 0.25 ± 0.05] for direct specification.

5.4.2 Grading flow divisions

In this section the modelling of the various grading line divisions is presented. This includes manual grading, mechanical grading and optical grading, where the division is dependant on one or more fruit characteristic.

5.4.2.1 Manual grading

Manual grading is usually first used just after the washing process, before any wax or fungicide is applied. When used this early it is referred to as *pre-grading* and green and Grade 4 fruit are separated from the main flow of fruit. Green fruit are sent to degreening and Grade 4 fruit are crated to be juiced. Pre-grading reduces costs for packaging materials, fungicides and waxes, and can improve the throughput of the packing line (Miller & Ismail, (s.a.):10).

The main application of manual grading is where second and third grade fruit are removed from the main flow of fruit. The main flow of fruit will typically be divided several times to reduce the linear speed of the fruit to facilitate grading (Miller *et al.*, 2001:6). The typical manual grading process is presented in Figure 5.8.

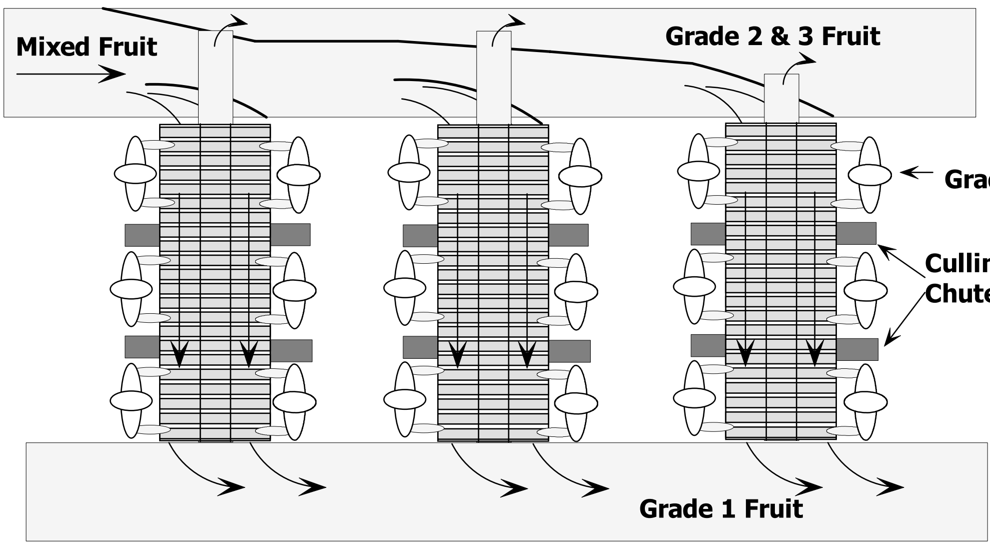


Figure 5.8: Typical grading table arrangement

In Figure 5.8 culling chutes and a conveyor above the grading table transports rejected fruit to their relevant processes. According to Wagner and Sauls ((s.a.)b:2) graders tend to remove about 30 fruit per minute, regardless of quality, so the rate of fruit flow or the number of graders should be varied according to the overall quality of a given lot of fruit. Fruit can move past the grading station on rotating rollers, that turn the fruit to facilitate observation, or on a conveyor belt that does not turn the fruit. The following table presents all the relevant capacity calculations to model manual grading tables.

Table 5.11: Capacity calculations for manual grading tables

Variable		Value/Origin	Unit
r	Average Fruit **r**adius	*Run Info*	millimetres
P_F	**P**roportion of ***Fruit*** to be removed	*Run Info*	(proportion)
G_N	***Number*** of **G**rading Tables	*User Defined*	grading tables
G_E	Type of **G**rading ***Equipment***	*User Defined*	roller-1/conveyor-0
L_W	Grading table ***Width***	*User Defined*	millimetres
G_T	Double/Single Sided **G**rading ***Table***	*User Defined*	1 or 2
G_S	Maximum **G**rading ***Stations*** per Side	*User Defined*	stations
S_{Max}	**Max**imum allowable **S**peed	*User Defined*	millimetres /second
L_D	***Distance*** between Rollers	*User Defined*	millimetres
G_H	**H**ands Available for Removal of Fruit	*User Defined*	1 or 2
T_G	Removal **T**ime per fruit per hand	*User Defined*	seconds/fruit
P_C	***Conveyor*** packing **P**roportion	0.772 ± 0.020	(proportion)
R_{GR}	***Roller*** table maximum input **R**ate	$\frac{L_W}{2r} \times \frac{S_{Max}}{L_D}$	fruit/second
R_{GC}	***Conveyor*** table maximum input **R**ate	$\frac{P_C \times L_W \times S_{Max}}{\pi \times r^2}$	fruit/second
R_{GT}	Table ***Type*** maximum input **R**ate	$G_E \times R_{GR} + (1 - G_E) \times R_{GC}$	fruit/second
GR_R	***Removal*** **R**ate per person	$\frac{G_H}{T_G}$	fruit/second/person
GR_{Max}	Total **R**emoval rate ***Maximum***	$\frac{G_H}{T_G} \times G_T \times G_S \times G_N$	fruit/second
R_{Max}	***Max**imum* input **R**ate	$MIN\left(\frac{GR_{\max}}{P_F}, R_{GT} \times G_N\right)$	fruit/second
R_R	***Required*** input **R**ate	*Calculated*	fruit/second
G_{RG}	Number of **G**raders ***Required***	$\frac{R_R \times P_F}{GR_R}$	people
G_{RT}	Number of **G**rading ***Tables*** required	$IF \quad \frac{G_{RG}}{2 \times G_T} \leq G_N \quad then$ $Roundup\left[MAX\left(\frac{2 \times G_T}{G_{RG}}, \frac{R_R}{R_{GT}}\right)\right]$ $else \quad G_N$	

Table 5.11 continued…

G_{Ri}	**N**umber of **G**raders at *table **i***	$IF \quad G_{RT} < G_N \quad then$ $\lceil 2 \times G_T \rceil \quad graders \quad at \quad \lceil G_{RT} \rceil \quad tables$ $else$ $\theta^- = G_T \times \left(Rounddown \left(\frac{N_G}{G_N \times G_T} \right) \right)$ $\theta^+ = \theta^- + G_T$ $\psi = Roundup \left(\frac{N_G - (\theta^- \times G_{RT} \times G_T)}{G_T} \right)$ $\lceil \theta^- \rceil \quad graders \quad at \quad \lceil G_{RT} - \psi \rceil \quad tables$ $\lceil \theta^+ \rceil \quad graders \quad at \quad \lceil \psi \rceil \quad tables$
P_i	**P**roportion of fruit to *table **i***	$\frac{G_{Ri}}{\sum_{i=1}^{G_{RT}} G_{Ri}}$
S_i	Minimum **S**peed of *table **i*** (millimetres/second)	$G_E \times \left(\frac{2 \times r \times D \times P_i \times R_R}{L_W} \right) + (1 - G_E) \times \left(\frac{\pi \times r^2 \times P_i \times R_R}{P_C \times L_W} \right)$

User defined variables

Grading tables are usually found in sets with a flow division before and a flow convergence afterward. The ***N**umber of **G**rading (G_N) tables* represents the number of tables in the set. As mentioned earlier, there are two types of grading tables; roller and conveyor tables. The *type of **G**rading **E**quipment (G_E)* parameter has a Boolean value that specifies which type is to be represented by the model. The value of the *grading table **W**idth (L_W)* parameter is the width of the conveyor belt or the length of the rollers, depending on G_E. The next parameter signifies whether graders stand on both *sides of the **G**rading **T**able (G_T)* or only on one side. The *Maximum number of **G**rading **S**tations per Side (G_S)* is required so as to not assign more people than can fit at the grading table. The ***Max**imum allowable **S**peed (S_{Max})* at which fruit can successfully be observed must be established. Outspan (1998, chap.7:1) recommends eight metres per minute and adds that speeds should never exceed 12 metres per minute. At GHC 8.4 metres per minute was observed (personal observation, 2005).

The next two parameters are equipment specific; for roller table, the ***D**istance between Rollers (L_D)* and for the conveyor table, the ***A**rea **P**acking Density (P_A)* defined in Section 3.3.3 on p.35. The *removal **T**ime per fruit per hand (T_G)* is the time between two fruit removals per one hand, a fruit "inter-removal" time. This variable is dependant on the skill of the person removing the fruit, as well as the distance that needs to be moved and it is recommended that values are estimated using time studies. The *Number of **H**ands (G_H)* that can be used to remove fruit is sometimes limited by the equipment and therefore needs to be specified.

Run info

The ***P****roportion of* ***F****ruit* (P_F) that is to be removed is calculated and is determined by all the preceding processes, as well as the initial fruit input.

Calculations

The capacity of a grading table is limited by one of two factors, depending on the ***P****roportion of* ***F****ruit* (P_F) that must be removed. If quality is good, only a small number of fruit needs to be removed. If this is the case, the capacity is determined by the number of fruit that can be observed successfully. The *maximum input* ***R****ate on* ***R****oller* ***G****rading tables* (R_{GR}) is calculated as the number of fruit between each pair of rollers multiplied by the speed of the rollers. The *maximum input* ***R****ate on* ***C****onveyor belt* ***G****rading tables* (R_{GC}) is determined by calculating the number of fruit that will fit on one second's worth of conveyor belt and then multiplying the result with the maximum speed (S_{Max}).

If fruit quality is not that good and a substantial number of fruit needs to be removed per second, the ***R****emoval* ***R****ate per person* (GR_R) becomes the limiting factor. Where a conveyor belt is used the grading personnel typically use one hand to rotate fruit to observe blemishes, while the other hand removes fruit. Where green or very badly blemished fruit are removed, both hands can typically be used. GR_R is calculated as the number of hands available for grading per person (G_H), divided by the time it takes to remove one fruit. The *total* ***Max****imum removal* ***R****ate* (GR_{Max}) is then calculated by multiplying GR_R with the maximum number of people that can be present at all the grading tables. To calculate the relevant maximum feed rate, GR_{Max} is divided by the proportion of fruit that must be removed.

The ***Max****imum input* ***R****ate* (R_{Max}) is the minimum of the two calculated feed rates. A ***R****equired input* ***R****ate* (R_R), which must be smaller than R_{Max}, is calculated by the model and then used to determine the equipment and personnel setups. The total *number of* ***G****raders* ***R****equired* (G_{RG}) is then determined by calculating the number of fruit per second that needs to be removed and then dividing it by the rate at which each grader can remove fruit. Next, the graders (G_{RG}) need to be allocated between the grading tables. Outspan (1998, chap.4:12) specifies that at least two graders must be present on each side of the grading table. This complicates matters where, for example, seven grading tables are available, but only 16 graders are required. In such a case only four of the grading tables will be required with four graders per table. However, if only a very small proportion of fruit needs to be removed, four grading tables might not be enough to transport the complete volume of fruit at the slow speeds required for grading. In such cases it is assumed that the minimum ***R****equired number of* ***G****rading* ***T****ables* (G_{RT}) to successfully transport the fruit will each be assigned two graders per side. If more than two graders are available for each grading table side all the grading tables will be used.

Each *table i* is then assigned a certain *number of* ***G****raders* (G_{Ri}) according to the logic in Table 5.11. For instance, if 38 graders need to be assigned to seven double-sided tables; the first five tables will each be assigned six graders and each of the remaining two tables will be assigned four. Fruit flow is then divided proportionately *(P_i)* to the number of graders at each table and the *minimum table **S**peed (S_i)* of each table is calculated to facilitate accurate grading.

5.4.2.2 Mechanical grading

A wide variety of mechanical sizing equipment is available, much of it crop specific (Harris, 1998, chap.5.2). Two types of mechanical sizers will be modelled, namely the belt-and-roll and pony sizers, as they are commonly employed for the sizing of citrus fruit.

In pony sizers moving rollers are spaced with empty spaces in-between. Fruit lie between each pair of rollers and the smallest fruit fall through onto a conveyor belt. The maximum feed rate can be calculated using Table 5.7 described in Section 5.3.2 (p.73) for moving roller processes. The proportion of fruit that is to be graded out does not play any role in the capacity of the unit, but will determine the output flows.

The belt-and-roll sizer singulates fruit into lanes and fruit then fall through specific size openings between an angled belt and rollers. The smallest fruit fall through at the first roller, which is a small distance from the angled conveyor belt, and the openings are slightly larger for each consecutive fruit size. Efficiency depends on the relationship between the fruit contact speeds of the belt and roller. There exists a recommended relationship of 2.8:1 between the belt and roller speeds for smooth operation (Miller *et al.*, 2001:9). Table 5.12 presents the variables and capacity calculation for belt-and-roller sizers.

Table 5.12: Capacity calculations for belt-and-roll sizer

Variable		**Value / Origin**	**Unit**
d	Average fruit **d**iameter	*Run Info*	millimetres "/fruit"
S	Maximum fruit **S**peed	*User Defined*	millimetres/second/lane
N_L	**N**umber of ***L**anes*	*User Defined*	lanes
R_{Max}	Feed **R**ate ***Max**imum*	$\frac{S \times N_L}{d}$	fruit/second

User defined variables

The *Fruit **S**peed (S)* is the velocity at which fruit move in the lanes of this unit. Speeds of around 1.1 m/s are common (Miller *et al.*, 2001:9) and was observed at GHC (September 2005). The ***N**umber of **L**anes (N_L)* is essential as a belt-and-roller sizer usually consist of several identical lanes.

Calculation

The ***Max**imum Feed **R**ate (R_{Max})* is calculated as the maximum number of fruit that can pass a point in a second, multiplied by the number of lanes.

5.4.2.3 Optical grading

The operation of optical grading units is similar to that of *Singular pocket processes*. See Section 5.3.4 (p.77) and Table 5.9 for capacity calculations. The main difference is that the outputs are manifold as fruit are dropped at the exact packing table for its quality and size.

Optical grading was initially used for size grading only, but later for colour grading and these days for quality grading as well. A great advantage of optical sizing is that operators can easily adjust the size categories to maximize the output of desired sizes and to switch between types of fruit such as grapefruit and oranges (Miller *et al.*, 2001:9).

5.5 FLOW CONVERGENCE

Flow convergence will occur when two or more fruit flows converge into a single fruit flow. Figure 5.9 shows the flow convergence as a system.

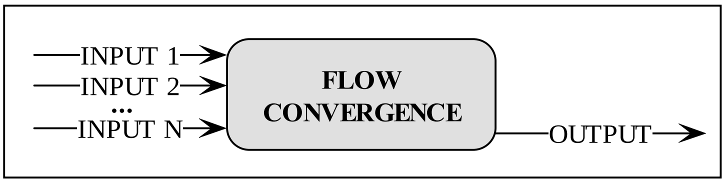


Figure 5.9: System diagram of flow convergence

The sum of the inputs will equal the output and margins of error will be joined into one. Where fruit flows have been previously split with margins of error, the margin now needs to be removed by reversing the flow division calculations done earlier. This is to ensure that the total system output is equal to the input.

5.6 PACKING OR STACKING

Export fruit are typically packed into cartons, with the number of fruit in each carton dependant on the size of the fruit. The cartons are later stacked onto pallets. Carton packing is the primary method used to package export fruit in South Africa (Ortmann, 2005:11). The packing and stacking of cartons are very similar, but fundamental differences require that they be modelled separately. The system representation of the packing and stacking processes is shown in Figure 5.10.

Figure 5.10: System diagram of packing and stacking processes

Other methods of filling such as bagging and filling of containers directly from a conveyor belt, also fall in this process group, but will only be represented as system outputs. The number of containers or bags required for each of these outputs can easily be calculated from the number of fruit per container. Background to packing and stacking processes and their relevant capacity calculations are presented in the two following sub-sections.

5.6.1 Carton packing

Carton packing is fundamentally different from all other fruit packing line processes as it is dynamic in time – fruit accumulate on the packing table and are worked away by packing it into cartons. Usually a common fruit size emerges in a packing run and results in certain packing tables being over-full. To avoid delaying the whole system, some packing tables have been divided into two or more sections as shown in Figure 5.11 (personal observation, 2005). While some fruit from the previous production run may still be present on the table, the next production run can be started without mixing the fruit.

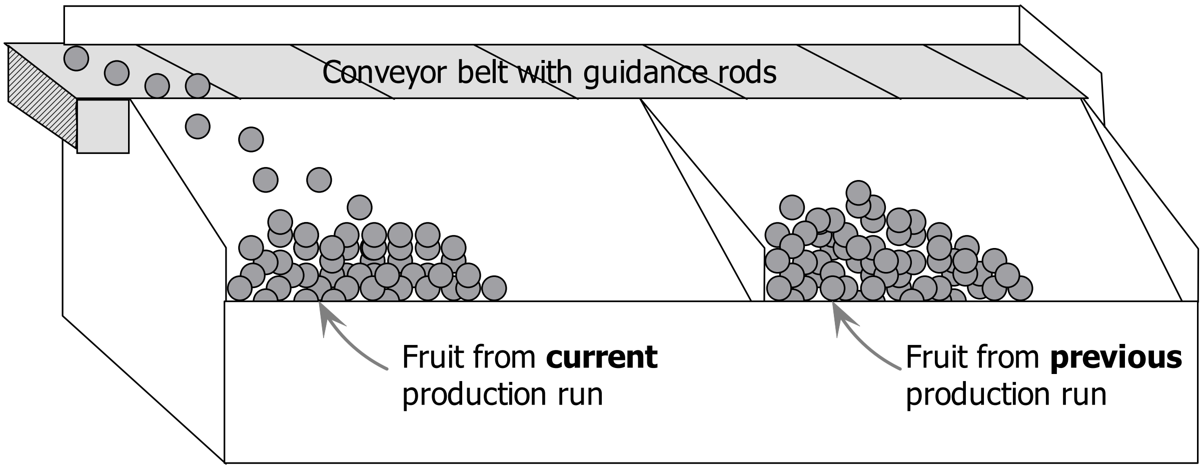


Figure 5.11: Packing table with sections

Fruit gather on packing tables and packing personnel use movable stands to hold the cartons during packing. Filled cartons are placed on a conveyor and an empty carton is usually delivered by an overhead crane system (Wagner & Sauls, (s.a.)b:2).

In the following table the capacity calculations for packing tables are presented.

Table 5.13: Capacity calculations for packing tables

Variable		Value/Origin	Unit
F_U	***U**nwrapped* **F**ruit per carton	*Fruit Info*	fruit
F_W	***W**rapped* **F**ruit per carton	*Fruit Info*	fruit
F_T	***T**otal* number of **F**ruit at table	*Run Info*	fruit
r	Average fruit **r**adius	*Run Info*	millimetres
$\rho_{AKV\text{-}5}$	**A**djusted **K**epler **V**alue ***5**%*	*0.632-0.018*	(proportion)
P_P	Number of **P**acking table ***P**arts*	*User Defined*	parts
V_{Ti}	**V**olume of packing *Table part **i***	*Used Defined*	cubic metre
F_{Ti}	***T**otal* number of **F**ruit in *part **i***	$\frac{3\times\rho_{AKV-5}\times V_{Ti}\times 10^9}{4\times\pi\times r^3}$	fruit
PS_i	Maximum **P**acking **S**tations *part **i***	*User Defined*	stations
T_U	**T**ime to pack a fruit – ***U**nwrapped*	*User Defined*	seconds/fruit
T_W	**T**ime to pack a fruit – ***W**rapped*	*User Defined*	seconds/fruit

Table 5.13 continued…

Variable		Value/Origin	Unit
T_N	**T**ime to start ***N****ext* carton	*User Defined*	seconds/cartons
C_P	**C**artons to be **P**acked	$\frac{F_T}{F_U + F_W}$	cartons
T_C	**T**ime to pack a ***C****arton*	$T_U \times F_U + T_W \times F_W + T_N$	seconds
T_{Min}	***Min****imum* packing **T**ime	$\frac{C_P \times T_C}{\sum_{i=1}^{P_P} PS_i}$	seconds
CR_{Max}	***Max****imum* **O**utput rate	$\frac{\sum_{i=1}^{P_P} PS_i}{T_C}$	cartons/second
R_{Max}	***Max****imum* feed **R**ate	$\frac{\sum_{i=1}^{P_P} F_{Ti}}{T_{\min}} + CR_{\max} \times (F_U + F_W)$	fruit/second
R_R	***R****equired* input **R**ate	Calculated	fruit/second
T_D	Fruit input **T**ime ***D****uration*	Calculated	minutes
PS_{Min}	**M**inimum **N**umber of packers required	**Round up** $\left(\frac{T_c}{F_U + F_W} \times \left(R_R - \frac{\sum_{i=1}^{P_P} F_{Ti}}{60 \times T_D}\right)\right)$	

User defined variables

The number of ***P****arts* of the **P**acking *(P_P)* table must be specified and for each part or section of the packing table the ***V****olume (V_i)*, in cubic metres, and the maximum number of ***P****acking* ***S****tations (PS_i)* must be specified. The ***T****imes* to pack ***W****rapped* and ***U****nwrapped fruit (T_W, T_U)*, as well as the ***T****ime* it takes to close a carton and start the ***N****ext (T_N)* one, must be estimated. The results of the time study later in this section can be used as a guide.

Run info

The ***T****otal number of* ***F****ruit (F_T)* parameter represents the number of fruit that will be packed at the packing table during a specific production run.

Fruit info

The number of ***U****nwrapped* and ***W****rapped* ***F****ruit (F_U, F_W)* which is packed into each carton is standard data for the fruit size and carton type.

Calculations

The *number of **F**ruit (F_{Ti})* that can accumulate in each section of the packing table is calculated by dividing the *section **V**olume (V_{Ti})* by the average volume per fruit for that production run. The lower limit of the ***A**djusted **K**epler **V**alues (ρ_{AKV},* see Section 3.3.2 on p.31) is used to estimate the expected maximum space lost between fruit.

The number of ***C**artons to be **P**acked (C_P)* is calculated by dividing the ***T**otal number of **F**ruit (F_T)* by the number of fruit in a carton, which is the sum of F_U and F_W. The ***T**ime to pack a **C**arton (T_C)* is calculated as the sum of the times to: pack the wrapped and unwrapped fruit and to switch to the next carton. The product of the ***C**artons to be **P**acked (C_P)* and ***T**ime to Pack a **C**arton (T_C)*, divided by the total number of packing stations provides the fastest time in which all the fruit can be packed. The ***Max**imum output **R**ate (R_{Max})*, in cartons per second, is the highest rate at which cartons can be packed at the table and is calculated by dividing the *total number of **P**acking **S**tations (Sum PS_i)* by the ***T**ime* it takes *to pack a **C**arton (T_C)*.

The ***Max**imum Feed **R**ate (R_{Max})* is the fastest allowable rate at which fruit may arrive at the packing table to avoid problems. R_{Max} is calculated as the sum of two parts; the first part is the time it would take to fill the table if no fruit were removed and the second, the maximum rate at which fruit can be removed. The first part, the fill time, is calculated by dividing the *number of **F**ruit (F_T)* that can be on the table, by the fastest time it can all be packed *(T_{Min})*.

If a ***R**equired input **R**ate (R_R)* and the *fruit input **T**ime **D**uration (T_D)* is specified the ***Min**imum number of **P**ackers (PS_{Min})* required at the table can be calculated. PS_{Min} resembles the required number of packers to stop the table from being over filled and is calculated by subtracting from the specified input rate *(R_R)*, the rate at which fruit will just fill up the table during the production run and dividing this by the average rate at which one packing station removes fruit. This figure is then rounded up.

Time study

A time study of 3 686 fruit was completed to analyse typical times and drivers for fruit packaging. Packing time per fruit was calculated and, while the average packing time per fruit was 0.75 seconds, the figure was found to be strongly dependant (p-value of 0.00) on the person doing the packing. When wax wrapping is used, fruit in every second layer are wrapped individually. After the effect of the person was removed the following average packing times (Equations 5-1 & 5-2) were calculated, with lower and upper expected values:

$$T_U = 0.631 \pm 0.154 \quad \textbf{\textit{sec}} \qquad \textbf{(5-1)}$$

$$T_W = 0.855 \pm 0.220 \quad \textbf{\textit{sec}} \qquad \textbf{(5-2)}$$

T_U is the average time to pack one fruit and T_W the average time to wrap and pack one fruit. The time it takes to close a packed carton, place it on a conveyor and start the next carton was also studied. The average carton change time, 95% lower and upper expected values, for eleven recorded times, is:

$$T_N = 21.0 \pm 2.2 \;\; sec \qquad \textbf{(5-3)}$$

Calculation details and captured times can be seen in Appendix G.

5.6.2 Pallet stacking

Cartons of fruit are built into pallets at pallet stacking stations. Each pallet has fruit of a particular quality and size (Wagner & Sauls (s.a.)b:5). Figure 5.12 displays the typical arrangement, whereby cartons enter the area on rollers. The number of cartons per pallet varies with the carton type and ranges from 45 to 360 cartons per pallet. For the most frequently used carton, the A15C size, 70 cartons are built into one pallet. See Appendix H from Capespan (Pty) Ltd Citrus Business Unit's Packing guide (2005:5) for more details.

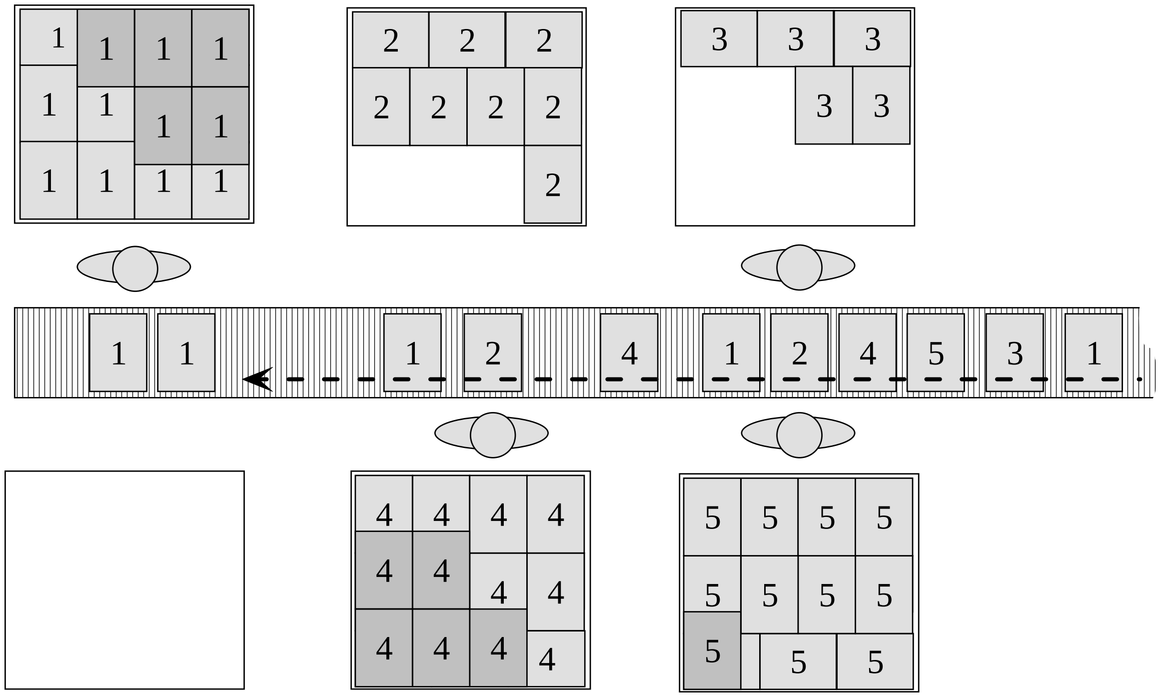


Figure 5.12: Pallet stacking viewed from above

The primary tasks are moving the cartons from the conveyor belt and then switching to the next pallet using a forklift. There are various other tasks associated with pallet building, such as strapping corner supports in place and inserting a thermocouple (Ortmann, 2005:37) to measure the inner temperature of the pallet during transport. The times associated with the above-mentioned tasks, depend on the nature of the tasks and the method employed to accomplish the desired result. For this reason time studies were not performed on these processes, but times are included in the capacity calculation table, Table 5.14.

Table 5.14: Pallet stacking capacity

Variable		Value/Origin	Unit
C_i	**C**artons per pallet for *carton type **i***	*Fruit Info*	cartons
PS	Maximum number of **S**tations	*User defined*	stations
T_C	**T**ime to stack a **C**arton	*User defined*	seconds/carton
T_N	**T**ime to start ***N**ext* pallet	*User defined*	seconds/pallet
T_O	**T**ime to do ***O**ther* tasks	*User defined*	seconds/pallet
T_{Pi}	**T**ime to stack a ***P**allet*	$T_C \times C_i + T_N + T_O$	seconds
CR_i	**C**arton output **R**ate per station	$\frac{C_i}{T_{Pi}}$	carton/seconds
CR_{Max}	**C**arton input **R**ate ***Max**imum*	$\sum_{i=1}^{PS} CR_i$	cartons/second

User defined variables

The *maximum number of **P**allet building **S**tations (PS)* is dependant on the physical equipment setup and refers to the number of pallets that can be built simultaneously. The ***T**ime to stack a **C**arton (T_C)* is the time it takes for a person to move a carton from the conveyor to the pallet. The ***T**ime* to replace a finished pallet with the ***N**ext (T_N)* empty one and the ***T**ime* spent on all ***O**ther (T_O)* tasks are defined per pallet. The various times are dependant on the physical pallet building station and the skill of the personnel. When these variables need to be specified, time studies will be required to determine typical times, as well as possible variance.

Fruit info

The number of ***C**artons per pallet (C_i)* will be dependant on the type of carton used. Typical carton numbers for various carton sizes are included in Appendix H.

Capacity calculations

The time to stack a pallet is calculated as the sum of *Number of **C**artons (C_i)* on the pallet multiplied by the ***T**ime* it takes *to stack one **C**arton (T_C)*, the time to perform ***O**ther (T_O)* tasks and the time to switch to the ***N**ext* pallet *(T_N)*. The ***C**arton output **R**ate per pallet stacking station (CR_i)*, measured in cartons per second, is calculated for each carton type by dividing the number of ***C**artons per Pallet* by the ***T**ime to stack a **P**allet (T_{Pi})*. Both variables, C_i and T_{Pi}, are carton type specific. The ***Max**imum **C**arton input **R**ate (CR_{Max})* is the sum of all the station output rates *(CR_i)*.

5.7 FLOW CONTROL

Flow control processes are usually placed after sizing units (optical or mechanical) and prior to a set of packing tables in the packing line. Each input flow contains a specific fruit size and the unit can send each fruit size to a selection of packing tables. This process is always a non-grading process as fruit are already graded when arriving at this unit. Figure 5.13 shows the system diagram of a flow control process.

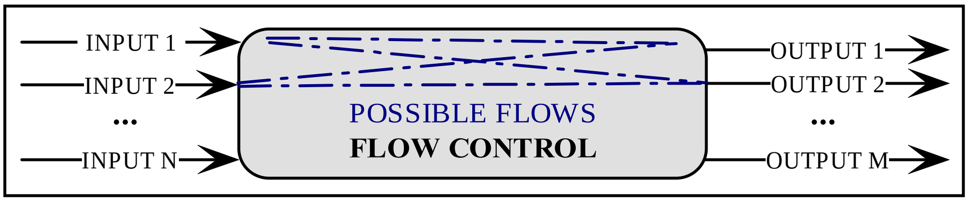


Figure 5.13: System diagram of a flow control process

As the assignment of inputs to outputs is strongly dependant on the packing table capacities and the volume of each fruit flow input, decision logic has specifically been developed to assign inputs to outputs. The decision logic is, however, dependant on several physical factors which are presented below.

The first factor is the possible flow selections that can be made, i.e. between which inputs and outputs the fruit can be transferred. Figure 5.14 shows a typical arrangement with multiple options for each input and output.

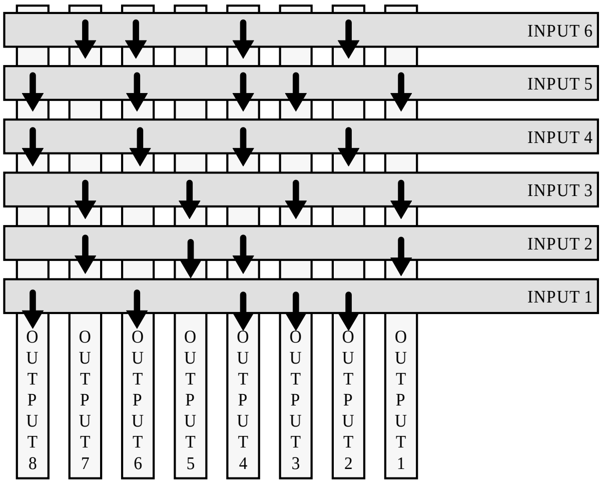


Figure 5.14: Flow control possibilities

The capacity of each outgoing line may also be a limiting factor. For conveyor applications, the line width and maximum conveying speeds must be specified for each output. The conveying capacity assumption correction of Section 3.3.3 (p.35) is used with the width and speed to allocate inputs to outputs.

Where optical sizing is used, the outgoing lines contain moving pockets that can carry one fruit per pocket. The number of lines and the pocket speed are used to determine the capacity. Optical grading units have numerous outputs, as many as one for each size-grade combination. Each pocket drops open when the appropriate table is reached. Any combination of input to output is therefore possible when singular moving pockets are used.

The assignment of packing tables can be done in many ways. A specific assignment method was constructed by modifying a method developed by Winston (1994:373-378) that assigns jobs to equipment. Two matrices are used; one for job versus equipment capacity or cost, depending on the problem, and one for assignment of jobs to equipment. In the packing line application of Winston's method, the *packing tables* represent the *equipment* and the *fruit flows* represent the *jobs*. In the first matrix of fruit flows versus packing tables, the capacity calculations of Section 5.6.1 (p.85) are used to determine the capacity of the packing tables for each specific fruit flow. Cell R_{ij} of the matrix is assigned the *maximum allowable feed* ***R****ate* for *fruit input flow* i and for *output table* j. The second matrix contains the assignment of fruit flows to packing tables and is expressed as x_{ij}, where x_{ij} has a value of one when *fruit flow* i is assigned to *table* j, and a value of zero when it is not, as shown in Equation 5-8. For this specific application of Winston's assignment method, the various ***I****nput flows* (I_i) were added to the assignment method to represent the number of fruit per second of each input. The *possible flow* ***C****ombinations* (C_{ij}) were also added in the matrix with a value of one if *flow* i can be assigned to *table* j and a value of zero if it cannot. C_{ij} is used to manipulate R_{ij} to disallow impossible flows. The maximum expected fruit flow for each fruit size-grade combination is used in the calculations below. Consult Appendix I for an example of the various matrixes and testing of the algorithm.

Three allocation rules for x_{ij} were formulated from personal observation (GHC, 28 September, 2005) and industry interviews (G Koen, Stellenpak-Simondium, 14 Augustus, 2005 & J Wepener, Piketco 27 September, 2005). They are:

1. The assigned fruit flow input cannot be larger than the capacity R_{ij}.
2. As few tables as possible must be assigned.
3. The smallest possible tables must be assigned.

Together, rules 2 and 3 attempt to keep as many of the largest tables as possible open for the subsequent production run, which can then be started almost immediately if enough tables are available.

The objective function is to minimize the packing table capacity allocated *(Z)* for the production run, i.e.

$$\min Z = \sum_{b}^{O}\sum_{a}^{I} R_{ab}x_{ab} \qquad \textbf{(5-4)}$$

where I is the number of input flows, O the number of output flows, R the allowable feed rates, x the flow assignments and C the possible flows. The following conditions apply:

$$\sum_{b}^{O} R_{ib}x_{ib} \geq I_i \ , \qquad \textbf{(5-5)}$$

$$\sum_{a}^{I} x_{aj} \leq 1 \, , \qquad \textbf{(5-6)}$$

$$C_{ij} - x_{ij} \geq 0 \, , \qquad \textbf{(5-7)}$$

$$(x_{ij} = 0 \text{ or } x_{ij} = 1) \text{ and } (C_{ij} = 0 \text{ or } C_{ij} = 1). \qquad \textbf{(5-8)}$$

The condition in Equation 5-5 ensures that fruit are assigned to one or more tables that have enough capacity to handle the fruit flow. Equation 5-6 ensures that each packing table can only be assigned one input. Equation 5-7 ensures that *fruit flow* i is only assigned to *table* j if this transfer is physically possible.

The algorithm developed to assign packing tables starts by assigning the largest of I_i to the least number of the smallest possible tables, minimising first the number of tables and then the capacity allocated. For example, if fruit flow of 16.7 fruit per minute need to be assigned between six packing tables with capacities of [6.5; 6.5; 8.5; 8.5; 11.7; 11.7] fruit per minute respectively, it is clear that one packing table will not suffice. When combinations of two packing tables are considered, there are two options: the tables with capacities of 6.5 and 11.7 (total 18.2) and the tables with capacities of 8.5 and 8.5 (total 17.0). Keeping in mind that excess capacity must be minimised, the 8.5 and 8.5 combination is chosen. This process continues until all fruit flows have been assigned to packing tables.

The next step is to divide the excess capacity evenly where more than one grading table was assigned. The minimum number of packing personnel required at each packing table can then be calculated using the packing process calculations in Section 5.6.1 on p.85. The algorithm above was tested three times and compared to manually calculated, optimal results. The optimum assignment was made every time (see Appendix I). However, different packing lines might require different algorithms if the packing table assignment has other rules than those used, for instance if large packing tables need to be assigned first.

In this chapter, the fourth step of the generic modelling methodology, the model construction, was presented. In the modelling procedure, described in the next chapter, the calculations of this chapter are used as building blocks and they are combined with the results of the data analysis described in Chapter 4. The development of the computer model is also presented in the next chapter.

CHAPTER 6

MODELLING PROCEDURE

The development and implementation of the modelling procedure is presented in this chapter. The modelling procedure development is Step 5 of the generic modelling methodology (See Section 2.3.5 on p.17). Concurrently with the execution of this step, the process models described in Chapter 4 were translated into a computerized model. The structure of the computer model is discussed in Section 6.3 (p.99).

6.1 SETTING UP THE GENERIC MODEL

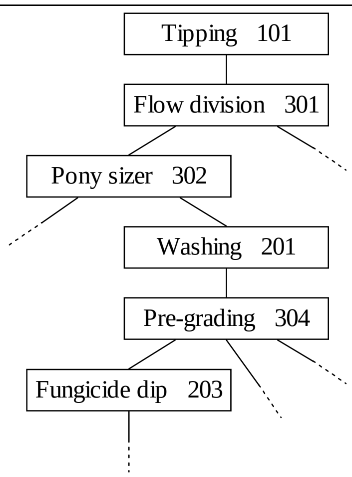
Before the modelling procedure, which is described later in this chapter, can be implemented, the generic model must be populated with fruit specific data (*Fruit info*, see Section 3.3.4 on p.35). The *Fruit info* consists of various industry standards such as size classifications, packaging specifications and processing durations, as well as modelling data such as the fruit size distribution estimation of hard citrus (see Section 4.2.1 on p.47). These parameters are all fruit type specific and values have been collected and calculated for hard citrus fruit throughout this study.

After the specification of the relevant *Fruit info*, the generic model must be set up to represent a *specific "reality"* in the set of realities to which the generic model applies. The specific reality can be an existing packing line, a hypothetical/proposed packing line or a combination when proposed changes to an existing packing line need to be analysed.

The definition of a specific packing line/reality consists of two parts. The first part of the *specific reality definition* is a list of all the processes in the specific packing line. For each process, the number of outputs and the subsequent process for each output has to be specified. An example of a process list and output specification is shown in Table 6.1.

Table 6.1: Example of a process flow table

Process	ID	Outputs	Output Process
Tipping	**101**	1	301
Flow division	**301**	2	302,303
Pony sizer	**302**	2	201,501
Washing	**201**	1	304
Pre-grading	**304**	3	203,504,505
Fungicide dip	**203**	1	204
etc	...	...	...



Each process is assigned an ID number of which the first digit signifies the generic process type (see Section 3.3.5 on p.36) and the following two digits are used to identify the specific process. The process flow diagram in Table 6.1 is a graphical representation of the data the table contains. For each process instance, the number of outputs, which is one for all except for the *flow division* and *flow control* processes, and the ID number of the next process, are required.

The second part of the *specific reality definition* is the specification of relevant *User defined* (see Section 3.3.4 for definition of *User Defined* on p.35) variables for each process in the list of processes (see Chapter 5 for variables relevant to each process). The specific reality, or packing line, is then fully defined by the specification of the process flow table and *User defined* variables.

After having fully defined a specific packing line, an accurate estimate of the system input is required to analyse a production run. The definition of the system input is the first step of the modelling procedure described in the next section.

6.2 STEPS OF THE MODELLING PROCEDURE

The modelling procedure is the fifth step, indicated in Figure 6.1, of the seven step modelling methodology of Hangos and Cameron (2001:25), which was the basis of the generic modelling methodology that was described in this study.

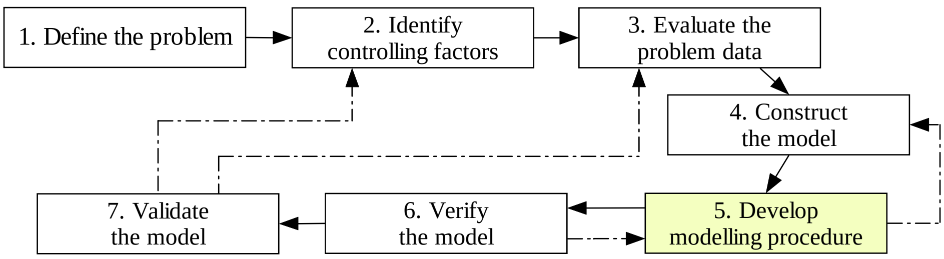


Figure 6.1: Systematic model building steps (Hangos & Cameron, 2001:25)

The modelling procedure was developed to calculate the expected system behaviour for a single production run and is divided into five steps. Each of the steps will now be briefly introduced before calculation detail is presented. First, the input of the system is defined using the fruit characteristic distributions and estimation method described in Chapter 4 (*System Input*, 6.2.1). Secondly, the maximum allowable fruit flow input of each process is calculated for the system input, using the capacity calculations in Chapter 5. The input and output of each process are then determined in terms of the fruit distributions and number of fruit that will pass through the process during the production run (*System flows*, 6.2.2).

The third step consists of the selection of a processing speed (maximum fruit flow) for the production run. Selection is based on the maximum flow of the constraining process in the production run. A tipping rate for which the fruit flow is not expected to exceed the selected maximum flow (*Processing speed*, 6.2.3) is then suggested. In the fourth step, the selected maximum flow is used and, for each process, the relevant fruit flow is calculated by subjecting it to the maximum allowed system flow. Packing table selections are then calculated and "best" personnel setups are determined for grading and packing tables as well as "best" equipment setups, such as roller speeds and wax application rates (*Setups*, 6.2.4). Lastly, the number of containers, pallets and crates of fruit for all outputs need to be calculated, enabling the estimation of packaging materials that will be consumed during the production run (*System output*, 6.2.5).

Each step of the above-mentioned steps and relevant calculations are presented in detail below. A method to analyse the effect of varying fruit size, quality and colour on the complete system is then discussed.

6.2.1 System input

The system input consists of the estimation of the various fruit distributions, as well as the number of fruit that will be packed during a production run. The fruit size distribution can be estimated by specifying the average size and then using the beta distribution, but this is only valid for an average fruit size between 69.2mm and 84.0mm (see Section 4.2.1 on p.47). The fruit quality distribution can be specified by estimating the proportion of Grade 1 fruit (see Section 4.2.2 on p.54).

Similar distribution estimations will be required for other fruit types in future if the modelling concept is acceptable. However, the empirical distribution can also be used as an alternative where distribution estimations have not been calculated. In this study only citrus fruit, which are divided into ten size categories, were analysed, but to enable the addition of more fruit types, the number of size, quality and colour categories can be decreased or increased to fit the applicable industry standard by adding data to the *Fruit info* of the model.

For each system input process where fruit are introduced into the system, the input must be described in a table such as Table 6.2.

Table 6.2: System input description

QUALITY	Grade 1		Grade 2		Grade 3		Grade 4			
Lower	0.61		0.78		0.96		1.00			
Upper	0.68		0.82		0.98		1.00			
SIZE	1	2	3	4	5	6	7	8	9	10
Peaked	0.01	0.03	0.06	0.26	0.59	0.86	0.99	1.00	1.00	1.00
Flat	0.02	0.07	0.19	0.36	0.55	0.74	0.91	0.98	1.00	1.00
COLOUR	Acceptable					Not acceptable				
Lower	0.88					1.00				
Upper	0.92					1.00				
Number of crates	312									

In Table 6.2, fruit quality, size and colour are represented by two cumulative distributions each. Fruit quality and colour distributions are specified as a lower distribution and an upper distribution, representing the uncertainty in predicting what the actual fruit quality and colour are. The uncertainty of the fruit size distribution is represented as a peaked distribution and a flat distribution (see Section 4.2.1 on p.47). The distributions can be estimated with the method described in Section 4.3 (p.61), which employs historical data of the producer.

The next step of the modelling procedure entails the calculation of maximum throughputs as well as fruit flow for each process by using the system input defined above.

6.2.2 System flows

As mentioned in Section 3.2.2.2 (p.28), all statistical ranges of estimates were calculated using a two-tailed 95% level of confidence. The calculations in this step aim to maintain the level of 95% confidence of maximum and minimum flows and fruit distributions.

Starting with the fruit introduction processes, the output fruit distributions, expected number of fruit and the allowable fruit flow for each process are calculated using the capacity calculations in Chapter 5. The output of each process is accepted as the input for the next process on the flow table (see Table 6.1).

For example, if the fruit distributions of Table 6.2 were to be processed by a pony sizer, only the smallest fruit would be removed. The expected minimum and maximum number of fruit in 312 crates, using the volume estimation method (see Section 3.3.2 on p.31), is 303560 and 318872 units of fruit, respectively. The proportion of fruit that will be graded out is between 0.01 and 0.02. The maximum and minimum number of fruit for the two outputs are given in Table 6.3.

Table 6.3: Example of number of fruit calculations

	Main flow min	Main flow max	Graded out min	Graded out max
Calculation	303 560 x 0.980	318 872 x 0.990	303560 x 0.010	318 872 x 0.020
Result	297 489	315 683	3036	6377

The input of the washing process, which succeeds the pony sizer, is therefore less than the input of the pony sizer.

The colour and quality distributions for fruit will remain unchanged as independence was assumed in Section 4.2.4 on p.58. The size distribution must, however, be recalculated. For the graded out flow of fruit, this calculation is simple as the Size 1 category will now represent 100% of this fruit. For the main flow of fruit, each fruit size category must be divided by 0.98 and 0.99, respectively to normalise the distribution after a proportion of fruit has been removed, as shown in Table 6.4.

Table 6.4: Example of the recalculation of fruit size distribution

SIZE	1	2	3	4	5	6	7	8	9	10
Original peaked	0.010	0.030	0.060	0.260	0.590	0.860	0.990	1.000	1.000	1.000
Original flat	0.020	0.070	0.190	0.360	0.550	0.740	0.910	0.980	1.000	1.000
New peaked 1	**0.000**	0.020	0.050	0.250	0.580	0.850	0.980	0.990	0.990	**0.990**
New flat 1	**0.000**	0.050	0.170	0.340	0.530	0.720	0.890	0.960	0.980	**0.980**
Recalc. peaked	0.000	0.020	0.051	0.253	0.586	0.859	0.990	1.000	1.000	1.000
Recalc. flat	0.000	0.051	0.173	0.347	0.541	0.735	0.908	0.980	1.000	1.000

It is clear that the average fruit size of the input and main output will differ as the recalculated fruit distribution has no fruit of the smallest size (Size 1). Fruit size plays a role throughout the packing line and is therefore recalculated each time the fruit distribution is changed. In the calculations above it is assumed that, for all grading processes, the grading operation is completely successful. This assumption depends on the fact that the relevant capacity limit, which is calculated using the equations in Chapter 5, is not exceeded.

The order of the above-mentioned calculations is determined by the order of the processes defined in the flow table. A first-in-first-out (FIFO) queue is used and the system input processes (tipping) entered first. The first process is then analysed and its outputs are added to the FIFO queue. The first few iterations of this process, for the process flow example of Table 6.1, are shown in Table 6.5.

Table 6.5: Order of process calculations

Iteration	FIFO queue	Completed processes
0	101	
1	301	101
2	302, 303	101, 301
3	303, 201, 501	101, 301, 302

In the next phase of the modelling procedure, the maximum flows of all the processes are compared and the constraining process determined.

6.2.3 Processing speed

The maximum flow for each process was calculated in the previous step. The fastest allowable feed rate for the system is the slowest of all the maximum flows. Once selected, the maximum tipping rate is calculated by reversing the earlier calculations that determined the expected number of fruit per crate. The maximum feed rate is divided by the highest expected number of fruit per crate to determine a tipping rate that is not expected to exceed the maximum flow rate. However, ensuring that the maximum allowable rate is not exceeded, results in an expected average rate that is slightly lower than the maximum as shown in the example below.

For example, if the maximum flow rate was selected as 44 fruit per second, the resultant output of the tipping unit must not exceed it. If there is between 973 and 1022 fruit in each crate, then a crate must be emptied every 23.2 seconds (1022/44) or 2.58 crates per minute (44x60/1022). As the confidence level ensures that 95% of the crates will not contain less than 973 or more than 1022 fruit, these calculations provide for a 97.5% confidence that the fruit rate will not exceed 44 fruit per second. When the expected average number of fruit per crate, which is 997.5 ((973+1022) / 2), is used the expected fruit per second rate is 42.9 (997.5/1022 x 44) fruit per second.

The minimum and maximum expected flow rates are used in the next phase of the modelling procedure to analyse each process and to recommend best setups for personnel and equipment.

6.2.4 Equipment and personnel setup

The expected maximum flow rate from the previous step is used with the grader allocation calculations in Section 5.4.2.1 (p.79) to allocate the required number of grading personnel to each grading table. The minimum and maximum flow rates can be used to determine speed settings for processes such as crate tipping and fruit drying, as well as the proportion of fruit for each output for adjustable random flow divisions.

Where multiple flows of fruit enter a flow control process, packing tables are allocated using the algorithm described in Section 5.7 on p.89. The algorithm assigns the various size (and grade if optical grading is used) combinations that enter a flow control process to the packing table or tables that are the most suitable in terms of capacity. Labelling equipment, which is usually found between flow control processes and packing tables, need to be set up to label each flow of fruit correctly according to the assignments.

When personnel allocations and equipment setups have been calculated, the expected system outputs and rate of output can be calculated.

6.2.5 System output

After the previous four steps of the modelling procedure have been completed the system output is estimated. All packaging material and consumable requirements for the production run can also be calculated. Calculations for the number of cartons, pallets, crates and labels required have been studied and are included in the model. However, other consumables, such as wax and soap, have not been included in this study and can be included in the model at a later stage, after the rate of application per fruit surface area has been determined. These calculations should assist packing house personnel in the procurement of packaging materials and consumables to minimise waste.

This concludes the description of the theoretical development of the modelling procedure. The next section of this chapter describes the development of a computer model which uses the first three steps of the above modelling procedure repeatedly for various fruit distributions to create a graphical representation of the capacity of a packing line and the effect that fruit size and quality has on it.

6.3 COMPUTER MODEL DEVELOPMENT

Throughout this study, research was conducted to facilitate the development of a computerized generic model for citrus packing lines. In order to create a computer model, a suitable programming package needed to be identified. Initially, Borland Delphi, Java, Simul8 and Arena were investigated as possibilities, but it was found that to use Borland Delphi or Java (Sun Microsystems) would result in too much time being spent on managing data and designing a user interface, which are not requirements of this study. Simul8 and Arena (Rockwell) were rejected for mainly two reasons, firstly the cost of these packages would be too much for small packing houses and, secondly, while it is possible to model deterministic systems with Arena, the need to define entities would have been problematic.

As the research has led to various types of information and data, tables of information (see Figure 6.2) have been identified. These tables will be extended in future to accommodate more fruit types and their relevant processes. For these reasons it was decided to develop the model using *Microsoft Excel* and the *Visual Basic for Applications* programming package that is included with it. Using these packages, the tables of data could easily be constructed in Excel spreadsheets, removing the need to design a user interface for the various tables in the program database (see Figure 6.2). The model application that was developed in Visual Basic for Applications constantly reads and writes values from and to these tables. As Excel has built in graphical charting, creating graphical results was also facilitated.

To allow for a completely generic model, in which new fruit types and processes can be added and packing line flow can be changed, a database was designed to contain all the fruit, process and setup information. Figure 6.2 shows all the data tables that were implemented in the computer model. Refer to Appendix J for detail on the contents of each table.

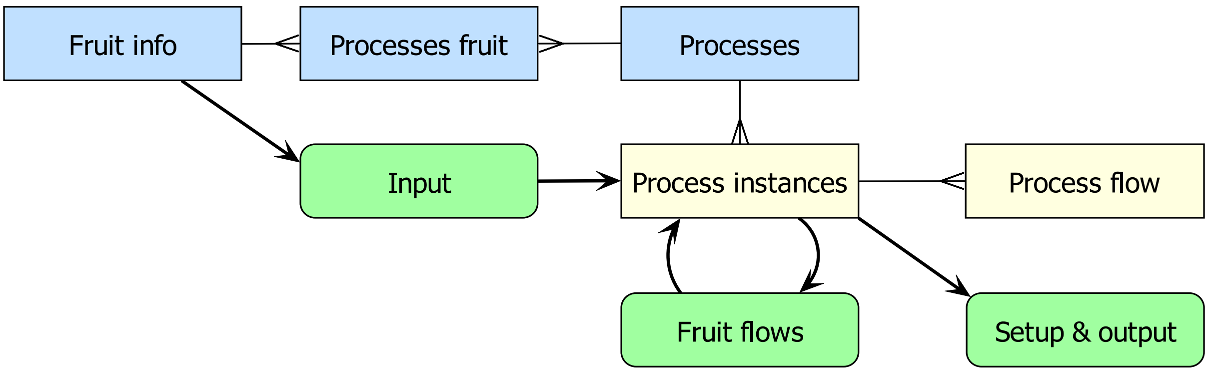


Figure 6.2: Data design for computer model

Three types of data are used by the generic model. First, in blue in Figure 6.2, are three tables that contain static fruit and process information. The *Fruit info* table contains all relevant information that is not process specific, for each fruit type. The *Processes* table is a list of all the types of processes found in the packing industry and data for their capacity and throughput calculations. For each process that can be used on each fruit type, the *Processes fruit* table contains an entry that includes all relevant information for when that particular fruit type is processed by that specific process.

The second data type, in yellow in Figure 6.2, concerns a specific reality that is represented by the generic model. The *Process instances* table has an entry for each process in the packing line that is modelled. The *Process flow* table, of which Table 6.1 is an example, links all the process instances to each other in the order they occur in the packing line. Data in these two tables represents the *User Defined* parameter group and is only entered once for each reality that is modelled.

The third data type, shown in green in Figure 6.2, contains production *Run Info* and has three tables that are populated during the analysis of a single production run. The *Input* table is defined by the user through direct specification, historical estimation or distribution approximation (see Chapter 4), and Table 6.2 is an example of a production run input data set. The *Input* data typically makes use of standard *Fruit info*, such as number of fruit in a crate or number and size of fruit distributions divisions, to create the system input. Defining the input is incidentally also the first step of the modelling procedure (see Section 6.2.1 on p.95) defined earlier.

The fruit flow calculation is then initiated by using the defined *Input* to calculate the output and expected flow rates for the first process of the packing line. The *Fruit flow* distributions and flow rates are then calculated for each link in the packing line process chain as well as for the output of the system. These calculations make use of the logic of the second and third step of the modelling procedure (see Sections 6.2.2 & 6.2.3 on pp.96 and 97).

The equipment and personnel setup for each process, as well as the packing table allocations are calculated next using their respective capacity calculations and assignment logic described earlier (see Chapter 5). These assignments and calculations form part of the fourth step of the modelling procedure (see Section 6.2.4 on p.98). The number of containers, for each fruit output, and system consumables are calculated as the final step of the modelling procedure (see Section 6.2.5 on p.98).

For each process type an independent function was developed to do capacity calculations. Whenever the main control program must analyse a specific process with specific fruit distributions, the relevant *process function* is populated with the fruit data and process setup information and executed.

To allow for the analysis and comparison of packing line capacities and the effect of different fruit characteristics, the computer model was extended with a capacity analysis tool. The capacity analysis tool increments the fruit quality (from 20% to 95% – Grade 1), the unacceptable fruit colour (from 0% to

15%) and average fruit size (from 68mm to 88mm) with small increments (1%, 0.5% and 0.5mm, respectively), to create 90 000 production run *Input sets*. By repeating the steps of the modelling procedure for each *Input set* to determine the maximum allowable fruit per second rate as well as the constraining process, two capacity graphs can be formed. As the capacity graphs are three dimensional, with the three fruit characteristics (size, quality and colour) as independent variables and the maximum rate and the constraining process as dependant variables, cross sections at specified levels of green fruit are used to allow graphical representation. In Section 7.5 (p.113-116) cross sections of two sets of these graphs are presented.

A scheduling algorithm, to calculate a weekly schedule for optimum packing line utilisation and to minimize setup times between production runs, has not been added to the generic model as it falls outside the scope of this study. It is however a topic that can be investigated in future research.

In this chapter, the development and implementation of the modelling procedure is presented. The implementation was in the form of a computer model that was developed using Microsoft Excel and Visual Basic for Applications. The implementation of the capacity calculations in the computer model was verified by comparing the behaviour of the model on a process function scale and complete system scale. The development of the modelling procedure and the verification of the model are the fifth and sixth steps of the Generic Modelling Methodology (see Sections 2.3.5 & 2.3.6 on p.17). In the next chapter the validation of the model, which was accomplished by doing a case study on two production runs at one of the packing lines at GHC, is presented.

CHAPTER 7
VERIFICATION, VALIDATION & TESTING

In this chapter the generic model is verified, validated and tested. Model verification and validation are the sixth and seventh step of the generic modelling methodology described in Chapter 2. Validation of the model provides the answer to the *problem statement* in Section 1.2 (p.3): *Develop a generic model for hard citrus packing lines.*

Hangos and Cameron (2001:29) states that the thoroughness of validation is dependant on the requirements of the modelling goal. As the primary goal of this study is to answer the above problem statement, precise validation is not required. Also, in modelling, a single reality is usually imitated by the mathematical model, and not a *class of realities* as is the case with generic modelling. Validating all the realities, which is more than 850 packing lines (Ortmann, 2005:49), would be an almost impossible task. For these reasons only partial validation was done to establish the legitimacy of the concept that a packing line can be modelled as unit operations linked with fruit flow.

Once the validation showed that the model was able to accurately represent the behaviour of an existing packing line, production runs and full capacity analyses were done on a hypothetical packing line. These analyses give an indication of what the value of the developed generic model can be when implemented and integrated at existing operational packing lines.

7.1 VERIFICATION OF THE MODEL

Verification is performed by testing the behaviour of the model against expected behaviour using test data (see Section 2.3.7 on p.17). The behaviour of each process function was tested separately as well as the behaviour of the complete model with the implemented modelling procedure.

Throughout the model development process, the behaviour of each process function (see Section 6.3 on p.99) was tested by using test data. During the translation into a computer model, if errors were made in the coding of the capacity calculations (see Chapter 5) or were found in the logic of the capacity calculations, the faults were indicated when the relevant process functions produced unexpected results. This resulted in either the coded function being modified and tested again, or the re-evaluation of the logic of the capacity calculations (see Chapter 5). Both types of errors were found and corrected throughout the coding of the process functions.

To ensure that the model as a whole and the interaction between processes were correct, a test packing line was modelled and analysed using the computer model as well as manual calculations. Where discrepancies emerged the reason for the error was located using the *Watch List* debugging tool of *Visual Basic for Applications* and stepping through the calculations one by one. The manual calculations were then compared to the computer model calculations throughout the calculation stepping process and, at the step where the discrepancy emerged, it could be rectified. If a specific part of code was questionable a *Break point* was used to stop the computing at a specific step to enable stepping through calculations from that point onwards. The testing of the output was completed several times with various fruit distributions and equipment configurations.

The verification described in the preceding paragraphs was performed during the development of the computer model. Further verification also occurred while the model was validated, which is described in the next section.

7.2 VALIDATION OF ASSUMPTIONS

In Section 2.3.7 (p.17) various methods of validation are listed, of which the first method is *experimental verification of the simplifying assumptions*. Throughout this study, assumptions were verified by experimentation and comparison to process data. The validation of these assumptions will now be briefly reviewed.

During the analysis of the area covered by fruit on rollers/brushes, two assumptions were made (see Section 3.3.1 on p.29). When these assumptions were tested, it was found that the number of fruit was estimated at approximately 95% of the true number of fruit. The assumptions were corrected by using Equation 3-1 which utilizes a 95% level of statistical significance. This is also the case in Sections 3.3.2 and 3.3.3 (pp.31 and 35), where the estimation of the volume and area of fruit are presented.

As described in Section 4.2.4 (p.58), it is assumed that the three fruit distributions of colour, size and quality, are independent of each other. This was verified through visual analysis and statistical independence testing of production data. As described in Sections 5.4.2.1 and 5.6.1 (pp.78 and 85), the results of time studies were used as part of the model building exercise and various assumptions were made of the manual fruit grading and packing processes.

The accuracy of the estimation of system inputs and resultant outputs was identified as crucial to the development of the generic model. For this reason, extensive data of more than 33 million kilograms of fruit was analysed to enable the accurate estimation of system inputs and outputs, as presented in Chapter 4.

7.3 VALIDATION BY TESTING

The generic model, as set up for the verification of the previous section, was tested with an exact number of fruit. It is logical that every single fruit that enters the system should also leave the system. A specific number of crates with exact amounts of fruit were specified by bypassing the *number of parts per container* estimation calculations (see Section 5.2, on p.67). For this particular test the confidence ranges were set to zero and the size distribution defined empirically. This was done as the sum of the maximum expected outputs is more than the actual number of fruit, and the sum of the minimum expected outputs is less. The minimum and maximum number of fruit expected at each output therefore both equalled the expected value in this specific test and the sum of each must add up to the total number of fruit. The production run input was defined as shown in Table 7.1.

Table 7.1: Input of specific number of fruit with no range estimation

QUALITY	**Grade 1**		**Grade 2**			**Grade 3**			**Grade 4**	
Lower & upper	0.700		0.792			0.953			1.000	
SIZE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Run A: Peaked	0.001	0.010	0.018	0.062	0.201	0.429	0.686	0.917	0.988	1.000
Colour accept	0.950		**Crates**				100			
Green	0.050		**Number of fruit**				150 000			

The output results of the model are shown in Table 7.2. The first three outputs in Table 7.2 are shown in the order they are removed from the flow of fruit. From the specification above it is simple to manually calculate al the fruit outputs and compare with the model output. The model output was found to be correct.

Table 7.2: Output results of test with no range estimation

	Number of fruit	**Proportion of total**		**Number of fruit**	**Proportion of total**
Undersize	160	0.001	Grade 2, Count 125	110	0.001
Green	7 492	0.050	Grade 2, Count 105	656	0.004
Grade 4	6 690	0.045	Grade 2, Count 88	1 733	0.012
Grade 1, Count 125	836	0.006	Grade 2, Count 72	2 851	0.019
Grade 1, Count 105	4 990	0.033	Grade 2, Count 64	3 208	0.021
Grade 1, Count 88	13 185	0.088	Grade 2, Count 56	2 886	0.019
Grade 1, Count 72	21 693	0.145	Grade 2, Count 48	888	0.006
Grade 1, Count 64	24 407	0.163	Grade 2, Count 40	149	0.001
Grade 1, Count 56	21 957	0.146	Grade 2, Count 36	0	0.000
Grade 1, Count 48	6 758	0.045	Grade 3	28 217	0.188
Grade 1, Count 40	1 132	0.008			
Grade 1, Count 36	2	0.000	**Total**	**150 000**	**1.000**

Similar tests were done with absurd equipment set ups as well as unrealistic distributions, such as only Grade 4 fruit. While manual calculations of the theoretical model worked as expected, the computer model produced some *divide by zero* errors because some fruit classifications had no fruit in them. Thus, in cases where there were no fruit entering a process, the computer model might try to divide the flow or recalculate the output diameters, causing the *divide by zero* error. The computer model was reworked where such errors were found, but it is expected that, in the almost 1 000 lines of code, some errors still persist. The model was not built to be fool-proof as the computer model will need to be extended considerably to other fruit types and their relevant processes. During this process errors will again be made and the model will then need to be checked thoroughly.

7.4 VALIDATION BY COMPARISON

To validate the generic model, the *Process instance* and *Process flow* tables (see Section 6.3 on p.99) were populated with information after measuring and studying a packing line at Goede Hoop Citrus in Citrusdal. The generic model was therefore set up to represent a specific, existing packing line. The detail design specifications of the packing line are confidential information and have therefore not been included in this document.

7.4.1 Input data estimation

The expected results of two production runs (production runs A and B on 28 September, 2005) were discussed with packing line operational staff before the production runs were started. Their expectation was that around 80% of the fruit in the 384 crates of run A and 75% of the fruit in the 376 crates of run B would be Grade 1 fruit. Also, run A was expected to have an average fruit diameter of approximately 80mm, while 75mm was expected for run B. Fruit colour was fully developed at that stage of the season and was therefore not an issue.

After the production runs were completed, the production run reports were acquired from GHC. The percentage of fruit accepted as Grade 1 was 78.8% and 75.6% and the average fruit diameter was 81.1mm and 77.2mm for the production runs A and B respectively.

Using the expected production run figures in the fruit distribution estimation equations of Chapter 4, with a 5%-level of uncertainty for fruit quality, the system inputs, displayed in Table 7.3, were calculated.

Table 7.3: Estimated inputs for two production runs

QUALITY	Grade 1	Grade 2	Grade 3	Grade 4
Run A: Lower	0.750	0.811	0.941	1.000
Run A: Upper	0.850	0.886	0.965	1.000
Run B: Lower	0.700	0.773	0.929	1.000
Run B: Upper	0.800	0.848	0.953	1.000

SIZE	1	2	3	4	5	6	7	8	9	10
Run A: Peaked	0.000	0.001	0.018	0.079	0.345	0.635	0.897	0.983	1.000	1.000
Run A: Flat	0.008	0.029	0.091	0.182	0.391	0.574	0.776	0.902	0.994	1.000
Run B: Peaked	0.000	0.001	0.017	0.061	0.266	0.290	0.261	0.086	0.017	0.000
Run B: Flat	0.008	0.021	0.062	0.091	0.209	0.183	0.202	0.126	0.093	0.006

Volume	Crates	Kilograms	Number of fruit by FMF
Run A	384	130 707	Between 495 058 and 517 506
Run B	376	123 986	Between 555 133 and 583 982

The range for the expected number of fruit were calculated using the *Fruit Mass Function* described in Section 4.2.5 on p.59. The next step was to estimate the system outputs from the system inputs. In

Table 7.4, a comparison is made between the estimated values and the actual values of the Grade 1 outputs.

Table 7.4: Comparison of predicted and actual outputs

	Run A – Cartons		Run B – Cartons	
Grade 1	**Predicted**	**Actual**	**Predicted**	**Actual**
Count 40	158 – 1 019	532	0 – 176	116
Count 48	665 – 1 155	909	24 – 433	381
Count 56	1 337 – 2 054	1348	361 – 1 008	816
Count 64	1 062 – 1 996	1403	1 004 – 1 409	1350
Count 72	1 076 – 1 625	1512	1 468 – 2 999	2291
Count 88	257 – 456	396	710 – 1 097	1016
Count 105	58 – 259	113	281 – 607	331

The upper and lower limits of the *predicted* columns are calculated from the 95% range limits of the beta distribution fruit size estimation method. This method bases its estimate on an extremely flat and an extremely peaked fruit size distribution for the estimated fruit size. The proportions of fruit in each fruit size category were then used to determine the expected number of cartons of each size. It is clear from Table 7.4 that the range of the estimated fruit size and quality distributions include the actual production run results. This can be attributed to the fact that the estimation of the percentage of Grade 1 fruit and average fruit size by packing line personnel, of 80mm and 75mm, were very close to the actual values.

7.4.2 Process analysis

As mentioned earlier, all the processes of the packing line were measured and studied and entered into the generic model. The generic model was used to calculate optimum tipping rates and equipment setups. However, these results were not implemented on the day of testing as the implementation of the model is an unproven technique and the financial risk if the model calculations were incorrect was too high. The observations of actual events and those of predicted/proposed events will now be presented.

As the two production runs under scrutiny took place on the same day, the same equipment and personnel setups were used. The fruit flow rate was observed for both production runs at several locations throughout the packing line. The tipping rate for both production runs, even though they had different fruit distributions, were found to be the same, at 45 to 48 (various observations) fruit per second entering the system.

During the production runs, the packing line was observed and studied in an attempt to locate a system constraint for each production run. Although it seemed as if the packing tables were constraining the process, as several tables were overfull, other packing tables were not being used at all. The physical capacity of the pre-grading tables was observed to be close to its maximum limit during the first production run. The fruit were, however, only moving at eight metres per minute and the grading personnel were removing few fruit as the quality was good. At the grading tables where Grade 2 and 3 fruit were being removed, there was an obvious over allocation of tables and personnel, especially for the first production run, which had the higher proportion of Grade 1 fruit. It was concluded that the packing line was not operating at an optimum rate for either production run, even more so for the first production run.

After the above observations were made, the generic model was set up with the actual packing line parameters and the estimated fruit input distributions were used as input. The theoretical maximum allowable fruit rate was calculated as 58.4 and 69.1 fruit per minute for the two production runs, A and B respectively. To ensure that the rate does not exceed the allowable maximum, the rates were altered to 57.1 and 67.4 fruit per minute respectively (see Section 6.2.3 on p.97). At these rates, the theoretical constraining processes are Grade 1 packing tables (with an altered packing table assignment to what was used) for run A and secondary grading, where Grade 3 fruit are removed, for run B. This can be attributed to the fact that the fruit of the second production run were smaller, thus not constraining physical space but increasing the number of fruit handled, and of lower quality, which also increases the number of fruit handled at the secondary grading tables (where Grade 3 fruit are removed).

For both production runs six tables with four graders each were allocated. It should also be noted that the above rates resulted in fewer primary grading tables (where Grade 2 and 3 fruit are removed) being allocated. However, using grading table capacity calculations (see Section 5.4.2.1 on p.79), it was determined that only four tables each with four graders, were required for the first production run, while five tables with four graders each, were required for the second run. This confirmed original observations of the primary grading tables being over allocated.

From the above validation studies, it is concluded that the generic model is able to sufficiently represent the packing line that was studied, as well as the production runs that were tested. The concept of generically modelling citrus packing lines can therefore be accepted. However, it is expected that several improvements will be made through implementation and use of the current generic model over time. The developed generic model will provide the basis for these improvements.

7.5 TRIAL PACKING LINE

For verification and validation purposes the generic model was set up to represent a trial packing line. The process flow of the trial packing line is shown in Figure 7.1. The numbers next to each process are also assigned in the computer model. The first digit refers to the generic group (see Section 3.3.5, on p.36) and the remaining two digits to the process instance.

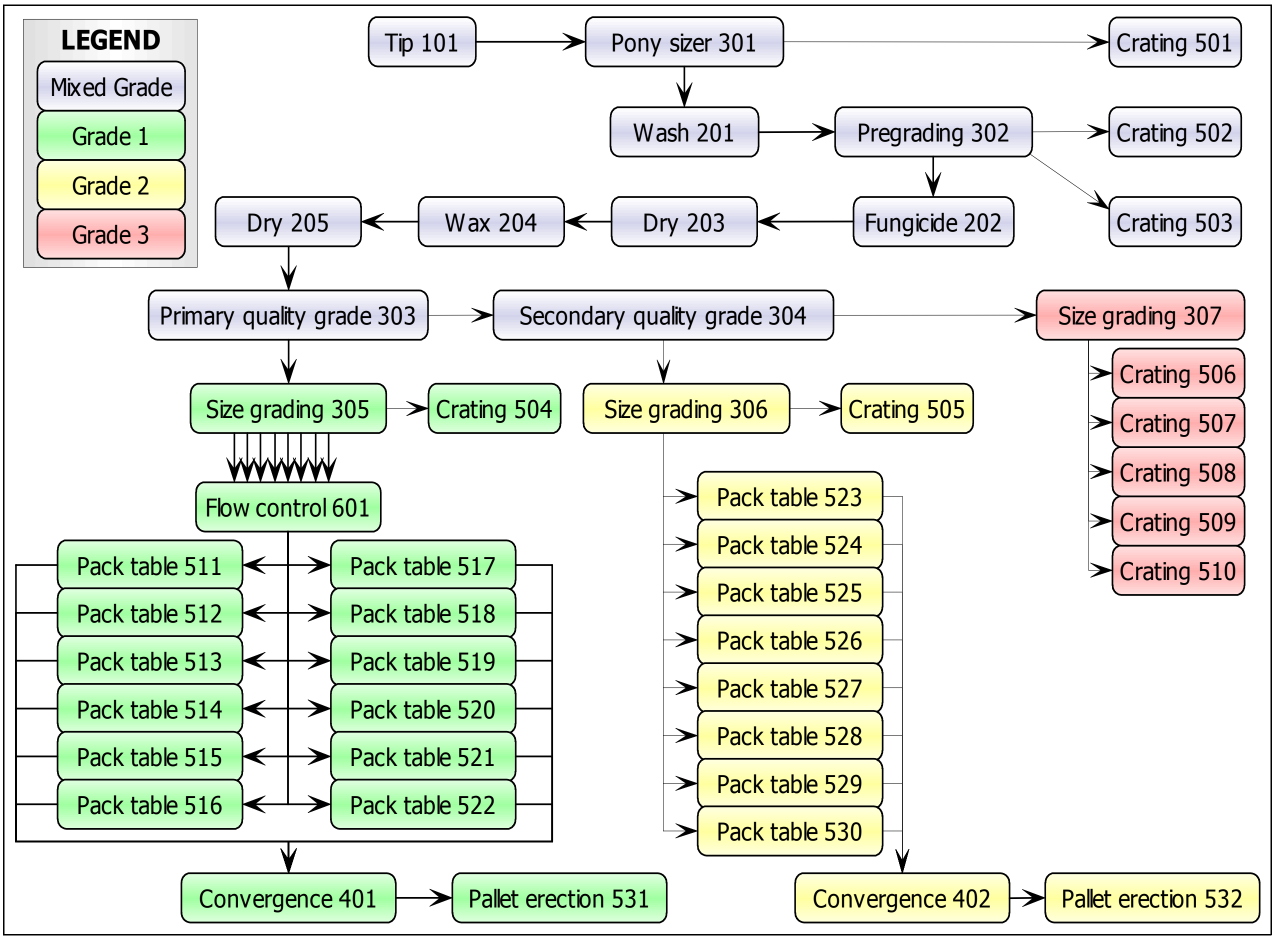


Figure 7.1: Process layout of trial packing line

It is important to note that, while there is a flow control unit (ID: 601) before the Grade 1 packing tables (ID: 511 to 522), no such unit is present before the Grade 2 packing tables (ID: 523 to 530). Each size output of the Grade 2 size grading unit (ID 306) therefore goes to a fixed packing table. The smallest fruit (Count 125) go to packing table 523 and the largest (Count 40) to packing table 530. Initially the *user defined* variables were set to represent a typical packing line. The initial values are shown in Table 7.5.

Table 7.5: Initial values of user defined variables of trial packing line

1 – Tipping Section 5.2 on p.67			**101**	
	TR_{Max}	containers/minute	5	
2 – Static brush Section 5.3.1 on p.70			**201**	**204**
	B_T	brushes	38	16
	B_S	brushes	20	0
	L_W	millimetres	1700	1700
2 – Moving roller Section 5.3.2 on p.73			**203**	**205**
	L_D	millimetres	85	85
	L_W	millimetres	2200	2200
	L_U	millimetres	8000	6000
	S_{Max}	millimetres/second	1.5	1.5
2 – Dipping Processes Section 5.3.3 on p.75			**202**	
	A	square metres	10	
	ρ_D	layers	1.6	

Table 7.5 continued…

Process	Symbol	Unit	302	303	304
3 – Manual grading Section 5.4.2.1 on p.79	G_E	type	1	1	1
	L_W	millimetres	1200	1200	1200
	S_{Max}	millimetres/second	160	160	160
	L_D	millimetres	80	80	80
	T_G	seconds	1.25	1.15	1.15
	G_T	sides	2	2	2
	G_S	graders/side	2	3	3
	G_H	hands	2	2	2
	G_N	tables	3	4	2

Process	Symbol	Unit	301		
3 – Mechanical grading Section 5.4.2.2 on p.83	L_D	millimetres	80		
	L_W	millimetres	2000		
	L_U	millimetres	1200		
	S_{Max}	millimetres/second	300		
			305	**306**	**307**
	S	millimetres/second/lane	1200	1200	800
	N_L	lanes	10	4	3

Process	Symbol	Unit	511	512	513	514	515	516	517	518	519	520
5 – Packing Section 5.6.1 on p.85	V_{T1}	cubic metres	2.2	2.2	2.2	2.8	2.8	2.8	3.8	3.8	3.8	2.8
	PS_i	Packers	4	4	4	6	6	6	8	8	8	6
			521	**522**	**523**	**524**	**525**	**526**	**527**	**528**	**529**	**530**
	V_{T1}	cubic metres	2.8	2.8	1.8	1.8	3.6	3.6	3.6	3.6	1.8	1.8
	PS_i	Packers	6	6	4	4	4	4	4	4	4	4

Process	Symbol	Unit	531	532
5 – Stacking Section 5.6.2 on p.88	PS	stations	12	8

Process	Output	Input:	I_1	I_2	I_3	I_4	I_5	I_6	I_7	I_8
6 – Flow Control Section 5.7 on p.89 (601)	O_1	ID: 511	1	0	1	1	1	0	1	0
	O_2	ID: 512	0	1	0	1	0	1	1	1
	O_3	ID: 513	1	0	1	0	1	1	1	0
	O_4	ID: 514	1	1	1	1	0	1	0	1
	O_5	ID: 515	1	0	1	1	1	0	1	0
	O_6	ID: 516	0	1	0	1	0	0	1	1
	O_7	ID: 517	1	0	1	1	1	0	1	0
	O_8	ID: 518	0	1	1	1	0	1	0	1
	O_9	ID: 519	1	0	1	0	1	1	1	0
	O_{10}	ID: 520	0	1	0	1	0	1	0	1
	O_{11}	ID: 521	1	0	1	1	1	0	1	0
	O_{12}	ID: 522	0	1	0	0	1	1	0	1

7.5.1 Calculations of a specific production run

After the generic model was set up with the criteria in Table 7.5, output was generated for a production run of 300 crates. The following expected fruit statistics were used as input for the calculations: average fruit size of 78mm, green fruit of 10% and Grade 1 fruit of 62.5%. The Beta distribution for fruit size estimation (see Section 4.2.1, on p.47) and the fruit quality equations (see Section 4.2.2, on p.54) developed during this study, were used to calculate the empirical input distributions for the crate tipping process (ID: 101), shown in red in Table 7.6. For each process the extreme lower and upper values for each distribution are shown. The output of the tipping process was then calculated using the fruit mass function (see Section 4.2.5, on p.59) to estimate the total number of fruit for the production run. As the fruit distributions are not modified by the tipping process, the empirical input distributions for the pony sizer (ID: 301) are identical to that of the system input.

Table 7.6: Empirical fruit distributions for a production run

ID	Number of units	Fruit quality				Fruit color		Fruit size categories									
		1	2	3	4	Accept	Reject	1	2	3	4	5	6	7	8	9	10
101	*300*	*0.60*	*0.10*	*0.21*	*0.09*	*0.90*	*0.10*	*0.00*	*0.00*	*0.03*	*0.12*	*0.26*	*0.31*	*0.23*	*0.04*	*0.00*	*0.00*
	300	*0.65*	*0.08*	*0.18*	*0.08*	*0.90*	*0.10*	*0.01*	*0.03*	*0.09*	*0.14*	*0.18*	*0.19*	*0.21*	*0.11*	*0.05*	*0.00*
301	400091	0.60	0.10	0.21	0.09	0.90	0.10	0.00	0.00	0.03	0.12	0.26	0.31	0.23	0.04	0.00	0.00
	477619	0.65	0.08	0.18	0.08	0.90	0.10	0.01	0.03	0.09	0.14	0.18	0.19	0.21	0.11	0.05	0.00
201	395244	0.60	0.10	0.21	0.09	0.90	0.10	0.00	0.00	0.03	0.12	0.26	0.31	0.23	0.04	0.00	0.00
	477570	0.65	0.08	0.18	0.08	0.90	0.10	0.00	0.03	0.09	0.14	0.18	0.19	0.21	0.11	0.05	0.00
501	41	0.60	0.10	0.21	0.09	0.90	0.10	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	5786	0.65	0.08	0.18	0.08	0.90	0.10	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
302	395244	0.60	0.10	0.21	0.09	0.90	0.10	0.00	0.00	0.03	0.12	0.26	0.31	0.23	0.04	0.00	0.00
	477570	0.65	0.08	0.18	0.08	0.90	0.10	0.00	0.03	0.09	0.14	0.18	0.19	0.21	0.11	0.05	0.00
202	321997	0.66	0.11	0.23	0.00	1.00	0.00	0.00	0.00	0.03	0.12	0.26	0.31	0.23	0.04	0.00	0.00
	394160	0.71	0.09	0.20	0.00	1.00	0.00	0.00	0.03	0.09	0.14	0.18	0.19	0.21	0.11	0.05	0.00
502	32785	0.00	0.00	0.00	1.00	0.90	0.10	0.00	0.00	0.03	0.12	0.26	0.31	0.23	0.04	0.00	0.00
	45274	0.00	0.00	0.00	1.00	0.90	0.10	0.00	0.03	0.09	0.14	0.18	0.19	0.21	0.11	0.05	0.00
503	39524	0.66	0.11	0.23	0.00	0.00	1.00	0.00	0.00	0.03	0.12	0.26	0.31	0.23	0.04	0.00	0.00
	47757	0.71	0.09	0.20	0.00	0.00	1.00	0.00	0.03	0.09	0.14	0.18	0.19	0.21	0.11	0.05	0.00
203	321997	0.66	0.11	0.23	0.00	1.00	0.00	0.00	0.00	0.03	0.12	0.26	0.31	0.23	0.04	0.00	0.00
	394160	0.71	0.09	0.20	0.00	1.00	0.00	0.00	0.03	0.09	0.14	0.18	0.19	0.21	0.11	0.05	0.00
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...

In the trial packing line the small fruit elimination process (ID: 301) removes undersize (Size 1) fruit from the main fruit flow. Its two consecutive processes (ID: 201 & 501) therefore have adapted fruit size input distributions. The maximum expected number of undersize fruit that are to be removed and crated (ID: 501), is calculated by multiplying the maximum number of fruit of the preceding process (ID: 301), which is 477 619 fruit, with the maximum expected proportion of undersize fruit (0.012114). The calculation of the minimum expected number of undersize fruit is similar, but uses the minimum expected values. The result is that between 41 and 5786 fruit are expected to be removed because they are too small. Similar calculations are used to determine the empirical distributions and number of fruit for each process throughout the system.

Where the fruit size distribution is adapted, as described above, the average fruit size input of subsequent processes also changes accordingly. The average fruit size is recalculated for each fruit size distribution in Table 7.6. Using the process capacity calculations (see Chapter 5), the maximum rate at which fruit can pass through was calculated for each process (*Maximum rate – Process* in Table 7.7). By expressing the expected number of fruit (units) of each process as a *proportion of the total number of fruit*, the proportion of fruit that will be passing through each process is calculated. The proportion is then used to calculate the maximum allowable rate (*Maximum rate – System* in Table 7.7) for each process, relevant to the flow divisions of the specific production run.

For example, after pre-grading (ID: 302), between 80.48% and 82.53% of the fruit are expected to continue as the primary fruit flow to fungicide application (ID: 202). The maximum allowable feed rate for the fungicide dip tank is 85.62 fruit per second. But when taking into account that a maximum of 82.53% of the fruit will be passing through, the maximum feed rate for the fungicide dip tank is recalculated as 103.75 (85.62/0.8253) fruit per second.

Table 7.7: Maximum fruit rate for a production run

Process ID	Number of Units	Average fruit diameter (mm)	Maximum rate – Process (fruit per second)	Proportion of total fruit	Maximum rate – System (fruit per second)
101	*300*	*78.00*	*111.14*	*1.00*	111.14
	300	*78.00*	*132.67*	*1.00*	132.67
301	400091	78.00	96.11	1.00	96.11
	477619	78.00	96.13	1.00	96.13
201	395244	78.04	99.01	0.99	100.22
	477570	78.25	99.01	1.00	99.02
501	41	59.00	100	0.00	
	5786	59.00	100	0.01	
302	395244	78.04	92.26	0.99	93.14
	477570	78.25	92.01	1.00	**92.02**
202	321997	78.04	85.62	0.80	103.75
	394160	78.25	86.08	0.83	104.30
502	32785	78.04	100	0.08	
	45274	78.25	100	0.09	
503	39524	78.04	100	0.10	
	47757	78.25	100	0.10	
203	321997	78.04	89.86	0.80	111.35
	394160	78.25	89.62	0.83	108.59
…	…	…	…	…	…

In this way the constraining process and the maximum allowable system input rate can be determined. For this particular production run the pre-grading process (ID: 302) is the system constraint. The maximum rate of 92.02 fruit per second is then used as the maximum allowable fruit input rate and a recommended fruit per second rate, of 90.98 fruit per second, is calculated as the maximum rate that must not be exceeded. There is a level of uncertainty linked to the number of fruit in each container. The 92.02 fruit per second rate is, however, used in the capacity and equipment assignment calculations of each process (see Chapter 5).

Tipping calculations

The expected duration of tipping will take place for the production run T_D (see Section 5.2, on p.67) can be determined. If the maximum required fruit rate is 92.02 fruit per second and the upper limit of the number of fruit in a container is 1592, the *required tipping rate* can be calculated as 3.47 (92.02 x 60 /

1592) containers per minute. For the 300 containers, this will result in fruit entering the system for 86.5 (300 / 3.47) minutes.

Grading table calculations

If, for instance, the rate is applied to the primary grading tables (ID: 303), the grading table capacity calculations (see Section 5.4.2.1, on p.79) are used to allocate graders. If the maximum rate is 92.02 fruit per second initially, and a maximum of 82.53% of the fruit will reach the grading table, a maximum of 33.72% of fruit (specified for the production run), or 37.55 (0.3372 x 92.02 x 0.8253) fruit per second, will need to be removed manually, requiring 16 (37.55 * 1.15 / 2 = 15.8) graders. Each of the four tables can be allocated three graders per side; a total of 24 graders can therefore be assigned. Using the assignment logic (see Section 5.4.2.1, on p.79), four graders are allocated to each of the four tables. The flow dividers will therefore need to be set up to divert 25% of the flow to each table. Minimum table speeds can then be calculated as 106.6 millimetres per second (or 6.4 metres per minute) to facilitate improved grader efficiency.

Packing table calculations

For this production run the largest proportion of fruit is in the Size 6 category (up to 31%, see Table 7.6), which is Count 64. The packing table assignment algorithm assigned two packing tables (ID: 517 and 518) to Size 6 fruit. The total volume at these tables is 7.6 (3.8+3.8) m^3 and a total of 16 (8+8) packers can be assigned to these tables. The *total number of fruit* that these tables can accommodate if nothing is removed is 18 046 ($3x0.613x8.6 \times 10^9/(4x\pi x39.5^3)$) fruit (see calculation of F_{Ti} in Section 5.6.1 on p.85).

From the maximum expected 92.02 fruit per second rate it can be calculated that up to 14.12 (92.02 x 0.31 x 0.65 x 0.90, size, quality, colour) fruit can arrive at the packing tables per second for the duration of fruit tipping, which is 86.5 minutes. The maximum expected number of fruit can be calculated as 73 283 (14.12x86.5x60) fruit, and it follows that a maximum of 1 145 cartons will need to be packed with 64 fruit each. The maximum expected time to pack a carton is 82.7 (36x0.785 + 36x1.075 + 23.2) seconds (see Time Study in Section 5.6.1, on p.85). The *minimum packing time* for 16 packers is 5 918 (82.7x1145/16) seconds, or 98.6 minutes, which is 12.1 minutes longer than the 86.5 minutes that fruit will be arriving. The minimum number of packers required (see formula for PS_{Min} in Section 5.6.1, on p.85) can be calculated as 14 ((82.7/64)x(14.12 – 18 046/5 190) = 13.87) packers at the two tables. If only the 14 packers are used throughout the packing line and the expected maximum values transpire, they will be packing for 112.7 ((82.7x1145)/(16x60)) minutes, which extends 26.2 minutes after the last fruit has arrived.

In this section capacity calculations for the tipping process, primary quality grading and two packing tables are presented. This constitutes calculations for four of the 48 processes of the trial model. Using the computer model, the full set of calculations for all 48 processes is done almost instantaneously. In the next section a full capacity analysis is done by testing 3 000 production runs.

7.5.2 Capacity evaluation

To gain insight into the effect of varying fruit statistics the model was used to do a full evaluation of the capacity and constraining processes of the trial packing line. The capacity analysis tool designed to do the evaluation repeatedly increases the *average fruit size* (from 68mm to 88mm), *Grade 1 percentage* (from 20% to 95%) and *green fruit percentage* (from 0% to 15%) in increments of 0.5mm, 1% and 0.5% respectively, for a specified number of input cartons. If the full evaluation is done, 90 000 production run input sets are calculated and analysed with the computer model.

To show typical results of the analysis the percentage of unacceptable green fruit was kept at a level of 10%. The size and quality was varied as described in the previous paragraph and the analysis was done for production runs of 300 crates each. For a total of 3 000 production runs, the maximum processing rate and the constraining process were determined.

The following two figures are cross sections of the capacity evaluation results at a level of 10% green fruit. The horizontal axes on the figures represent the percentage of fruit that is acceptable as Grade 1 fruit. The percentage of Grades 2, 3 and 4 were determined using equations developed for this purpose (see Section 4.2.2, p.54). On the vertical axes the average fruit size used for the calculations is displayed. The average fruit size was used to determine the extreme size distributions (see Section 4.2.1, p.47). Figure 7.2 shows the constraining process for the two selected fruit statistics (size and quality). If, for example, a production run with an average fruit size of 78mm and 60% Grade 1 fruit, of 300 crates is planned, the model predicts that the constraining process would be process 302, which is pre-grading.

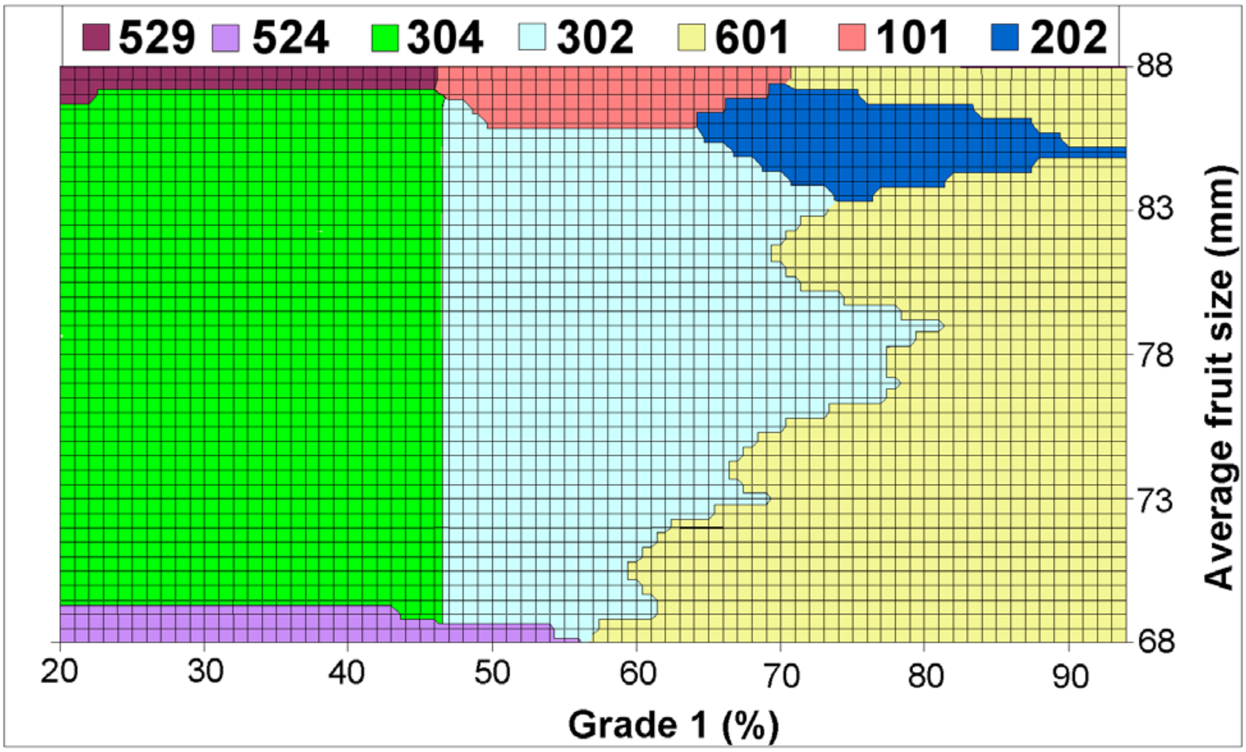


Figure 7.2: Constraining process of *initial* trial packing line

Figure 7.3 shows the maximum rate at which fruit can pass through the system and is determined by the relevant constraining process in Figure 7.2. Continuing the example, for a production run with an average fruit size of 78mm and 60% Grade 1 fruit, the generic model recommends not exceeding a rate of 92 fruit per second. In Figure 7.2 the flow control process is indicated as the constraining process for production runs with a high percentage of Grade 1 fruit. This will be the case when the capacity of the Grade 1 packing tables becomes the constraining process. The various assignment possibilities of packing tables are the reason for the zigzag on both figures in the region of the 80% Grade 1 level. For very large and very small, low quality fruit, the constraining processes are 529 and 524, respectively. These are Grade 2 packing tables for fruit Counts 105 (ID: 524) and 48 (ID: 529). A sharp decline in capacity can be seen in Figure 7.3 in the areas where these two processes are the system constraint.

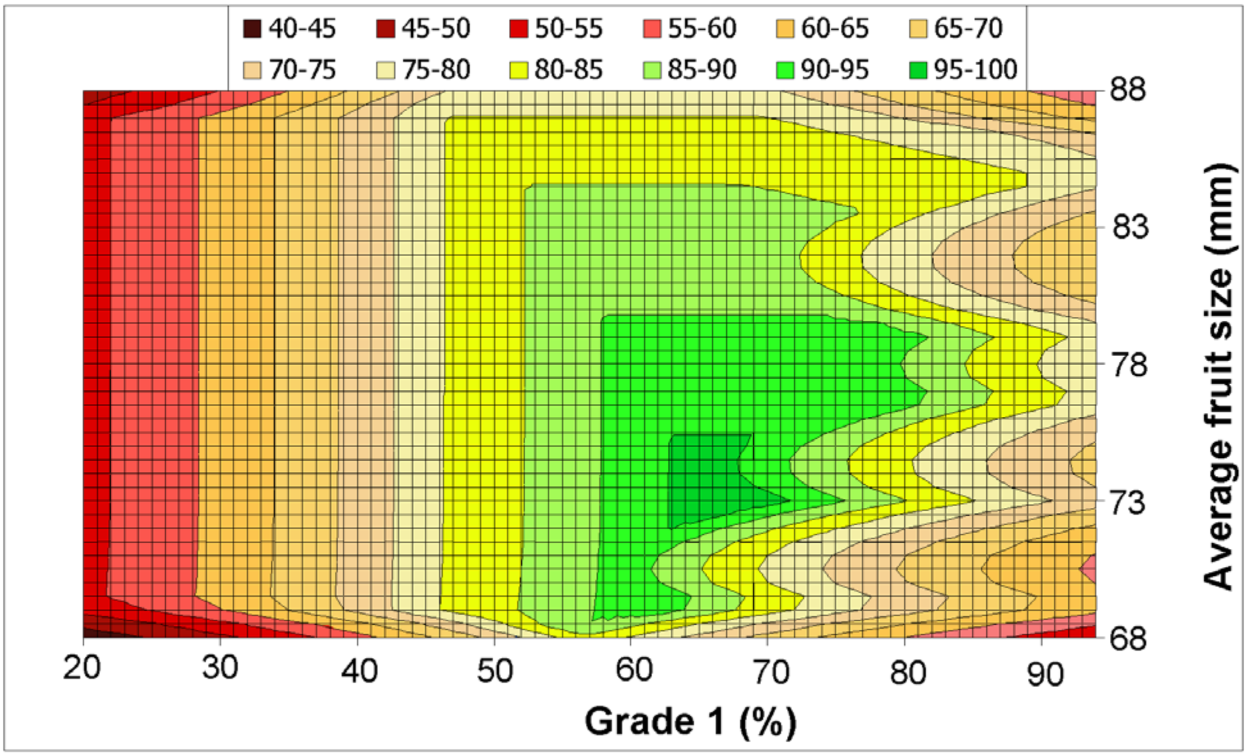


Figure 7.3: Capacity of *initial* trial packing line (fruit per second)

The capacity and constraining process graphs indicate that two production runs with a large quality difference may operate at the same fruit per second rate. For instance, for two production runs, both with an average fruit size of 78mm, but with 50% and 90% Grade 1 fruit, the maximum allowable fruit per second rate is close to 80 fruit per second. However, the constraining process for the 50% Grade 1 fruit production run is pre-grading (ID: 302), while it is the Grade 1 packing tables for the high quality fruit production run (ID: 601). This follows from Figure 7.2.

From Figure 7.3 it is clear that the allowable fruit flow is the highest if the input fruit have an average size of approximately 74mm and 65% of the input is of Grade 1. If it was found that if the fruit typically packed are of a lower quality, say in the region of 40% to 50% Grade 1, the initial trial configuration of the packing line is no longer suitable for the fruit being packed. This could be due to incorrect design, annual variance of the fruit statistics or other aspects. The constraining processes of the *initial* trial packing line, for 40% to 50% Grade 1 fruit, are pre-grading and secondary grading (ID: 302 and 304, see Figure 7.2). In an attempt to provide better for production runs with low fruit quality the capacity of the two constraining processes were increased to form an *improved* trial packing line. At pre-grading (ID: 302) the maximum number of graders per table side was increased from two to three, while a third grading table was added to secondary grading (ID: 304).

The full capacity and constraining process evaluation was repeated for the *improved* trial packing line for the same production run specifications used previously. The following two figures display the resultant increase in capacity and the relevant constraining processes. For production runs during which the pre-grading and secondary grading processes were previously predicted as the constraining processes, the pony sizer (ID: 301) and primary quality grading (ID: 303) have become the new system constraints. However, their respective areas on Figure 7.4 are smaller than their predecessors as the area of other "boundary" processes have increased.

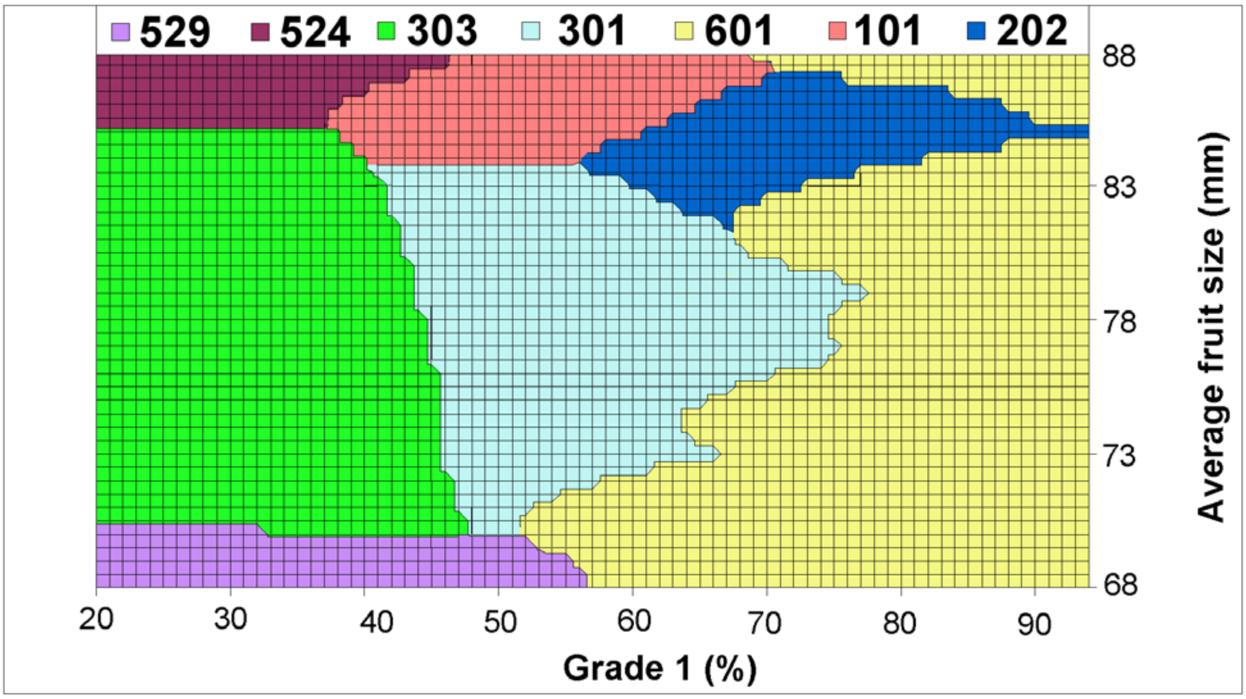


Figure 7.4: Constraining process of *improved* trial packing line

In Figure 7.5 the improvement of the maximum fruit per second processing rate can be observed. For production runs with less than 50% Grade 1 fruit, the fruit rate has been increased by as much as 15 fruit per second. If the quality of the fruit produced in the area is low, the *improved* packing line will now be able to process the resultant low quality production runs at a higher rate. Where the previous best combination of Grade 1 and size was 65% and 74mm, it is 50% and 71mm for the *improved* packing line.

If the volume of fruit produced in the area is such that the packing line needs to operate at 85 fruit per second for the complete season, one would use similar improvements to increase the area of the 85 – 90 fruit per second level as much as possible. If this was the case, the capacity of primary quality grading

(ID:303), which limits very low quality fruit (<35% Grade 1) to a maximum rate below 85 fruit per second, as well as the capacity of the Grade 1 packing tables (ID: 601), which limits high quality fruit (>70% for small and large fruit) to a maximum rate below 85 fruit per second, would need to be improved. If the capacity of these two processes is increased, the area in Figure 7.5 where 85 – 90 fruit per second is acceptable will be increased.

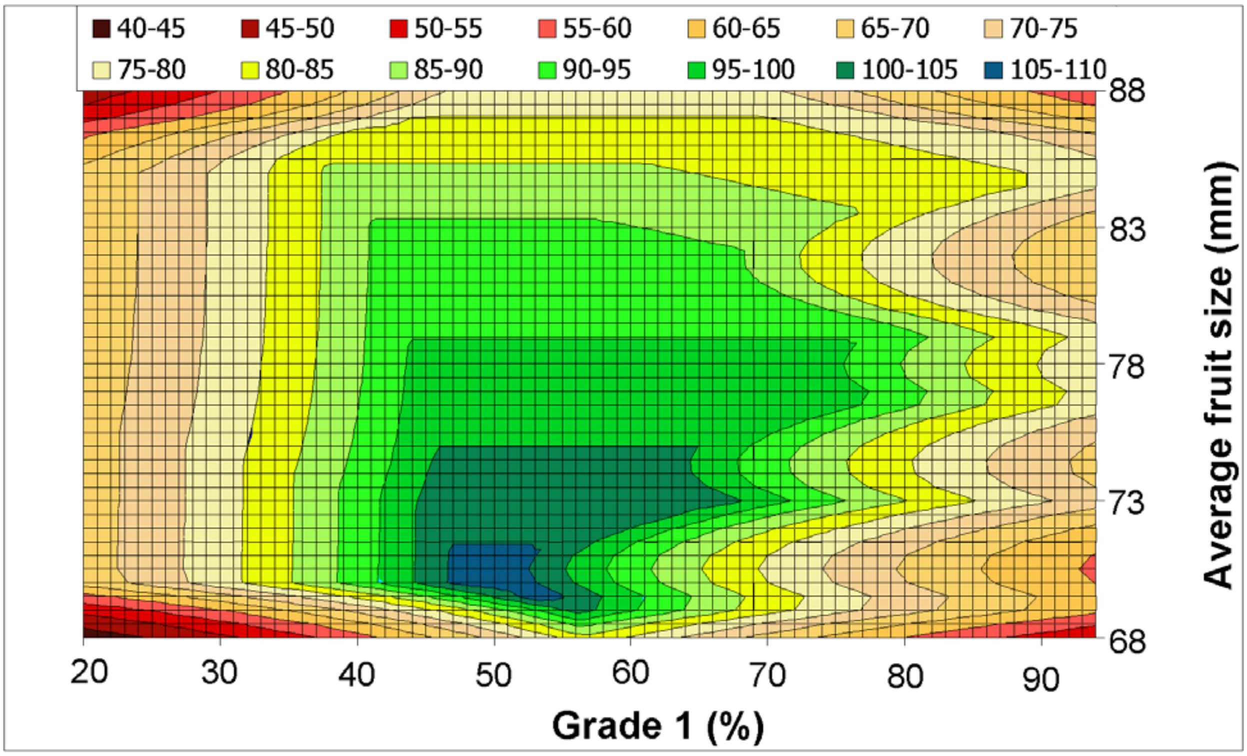


Figure 7.5: Capacity (fruit per second) of *improved* trial packing line

It is important to note that the capacity and constraining graphs presented above were calculated at a specific level of unacceptable green fruit of 10% and for production runs of 300 crates. If the proportion of green fruit is increased, the pre-grading process (ID: 302) might again become a system constraint for the *improved* packing line as more fruit will need to be removed at pre-grading. For production runs with a higher proportion of green fruit where the pre-grading process does not become a system constraint, the capacity of the packing line will be higher for the complete size and quality range, except where the pony-sizer, which precedes pre-grading, is the system constraint. On the other hand, reducing the proportion of green fruit would slightly lower the capacity values of the entire capacity graph, except where the pony sizer is the system constraint.

If the number of crates of the production run is increased, the area where packing tables are the system constraint will grow. However, the fewer number of crates the smaller the area will become. This can be attributed to the fact that packing tables fill up during the production run, and if they are the system constraint, the input rate needs to be controlled to avoid packing tables from overflowing.

The capacity graphs discussed above are therefore much more complex than just a single graph and changes in four dimensions: average fruit size, fruit quality, fruit colour and number of crates.

It is expected that the constraining process and capacity graphs can play a fundamental role in operating a packing line and when scheduling production runs. If a packing line manager knows which process is going to be the system constraint during a production run, he can give special attention to the system constraint to ensure that the packing line operates at an optimum level. Also, if he finds that the prediction of the fruit statistics was incorrect, the capacity and constraining process graphs can be consulted as a quick reference as to the level at which the packing line can operate. The tipping rate required for each production run can also be easily calculated.

Scheduling of production runs can also be facilitated as the duration of production runs can be easily determined. Improved scheduling should decrease setup times between production runs as the exact changes that are required can be determined beforehand. Shifting the system constraint between consecutive production runs could alleviate the stress on the employees as they are not required to work at a maximum pace for consecutive production runs.

The graphs can also become crucial when designing new, and when improving old packing lines as possible packing line changes can be fully evaluated without altering a single piece of equipment and future capacity increases can be planned with the original design. New packing lines can also be designed to suit the specific fruit of that area by ensuring that fruit distributions that are common to the area are well catered for.

In this chapter the verification of the developed model and translated computer model is described. This is followed by various model validation tests. Validation included testing the predictions of the model to that of production runs of an existing packing line. Model verification and validation are Steps 6 and 7 of the generic modelling methodology, which was described in Chapter 2.

The generic model was set up to represent a trial packing line on which capacity assessments were done to evaluate the effect of the variance of fruit size, quality and colour on the capacity of the trial packing line. The trial packing line was also improved and assessed again to visualise the effect of the improvement. In the next chapter the study is concluded and recommendations are made for future studies.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

In the previous chapter the generic modelling methodology, which was described in Chapter 2, was completed. A summary of the various topics described throughout this document, is presented in this chapter, as well as the findings and recommendations for future research.

In August 2005, the research proposal and preliminary findings of the study were presented at the 19th Southern African Institute for Industrial Engineering (SAIIE) and the 35th Operations Research Society of South Africa (ORSSA) annual conference. Positive feedback and some constructive criticism were received after the presentation and various discussions led to the formation of new ideas.

8.1 OVERVIEW OF THE STUDY

The study was initiated by Vizier Systems at the end of 2004. In Chapter 1 their requirements are translated into the problem statement, goal and objectives of the study. The objectives of the study, as presented in Chapter 1, are threefold and they were met at various stages of the study.

The first objective (1.3.2.1), *to investigate modelling theory and to select or develop a generic modelling methodology*, was met and described in Chapter 2 with the selection and alteration of the *seven step modelling procedure* of Hangos and Cameron (2001:25). This newly developed *generic modelling methodology*, which was the result of the work documented in Chapter 2, provided the foundation for the sequence of the research presented in Chapter 3 through to Chapter 7.

The implementation of the generic modelling methodology, which is the second objective (1.3.2.2), resulted in the development of a generic model of hard citrus packing lines. The development of the generic model, which comprises the first five steps of the methodology, is documented in Chapter 3 to Chapter 6. The implementation of the last two steps, verification and validation, is presented in Chapters 6 and 7 respectively.

The third objective (1.3.2.3) is *to translate the developed generic model into a computer model*. This was done concurrently with Step 5 of the generic modelling methodology and is presented in Chapter 6. The computer model was used in Chapter 7 to verify, validate and test the developed generic model.

In Chapter 7 the goal of the study, which is *to generically model hard citrus packing lines*, was achieved with the validation of the developed generic model, which was the last step in the *generic modelling methodology*. The computer model was used to analyse the effect of varying fruit characteristics on the capacity of a trial packing line. Constraining process and capacity charts, which shows the effect of varying fruit characteristics, were discussed.

8.2 CONCLUSIONS

Following the validation, described in Chapter 7, it was concluded that the concept of representing a packing line as a series of unit operations is legitimate. This conclusion is crucial to the future use of the developed model, because, if the concept was not valid, the study would have been of little use to the fruit industry, other than ruling out the use of the investigated concept. The developed generic model was also proven to be an adequate representation of a hard citrus packing line during the case study in Chapter 7.

Throughout the study, various mathematical tools relevant to the Citrus industry, and fruit packing in general, were developed. These tools, such as the fruit behaviour studies described in Chapter 3, the fruit distribution estimation formulas given in Chapter 4 and the capacity calculations for each packing line process given in Chapter 5, were developed using statistical significance of 95%. Each of these tools can therefore, on its own, make a contribution to the operational functions of packing lines and packing houses.

It is, however, in the union of all these tools that this study makes its greatest contribution. The modelling procedure, which merges all the developed tools, was used to develop a generic model with the capability to represent any citrus packing line in South Africa. It also lays the foundation for a future generic model that can be used to represent *any fruit packing line*.

It was observed, during validation studies and earlier observations in the industry, that packing lines often do not operate at optimum fruit flow rates and that, in cases where the system was constrained by a process, the constraining process had not been predicted beforehand. This resulted in personnel being over allocated and the successful operation of processes being compromised.

The generic model can be used to plan for specific production runs, which will assist in scheduling production runs to minimise cost, while assisting quality control by ensuring that optimal equipment setups and personnel allocations are made. The constraining process for each production run can also be identified and elevated by allocating the maximum number of resources, such as the best packing personnel, which is a basic requirement in modern engineering practices. The accurate prediction of packing run results will also minimise cost due to oversupply of packaging materials. Where packing line capacity becomes insufficient, due to increases in fruit production, the full packing line assessment, as described in Section 7.5 (p.107), could become invaluable in analysing possible packing line modifications. The constraining process and capacity charts, of which two examples are presented in Section 7.5 (p.113-116), are expected to make a notable contribution to the day to day production run scheduling and operational control of packing lines.

8.3 FUTURE RECOMMENDATIONS

The future recommendations for the study are mainly concerned with the extension of the developed generic model and the incorporation of it into current packing line management systems. Other recommendations, which are not concerned with the extension of the generic model, but rather with the future research of specific subjects, are presented first.

In Section 4.2.2 (p.54), a theoretical distribution for fruit quality is proposed. The section starts with the assumption that fruit quality is initially perfect and is then negatively influenced by several factors. The proposed distribution of fruit quality is therefore continuous and the quality specification of the target market can then be used to determine the proportion of fruit in each quality category. Further investigation in this specific area is recommended to enable a better understanding of the quality distribution of fruit.

It is also recommended that the annual fruit forecasting methodology, described in Section 4.3 (p.59), be tested with data of more years. The methodology was verified on a *producer to area* scale and it is expected that the concept of local variance will also be evident on an *orchard per producer* scale. If this is found to be true, the accuracy of the forecast of packing line inputs could be improved.

The first recommendation concerned with the generic model is that the process and fruit data, currently included in the generic model, be extended. Initially the extension should include fruit types of which large volumes are exported from South Africa and at a later stage, other fruit types of which smaller volumes are packed. The additional fruit can be studied in a similar fashion to how it was done in this study. If an additional fruit type has a specific process that has not been included in this study, the process must be studied and added to the collection of processes in the generic model.

Apart from extending the model to represent other fruit types, it is recommended that future development of the generic model occur in three stages. First, the generic model should be set to represent specific operational packing lines. The model should then be thoroughly tested for deviation from packing line behaviour and refined if deviation is found, as only preliminary testing has been completed as part of this study. The correction of deviations should be implemented at each packing facility where the model is being tested as it must remain a generic model that is applicable to all packing lines.

After thorough testing and ironing out of errors, the model should be used as a consultative system by analysing scheduled production runs. The recommendations of the model should be consulted when selecting personnel and equipment setups for each production run. Once the operational staff has gained confidence in the advice of the generic model, the generic model should be incorporated into the operational systems of the packing line, which is the third stage of the recommended future development.

It is envisioned that the generic model interact with historical and real time operational data to predict the input of each production run. If the interaction is extended to the degree that the generic model is "aware" of expected fruit arrivals as well as fruit that have arrived at the packing house grounds, production runs with similar setups can be scheduled consecutively to minimise excess capacity of the packing line. Schedules for ordering packing line consumables and packaging materials as well as the output of each day, can then be automatically produced by the generic model.

This chapter concludes the study by giving an overview of the study, drawing conclusions and giving recommendations for future studies, as well as future refinement and uses of the developed generic model.

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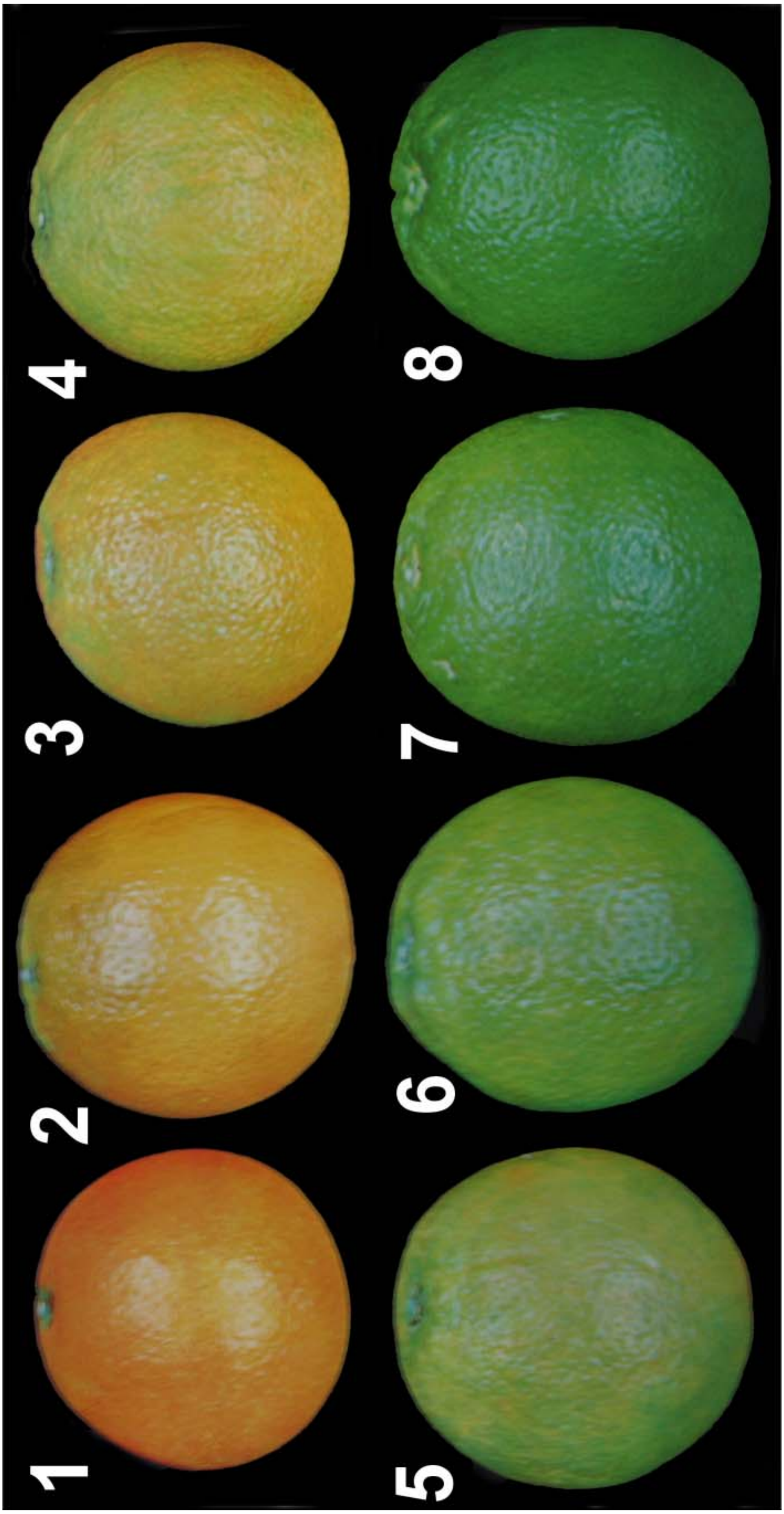
APPENDIX A

FRUIT COLOUR



Colour prints for blemish standards (Outspan)

APPENDIX B

ADJUSTED KEPLER VALUES

The *Adjusted Kepler Values* (ρ_{AKV}), which is 0.632±0.019, represents the proportion of volume of a container that is filled by fruit. The data captured and presented in Chapter 4 was used, as well as the fruit mass function described in Chapter 4.

									Container Volume, CV =		0.565	m^3	
P	Y	B	K	BK	d	SD	V	AK	FB	P	F	D	TF
Farm	Year	Crates	Total Mass (kg)	Kg/Bin	Fruit size (mm) Average	Fruit size (mm) Std Dev	Fruit Volume (mm^3)	Average fruit mass (kg)	Fruit/Bin	Fruit Volume/Bin (mm^3/bin)	Percentage of volume filled	Producer fill deviation	True volume fill
								$AK = FWF\left(A/2\right)$		Average(P) 0.357	Average(F) 63.2%		CI ±95% 1.9%
				$BK = B/K$			$V = 4/3\left(A/2\right)^3\pi$		$FB = BK/AK$	$P = BF/V$	$F = P/CV$		$TF = F + D$
21	2003	3254	1114872	342.62	77.78	5.79	246390	0.240	1428	0.352	62.3%	1.3%	63.5%
21	2003	434	150125	345.91	74.93	6.93	220253	0.216	1600	0.352	62.4%	1.3%	63.6%
21	2003	378	130765	345.94	76.08	6.77	230584	0.226	1533	0.353	62.5%	1.3%	63.8%
21	2003	974	338135	347.16	75.80	5.14	228043	0.223	1554	0.354	62.7%	1.3%	64.0%
21	2003	1760	616950	350.54	74.90	5.94	219993	0.216	1624	0.357	63.2%	1.3%	64.5%
22	2003	200	61540	307.70	84.03	8.67	310708	0.292	1054	0.328	58.0%	3.5%	61.5%
22	2003	980	314165	320.58	82.91	8.58	298428	0.282	1135	0.339	59.9%	3.5%	63.5%
22	2003	108	35460	328.33	82.59	6.64	294946	0.280	1173	0.346	61.3%	3.5%	64.8%
22	2003	664	220690	332.36	78.51	8.45	253409	0.246	1351	0.342	60.6%	3.5%	64.1%
23	2003	284	94860	334.01	81.22	7.23	280541	0.268	1244	0.349	61.8%	-0.8%	61.0%
23	2003	250	84880	339.52	78.17	4.97	250102	0.243	1397	0.349	61.8%	-0.8%	61.0%
23	2003	72	24820	344.72	79.17	6.33	259791	0.251	1371	0.356	63.1%	-0.8%	62.3%
23	2003	48	16900	352.08	74.60	5.63	217385	0.213	1650	0.359	63.5%	-0.8%	62.7%
23	2003	74	26160	353.51	74.36	5.68	215245	0.211	1672	0.360	63.7%	-0.8%	62.9%
23	2003	156	55255	354.20	72.45	6.61	199090	0.196	1811	0.361	63.8%	-0.8%	63.0%
24	2003	496	170166	343.08	70.98	3.58	187277	0.183	1871	0.350	62.0%	0.5%	62.5%
25	2003	663	234565	353.79	76.67	3.85	235966	0.231	1534	0.362	64.1%	-2.4%	61.7%
25	2003	30	10700	356.67	72.34	4.88	198204	0.195	1832	0.363	64.3%	-2.4%	61.9%
25	2003	867	310535	358.17	76.03	4.30	230104	0.225	1590	0.366	64.7%	-2.4%	62.3%
25	2003	160	57710	360.69	74.42	4.62	215839	0.212	1702	0.367	65.0%	-2.4%	62.6%
25	2003	883	319155	361.44	76.50	4.32	234428	0.229	1577	0.370	65.4%	-2.4%	63.0%
25	2003	294	106350	361.73	75.14	4.59	222149	0.218	1660	0.369	65.3%	-2.4%	62.9%
25	2003	228	82660	362.54	75.09	4.61	221715	0.218	1667	0.370	65.4%	-2.4%	63.0%
25	2003	232	84400	363.79	74.60	4.64	217341	0.213	1705	0.371	65.6%	-2.4%	63.2%
21	2004	242	80990	334.67	71.62	5.03	192353	0.189	1774	0.341	60.4%	1.3%	61.7%

Table B: ρ_{AKV} Calculations...continued

P Farm	*Y* Year	*B* Crates	*K* Total Mass (kg)	*BK* Kg/Bin	*A* Average Size (mm)	*SD* Std Dev Size (mm^3)	*V* Fruit Volume (mm^3)	*AK* Average fruit mass (kg)	*FB* Fruit/Bin	*P* Fruit Volume/Bin (mm^3/bin)	*F* Percentage of volume filled	*D* Producer fill deviation	TF True volume fill
21	2004	1372	461620	336.46	75.56	6.03	225917	0.221	1519	0.343	60.8%	1.3%	62.0%
21	2004	1050	355930	338.98	72.31	4.95	197968	0.194	1744	0.345	61.1%	1.3%	62.4%
21	2004	1096	377780	344.69	71.13	5.32	188444	0.185	1867	0.352	62.3%	1.3%	63.5%
21	2004	816	285240	349.56	70.68	5.35	184872	0.181	1933	0.357	63.2%	1.3%	64.5%
22	2004	330	106340	322.24	82.41	7.22	293070	0.278	1158	0.339	60.1%	3.5%	63.6%
22	2004	36	11940	331.67	77.26	5.32	241430	0.235	1408	0.340	60.2%	3.5%	63.7%
23	2004	66	22740	344.55	84.74	7.39	318638	0.298	1157	0.369	65.3%	-0.8%	64.5%
23	2004	200	69320	346.60	83.47	7.10	304506	0.287	1207	0.368	65.1%	-0.8%	64.3%
24	2004	140	47135	336.68	79.68	5.28	264898	0.256	1317	0.349	61.7%	0.5%	62.3%
24	2004	60	20220	337.00	75.94	5.54	229335	0.225	1501	0.344	60.9%	0.5%	61.4%
24	2004	40	13780	344.50	81.06	5.71	278849	0.267	1290	0.360	63.7%	0.5%	64.2%
24	2004	120	41420	345.17	76.59	5.39	235226	0.230	1501	0.353	62.5%	0.5%	63.0%
24	2004	216	75080	347.59	76.09	4.56	230675	0.226	1539	0.355	62.8%	0.5%	63.4%
25	2004	64	22280	348.13	79.25	5.42	260584	0.252	1381	0.360	63.7%	-2.4%	61.3%
25	2004	64	22580	352.81	77.64	5.53	245047	0.239	1478	0.362	64.1%	-2.4%	61.7%
25	2004	174	62085	356.81	80.17	6.28	269840	0.260	1374	0.371	65.6%	-2.4%	63.2%
25	2004	1225	441330	360.27	80.41	5.91	272258	0.262	1376	0.375	66.3%	-2.4%	63.9%
25	2004	841	307150	365.22	78.37	5.55	252020	0.245	1492	0.376	66.6%	-2.4%	64.2%
21	2005	749	245790	328.16	79.67	7.36	264795	0.256	1284	0.340	60.2%	1.3%	61.4%
21	2005	1652	554840	335.86	80.90	8.04	277191	0.266	1264	0.350	62.0%	1.3%	63.3%
22	2005	36	11140	309.44	88.19	6.38	359139	0.326	948	0.341	60.3%	3.5%	63.8%
22	2005	414	128860	311.26	82.40	7.67	292917	0.278	1119	0.328	58.0%	3.5%	61.5%
22	2005	377	120060	318.46	80.39	7.85	272010	0.262	1218	0.331	58.6%	3.5%	62.2%
23	2005	248	84530	340.85	85.66	7.42	329047	0.305	1116	0.367	65.0%	-0.8%	64.2%
23	2005	306	104630	341.93	86.70	7.88	341263	0.314	1089	0.372	65.8%	-0.8%	65.0%
23	2005	154	53160	345.19	83.88	6.93	308960	0.290	1188	0.367	65.0%	-0.8%	64.2%
24	2005	54	18235	337.69	80.80	8.12	276172	0.265	1275	0.352	62.3%	0.5%	62.8%
24	2005	88	29910	339.89	79.67	7.40	264779	0.256	1330	0.352	62.3%	0.5%	62.8%
24	2005	71	24460	344.51	81.45	7.93	282883	0.270	1274	0.361	63.8%	0.5%	64.3%
24	2005	25	8700	348.00	81.99	6.49	288582	0.275	1266	0.365	64.7%	0.5%	65.2%
25	2005	120	42380	353.17	83.34	6.50	303113	0.286	1235	0.374	66.2%	-2.4%	63.8%
25	2005	206	73250	355.58	86.74	6.98	341765	0.314	1131	0.387	68.4%	-2.4%	66.0%
25	2005	468	167990	358.95	80.59	6.22	274077	0.263	1364	0.374	66.2%	-2.4%	63.8%
25	2005	508	182530	359.31	82.76	7.16	296825	0.281	1278	0.379	67.1%	-2.4%	64.7%
25	2005	130	46740	359.54	81.28	6.95	281112	0.269	1337	0.376	66.5%	-2.4%	64.1%

APPENDIX C

ORIGINAL DATA

PRODUCTION RUN PACKOUT

[redacted]

Email: [redacted] Telephone: [redacted] Fax: [redacted]

Producer: [redacted] **Run Number:** [redacted]
Start Date: [redacted]

Pack Summary

FruitType: OR ORANGES Pool: GEN General
Tip Cultivar [redacted]

Grade	Kgs	%
1	34,384.00	71.92
2	6,960.00	14.56
3	3,857.00	8.07
JUICE	3,624.00	7.58
WASTE	180.00	0.38
Total KGs Tipped:	47,810.00	

Bin Tipping

Bin Type	Grade	Quantity	Kilograms	Average Kilograms	Orchard	Qty
BB	[redacted]	120	47,810.00	398.42		120
Total		120	47,810.00			120

PACKOUT:

Com	SVar	Grade	Ch	Pack	Brand	TM	Inv.	Count	Passed Cartons	Carton Weight	% Passed	On Floor & Reject	Kgs	% Packed
OR	MKN	1	[redacted]	A15C	[redacted]			40	15.00	240.00	0.50	0.00	0.00	0.50
OR	MKN	1	[redacted]	A15C	[redacted]			48	13.00	208.00	0.44	0.00	0.00	0.44
OR	MKN	1	[redacted]	A15C	[redacted]			56	17.00	272.00	0.57	0.00	0.00	0.57
OR	MKN	1	[redacted]	A15C	[redacted]			64	64.00	1,024.00	2.14	0.00	0.00	2.14
OR	MKN	1	[redacted]	A15C	[redacted]			72	1.00	16.00	0.03	0.00	0.00	0.03
OR	MKN	1	[redacted]	A15C	[redacted]			88	37.00	592.00	1.24	0.00	0.00	1.24
OR	MKN	1	[redacted]	A15C	[redacted]			105	21.00	336.00	0.70	0.00	0.00	0.70
OR	MKN	1	[redacted]	A15C	[redacted]			125	6.00	96.00	0.20	0.00	0.00	0.20
									174.00	2,784.00		0.00	0.00	
OR	MKN	1	[redacted]	A15C	[redacted]			40	32.00	512.00	1.07	0.00	0.00	1.07
OR	MKN	1	[redacted]	A15C	[redacted]			48	241.00	3,856.00	8.07	0.00	0.00	8.07
OR	MKN	1	[redacted]	A15C	[redacted]			56	589.00	9,424.00	19.71	0.00	0.00	19.71
									862.00	13,792.00		0.00	0.00	
									1,036.00	16,576.00	34.67	0.00	0.00	34.67
OR	VAL	1	[redacted]	A15C	[redacted]			64	430.00	6,880.00	14.39	0.00	0.00	14.39
OR	VAL	1	[redacted]	A15C	[redacted]			72	392.00	6,272.00	13.12	0.00	0.00	13.12
OR	VAL	1	[redacted]	A15C	[redacted]			88	259.00	4,144.00	8.67	0.00	0.00	8.67
OR	VAL	1	[redacted]	A15C	[redacted]			105	28.00	448.00	0.94	0.00	0.00	0.94
OR	VAL	1	[redacted]	A15C	[redacted]			125	4.00	64.00	0.13	0.00	0.00	0.13
									1,113.00	17,808.00		0.00	0.00	
									1,113.00	17,808.00	37.25	0.00	0.00	37.25
									2,149.00	34,384.00		0.00	0.00	71.92
OR	MKN	2	[redacted]	A15C	[redacted]			64	13.00	208.00	0.44	0.00	0.00	0.44
OR	MKN	2	[redacted]	A15C	[redacted]			48	24.00	384.00	0.80	0.00	0.00	0.80
OR	MKN	2	[redacted]	A15C	[redacted]			56	0.00	0.00	0.00	38.00	608.00	1.27
OR	MKN	2	[redacted]	A15C	[redacted]			88	8.00	128.00	0.27	0.00	0.00	0.27
OR	MKN	2	[redacted]	A15C	[redacted]			105	3.00	48.00	0.10	0.00	0.00	0.10
OR	MKN	2	[redacted]	A15C	[redacted]			125	1.00	16.00	0.03	0.00	0.00	0.03

PRODUCTION RUN PACKOUT

[redacted]

Email: [redacted] Telephone: [redacted] Fax: [redacted]

						49.00	784.00		38.00	608.00	
						49.00	784.00	1.64	38.00	608.00	2.91
OR	VAL	2	[redacted]		48	58.00	928.00	1.94	0.00	0.00	1.94
OR	VAL	2	[redacted]		56	110.00	1,760.00	3.68	0.00	0.00	3.68
OR	VAL	2	[redacted]		64	49.00	784.00	1.64	0.00	0.00	1.64
OR	VAL	2	[redacted]	[redacted]	72	25.00	400.00	0.84	51.00	816.00	2.54
OR	VAL	2	[redacted]	[redacted]	88	32.00	512.00	1.07	0.00	0.00	1.07
OR	VAL	2	[redacted]	[redacted]	105	20.00	320.00	0.67	0.00	0.00	0.67
OR	VAL	2	[redacted]		125	0.00	0.00	0.00	3.00	48.00	0.10
						294.00	4,704.00		54.00	864.00	
						294.00	4,704.00	9.84	54.00	864.00	11.64
						343.00	5,488.00		92.00	1,472.00	14.55
OR	MKN	3	[redacted]		L	341.00	2,387.00	4.99	0.00	0.00	4.99
OR	MKN	3	[redacted]		M	119.00	833.00	1.74	0.00	0.00	1.74
OR	MKN	3	[redacted]		XL	91.00	637.00	1.33	0.00	0.00	1.33
						551.00	3,857.00		0.00	0.00	
						551.00	3,857.00	8.06	0.00	0.00	8.06
						551.00	3,857.00		0.00	0.00	8.06

Rebins

Var	Grade	Size	Type	Brand	Reason Code	Quantity	Kgs	Perc.
MKN	JUICE	MX	BB	[redacted]	UNWAXED	1	222.00	0.46
MKN	JUICE	MX	BB	[redacted]	WAXED	10	3,402.00	7.12
MKN	WASTE	MX	BB	[redacted]		1	180.00	0.38
					Total	12	3,804.00	7.96

Rejected Plts:

SSCC	Com	Var	Grade	Pack	Brand	TM	Inv.	Count	Reason	Cartons
[redacted]	OR	VAL	2	A15C	[redacted]			125	[redacted]	3
[redacted]	OR	MKN	2	A15C	[redacted]			56	[redacted]	38
[redacted]	OR	VAL	2	A15C	[redacted]			72	[redacted]	51

PRODUCTION RUN PACKOUT

[redacted]

Email: [redacted] Telephone: [redacted] Fax: [redacted]

Producer: [redacted]
[redacted]

Run Number: [redacted] [redacted]
Start Date: [redacted]

Pack Summary

FruitType: NV NAVEL TYPE Pool: [redacted]
Tip Cultivar: NAV NAWELS

Grade	Kgs	%	Rejected portion of packout Kgs	Rejected portion of packout %
Grade1 - OTHER	17,112	23.89	1,176	1.64
Grade1 - [redacted]	4,655	6.50		
Grade2 - OTHER	9,794	13.68		
Rebins:				
Rebin Class 1	727	1.01		
Rebin Class 2	308	0.43		
Rebin Class 3	31,301	43.71		
Rebin Juice	3,767	5.26		
Rebin Waste	2,755	3.85		
Rebin Green	1,419	1.98		
Sub Total:	71,836			
Variance:	-220	-0.31		
Total Tipped:	71,616			

Tipping :

	Bin Type	Quantity	Kilograms	Average Kilograms	Del#	Orchard	Qty	
# = Green Rebins	BB	176	60,415	343	217	35	31	#
	BB	31	11,029	356	1,496	3	23	
					1,497	3	17	
					1,498	4	9	
					1,634	3	33	
					1,635	AB3	34	
					1,838	5	36	
					1,839	2	24	
Pallets		1	172	172				
	Total		71,616				207	

Packout :

Grade	Pack	Brand	Agent	Target	Count	Cartons	Spread %	Kgs	%	Despatched Export	Other*	Reject & Floor
Grade 1	A15C	[redacted]	[redacted]	[redacted]	40	133	36	2,140	2.99	133	0	0
Grade 1	A15C	[redacted]	[redacted]	[redacted]	48	114	30	1,789	2.50	114	0	0
Grade 1	A15C	[redacted]	[redacted]	[redacted]	56	100	27	1,602	2.24	100	0	0
Grade 1	A15C	[redacted]	[redacted]	[redacted]	88	27	7	419	0.59	27	0	0
Total Grade 1 & [redacted]						374	100	5,951	8.32	374	0	0
Grade 1	A15C	[redacted]	[redacted]	[redacted]	40	232	30	3,666	5.12	232	0	0
Grade 1	A15C	[redacted]	[redacted]	[redacted]	48	204	27	3,200	4.47	204	0	0
Grade 1	A15C	[redacted]	[redacted]	[redacted]	56	18	2	281	0.39	18	0	0
Grade 1	A15C	[redacted]	[redacted]	[redacted]	64	24	3	367	0.51	24	0	0
Grade 1	A15C	[redacted]	[redacted]	[redacted]	72	4	1	62	0.09	4	0	0
Grade 1	A15C	[redacted]	[redacted]	[redacted]	88	4	1	62	0.09	4	0	0
Grade 1	A15C	[redacted]	[redacted]	[redacted]	56	140	18	2,359	3.29	70	0	70
Grade 1	A15C	[redacted]	[redacted]	[redacted]	64	70	9	1,169	1.63	70	0	0
Grade 1	A15C	[redacted]	[redacted]	[redacted]	72	70	9	1,127	1.57	70	0	0
Grade 1	A15C	[redacted]	[redacted]	[redacted]	56	0	0	0	0.00	70	0	-70
Total Grade 1 & [redacted]						766	100	12,293	17.16	766	0	0

Report Date: [redacted] Report Time: [redacted] Run [redacted] Page 1

PRODUCTION RUN PACKOUT

[redacted]

Email: [redacted] Telephone: [redacted] Fax: [redacted]

Grade 1	A15C	[redacted]	[redacted]	105	11	5	167	0.23	0	11	0
Grade 1	A15C	[redacted]	[redacted]	64	129	59	2,104	2.94	59	70	0
Grade 1	A15C	[redacted]	[redacted]	72	79	36	1,251	1.75	79	0	0
Total	**Grade 1 & [redacted]**				219	100	3,523	4.92	138	81	0
Total	**Grade 1**				1359		21,767	30.40	1278	81	0
Grade 2	A15C	[redacted]	[redacted]	40	119	34	1,910	2.67	119	0	0
Grade 2	A15C	[redacted]	[redacted]	48	110	31	1,799	2.51	110	0	0
Grade 2	A15C	[redacted]	[redacted]	56	126	35	2,084	2.91	126	0	0
Total	**Grade 2 & [redacted]**				355	100	5,792	8.09	355	0	0
Total	**Grade 2**				355		5,792	8.09	355	0	0
Choice	A15C	[redacted]	[redacted]	105	5	2	85	0.12	5	0	0
Choice	A15C	[redacted]	[redacted]	64	157	63	2,514	3.51	157	0	0
Choice	A15C	[redacted]	[redacted]	72	70	28	1,117	1.56	70	0	0
Choice	A15C	[redacted]	[redacted]	88	18	7	286	0.40	18	0	0
Total	**Choice & [redacted]**				250	100	4,002	5.59	250	0	0
Total	**Choice**				250		4,002	5.59	250	0	0
Grand Total					1964		31,561	44.08	1883	81	0

Rebins :

Var	Grade	Count	Bin Type	Destination	Quantity	Kilograms	Percentage
NAV	R1	XL	BB		3	727	1.01
NAV	R2	XL	BB		2	308	0.43
NAV	R3	105	BB		1	363	0.51
NAV	R3	40	BB		1	438	0.61
NAV	R3	48	BB		19	7,110	9.93
NAV	R3	56	BB		12	4,201	5.87
NAV	R3	64	BB		14	5,025	7.02
NAV	R3	64	BB		2	683	0.95
NAV	R3	72	BB		10	3,689	5.15
NAV	R3	88	BB		2	757	1.06
NAV	R3	XL	BB		25	9,038	12.62
NAV	R4	MIX	BB		12	3,767	5.26
NAV	R5	MIX	BB		5	2,755	3.85
NAV	RGR	MIX	BB		4	1,419	1.98
			Total		112	40,275	56.25

Rejected :

Brand	Grade	Count	TMarket	Pack	Reason	Cartons	Kgs	%
[redacted]	1	64	[redacted]	A15	BESE	70	1,176	100.00
						70	1,176	100.00

QA Tests :

Test Code	Test Description	Average Result (%)
BEDSV	Bederf Suurvrot	0.22
BESGR	Beserings Gering	1.06
BREV	Brevipalpus	0.33
DOP	Dopluis	0.78
GRW	Growwe Skil	1.04
KLT8	Te Groen	16.22
KNVAL	Knoppies - Uitgeval	0.67

Report Date: [redacted] Report Time: [redacted] Run [redacted] Page 2

PRODUCTION RUN PACKOUT

[redacted]

Email: [redacted] Telephone: [redacted] Fax: [redacted]

KRA	Kraakskil	1.52
NAENT	Nawel Oopgebrste Ente	2.36
OLEO	Oleo	0.97
PITTE	Pitte	3.59
RIF	Riffel	2.40
ROET	Roet Skimmel	0.44
SAP	Sap %	14.56
SKA	SKAAPNEUS	0.35
SON	Sonbrand	4.37
STKD	Stinkluis dood	0.58
TOV	Totale Oplosbare Vastestowwe	4.87
VERH	Verhouding	5.51
VKMOS	Valskodlingmot Onsigbaar	1.14
VKMS	Valskodlingmot Sigbaar	1.35
WIND	Windmerke	22.78
WIT	Witluis	0.22

*** Despatched Other :**

Destination Code	Destination Description	Cartons
REPACK		70
TIPPING	TIPPING	11

Approved By: ______________________

Date: ______________________

[redacted] [redacted] Bladsy: [redacted]

LEDE GRADERINGS PER TELLING PER CULTIVAR - STANDAARD SEISOEN: [redacted] [redacted]

Lid: [redacted] [redacted]

Kultivar Kode	Kultivar Beskrywing	Totale Kratte	Vrugte Massa	Massa Uitskot	Massa Buite Grootte
[redacted]	[redacted]	160	57710.00	31.00	128.00

TELLINGS	036	040	048	056	064	072	088	105	125	144	Totaal	[redacted]	[redacted]
KLAS 1													
Kartonne	0.00	0.00	8.36	14.55	205.62	806.65	886.96	339.43	0.00	0.00	2261.57	60.46	56.96
Betalings	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]		
KLAS 2													
Kartonne	0.00	0.00	5.84	2.26	87.95	204.08	138.48	62.41	0.00	0.00	501.02	13.39	12.53
Betalings	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]		
KLAS 3													
Kartonne	0.00	0.00	2.80	22.31	35.66	167.33	89.06	77.04	0.00	0.00	394.20	10.54	20.50
Betalings	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]		
KLAS 4													
Kartonne	0.00	0.00	0.00	4.96	6.48	17.75	3.16	5.24	411.27	134.75	583.61	15.60	10.01
Betalings	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]		
SLO													
Kartonne	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Betalings	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]		
TOT KT:	0.00	0.00	17.00	44.08	335.71	1195.81	1117.66	484.12	411.27	134.75	3740.40		
TOT BET:	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]		

GRADEER VERSPREIDING - [redacted]

Pers K1	0.00	0.00	0.37	0.64	9.09	35.67	39.22	15.01	0.00	0.00	100.00
Pers K2	0.00	0.00	1.17	0.45	17.55	40.73	27.64	12.46	0.00	0.00	100.00
Pers K3	0.00	0.00	0.71	5.66	9.05	42.45	22.59	19.54	0.00	0.00	100.00
Pers K4	0.00	0.00	0.00	0.85	1.11	3.04	0.54	0.90	70.47	23.09	100.00

GRADEER VERSPREIDING - [redacted]

Pers K1	0.00	0.57	3.83	5.42	19.82	36.62	25.30	8.44	0.00	0.00	100.00
Pers K2	0.00	0.73	4.56	5.80	20.97	37.10	23.78	7.08	0.00	0.00	100.02
Pers K3	6.24	3.07	7.40	9.17	11.88	33.97	13.06	15.21	0.00	0.00	100.00
Pers K4	0.10	0.66	1.71	1.86	2.79	7.58	2.80	3.53	61.44	17.54	100.01

[redacted]
PRODUCTION REPORT: [redacted] [redacted]
[redacted]

Posbus [redacted]
Producer ID Client Name Fax
[redacted]

Tel: [redacted]
Date Packed Week Product Variety
Fax: [redacted]
NAV

Total Weight Weight Packed Tip Cost PercentageBins Used Intakes Used
106,580.00Kg 109,049.90 [redacted] 102.32 % 297 472, 480, 493, 496,
510, 511, 519, 524,

Pallet Details
Class : 1

Carton	Count	Pack Cost	Pack Material	Percentage	Total Weight	Total Cartons
A15C	105	[redacted]	[redacted]	2.20%	2,340.60 Kg	166
A15C	40	[redacted]	[redacted]	1.93%	2,060.10 Kg	144
A15C	48	[redacted]	[redacted]	12.25%	13,059.30 Kg	896
A15C	56	[redacted]	[redacted]	9.49%	10,112.40 Kg	699
A15C	64	[redacted]	[redacted]	6.38%	6,798.90 Kg	467
A15C	72	[redacted]	[redacted]	16.05%	17,109.60 Kg	1192
A15C	88	[redacted]	[redacted]	6.56%	6,987.00 Kg	491
D64D	50	[redacted]	[redacted]	0.57%	607.20 Kg	36
Total entries = Tota[redacted]			[redacted]	55.43%	59,075.10 Kg	4091

Pallet Details
Class : 2

Carton	Count	Pack Cost	Pack Material	Percentage	Total Weight	Total Cartons
A15C	105	[redacted]	[redacted]	0.75%	801.00 Kg	54
A15C	40	[redacted]	[redacted]	0.70%	750.00 Kg	50
A15C	48	[redacted]	[redacted]	2.57%	2,741.10 Kg	184
A15C	56	[redacted]	[redacted]	4.25%	4,533.00 Kg	307
A15C	64	[redacted]	[redacted]	0.34%	357.30 Kg	24
A15C	72	[redacted]	[redacted]	9.31%	9,923.40 Kg	663
A15C	88	[redacted]	[redacted]	1.27%	1,350.00 Kg	90
Total entries = Total[redacted]			[redacted]	19.19%	20,455.80 Kg	1372

Pallet Details
Class : 3

Carton	Count	Pack Cost	Pack Material	Percentage	Total Weight	Total Cartons
		[redacted]	[redacted]	0.00%	0.00 Kg	
	56/64	[redacted]	[redacted]	4.77%	5,085.00 Kg	
	72/88	[redacted]	[redacted]	5.30%	5,650.00 Kg	

[redacted]

LAR	[redacted]	[redacted]	5.23%	5,572.00 Kg
MEDI	[redacted]	[redacted]	4.46%	4,751.00 Kg
SMA	[redacted]	[redacted]	2.06%	2,194.00 Kg
X-	[redacted]	[redacted]	3.43%	3,652.00 Kg
Total entries = Total: 0	[redacted]	[redacted]	25.24%	26,904.00 Kg

Pallet Details
Class : 4

Carton Count	Pack Cost	Pack Material	Percentage	Total WeightTotal Cartons
105	[redacted]	[redacted]	0.34%	365.00 Kg
LAR	[redacted]	[redacted]	1.27%	1,350.00 Kg
Total entries = Total: 0	[redacted]	[redacted]	1.61%	1,715.00 Kg

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Printed by [redacted]

Pallet Details
Class : 5

Carton Count	Pack Cost	Pack Material	Percentage	Total WeightTotal Cartons
105	[redacted]	[redacted]	0.84%	900.00 Kg
Total entries = Total: 0	[redacted]	[redacted]	0.84%	900.00 Kg
Notes Grand Tota 5463	[redacted]	[redacted]	102.32%	109,049.90 Kg

Financial Summary: [redacted] [redacted]

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Printed by [redacted]

APPENDIX D

COMPLETE DATA SET

Data Group	Producer	Area	Month	Year	Fruit	Total kgs	Average Size (mm)	Std Dev Size (mm)	Proportion Grade 1	Proportion Green
1	11	1	6	2004	Navels	27552	85.93	5.77	0.18	
1	11	1	6	2004	Navels	30138	85.22	6.80	0.28	
1	11	1	6	2004	Navels	65440	85.47	6.32	0.20	
1	11	1	6	2004	Navels	24617	79.47	5.84	0.37	
1	11	1	7	2004	Navels	19052	79.30	6.13	0.20	
1	11	1	9	2004	Valencia	97789	85.56	5.27	0.63	
1	11	1	9	2004	Valencia	102924	84.86	5.53	0.69	
1	11	1	9	2004	Valencia	160373	84.73	6.62	0.66	
1	11	1	9	2004	Valencia	54736	85.77	6.07	0.63	
1	11	1	9	2004	Valencia	37727	82.45	7.10	0.65	
1	12	1	6	2004	Navels	45826	81.69	8.64	0.30	
1	12	1	6	2004	Navels	34245	81.21	9.13	0.32	
1	12	1	6	2004	Navels	9347	81.78	9.40	0.32	
1	12	1	6	2004	Navels	3882	81.17	8.20	0.24	
1	12	1	6	2004	Navels	23281	77.27	7.34	0.18	
1	12	1	9	2004	Valencia	93609	80.09	6.39	0.70	
1	12	1	9	2004	Valencia	27323	81.13	6.12	0.69	
1	12	1	9	2004	Valencia	46925	81.20	6.16	0.57	
1	12	1	9	2004	Valencia	47810	82.39	6.39	0.70	
1	12	1	9	2004	Valencia	85032	80.87	7.10	0.71	
1	13	1	5	2004	Navels	37954	80.82	7.97	0.46	
1	13	1	6	2004	Navels	58718	75.58	6.02	0.40	
1	13	1	6	2004	Navels	17558	76.44	6.26	0.41	
1	13	1	6	2004	Navels	38435	77.12	6.27	0.38	
1	13	1	6	2004	Navels	57419	78.48	6.65	0.39	
1	13	1	8	2004	Valencia	34838	77.88	5.47	0.76	
1	13	1	8	2004	Valencia	81830	78.17	6.31	0.71	
1	13	1	9	2004	Valencia	61639	75.32	5.86	0.75	
1	13	1	9	2004	Valencia	29845	74.51	4.08	0.78	
1	14	1	5	2004	Navels	162569	76.40	6.85	0.51	
1	14	1	6	2004	Navels	41082	77.42	8.14	0.36	
1	14	1	6	2004	Navels	44784	75.19	5.94	0.39	
1	14	1	6	2004	Navels	50817	77.52	8.49	0.32	
1	14	1	9	2004	Valencia	58436	82.15	7.27	0.38	
1	14	1	9	2004	Valencia	15885	81.56	7.43	0.48	
1	14	1	10	2004	Valencia	83919	80.51	7.22	0.59	
1	15	1	7	2004	Navels	82209	83.25	7.71	0.51	
1	15	1	7	2004	Navels	93959	84.78	7.53	0.57	
1	15	1	7	2004	Navels	35699	83.58	6.09	0.57	
1	15	1	7	2004	Navels	39429	83.79	5.97	0.56	
1	15	1	8	2004	Navels	5816	82.32	6.45	0.62	
1	15	1	9	2004	Valencia	46387	78.46	7.58	0.72	
1	15	1	9	2004	Valencia	105381	86.47	5.40	0.57	
2	21	2		2003	Valencia	616950	74.90	5.94	0.62	
2	21	2		2003	Valencia	150125	74.93	6.93	0.53	
2	21	2		2003	Valencia	130765	76.08	6.77	0.54	
2	21	2		2003	Valencia	338135	75.80	5.14	0.67	
2	21	2		2004	Valencia	377780	71.13	5.32	0.48	
2	21	2		2004	Valencia	285240	70.68	5.35	0.54	
2	21	2		2004	Valencia	355930	72.31	4.95	0.46	
2	21	2		2004	Valencia	461620	75.56	6.03	0.62	

Data Group	Producer	Area	Month	Year	Fruit	Total kgs	Average Size (mm)	Std Dev Size (mm)	Proportion Grade 1	Proportion Green
2	21	2		2004	Valencia	80990	71.62	5.03	0.43	
2	21	2		2005	Valencia	554840	80.90	8.04	0.50	
2	21	2		2005	Valencia	245790	79.67	7.36	0.48	
2	22	2		2003	Navels	35460	82.59	6.64	0.55	
2	22	2		2003	Valencia	314165	82.91	8.58	0.49	
2	22	2		2003	Valencia	220690	78.51	8.45	0.35	
2	22	2		2004	Navels	11940	77.26	5.32	0.56	
2	22	2		2004	Navels	7400	80.48	3.63	0.59	
2	22	2		2004	Navels	106340	82.41	7.22	0.32	
2	22	2		2005	Navels	11140	88.19	6.38	0.24	
2	22	2		2005	Navels	120060	80.39	7.85	0.23	
2	22	2		2005	Navels	128860	82.40	7.67	0.14	
2	23	2		2003	Navels	55255	72.45	6.61	0.45	
2	23	2		2003	Navels	16900	74.60	5.63	0.56	
2	23	2		2003	Navels	26160	74.36	5.68	0.49	
2	23	2		2003	Navels	94860	81.22	7.23	0.50	
2	23	2		2003	Navels	84880	78.17	4.97	0.43	
2	23	2		2003	Navels	24820	79.17	6.33	0.39	
2	23	2		2004	Navels	69320	83.47	7.10	0.42	
2	23	2		2004	Navels	22740	84.74	7.39	0.57	
2	23	2		2005	Navels	53160	83.88	6.93	0.29	
2	23	2		2005	Navels	104630	86.70	7.88	0.32	
2	23	2		2005	Navels	84530	85.66	7.42	0.29	
2	24	2		2004	Navels	20220	75.94	5.54	0.79	
2	24	2		2004	Navels	41420	76.59	5.39	0.54	
2	24	2		2004	Navels	47135	79.68	5.28	0.53	
2	24	2		2004	Navels	13780	81.06	5.71	0.64	
2	24	2		2005	Navels	18235	80.80	8.12	0.69	
2	24	2		2005	Navels	29910	79.67	7.40	0.61	
2	24	2		2005	Navels	24460	81.45	7.93	0.45	
2	24	2		2005	Navels	8700	81.99	6.49	0.51	
2	25	2		2003	Navels	57710	74.42	4.62	0.60	
2	25	2		2003	Navels	82660	75.09	4.61	0.64	
2	25	2		2003	Navels	234565	76.67	3.85	0.67	
2	25	2		2003	Navels	310535	76.03	4.30	0.67	
2	25	2		2003	Navels	319155	76.50	4.32	0.73	
2	25	2		2003	Navels	106350	75.14	4.59	0.52	
2	25	2		2003	Navels	84400	74.60	4.64	0.46	
2	25	2		2003	Navels	10700	72.34	4.88	0.39	
2	25	2		2004	Navels	307150	78.37	5.55	0.61	
2	25	2		2004	Navels	27355	81.28	6.28	0.65	
2	25	2		2004	Navels	441330	80.41	5.91	0.51	
2	25	2		2004	Navels	22580	77.64	5.53	0.45	
2	25	2		2004	Navels	22280	79.25	5.42	0.31	
2	25	2		2004	Navels	62085	80.17	6.28	0.41	
2	25	2		2005	Navels	46740	81.28	6.95	0.73	
2	25	2		2005	Navels	182530	82.76	7.16	0.47	
2	25	2		2005	Navels	42380	83.34	6.50	0.71	
2	25	2		2005	Navels	167990	80.59	6.22	0.71	
2	25	2		2005	Navels	73250	86.74	6.98	0.49	
3	21	2		2003	Navels	1467580	74.54	5.24	0.59	
3	21	2		2003	Navels	400166	74.58	4.83	0.57	

Data Group	Producer	Area	Month	Year	Fruit	Total kgs	Average Size (mm)	Std Dev Size (mm)	Proportion Grade 1	Proportion Green
3	21	2		2003	Navels	286769	72.57	4.41	0.43	
3	21	2		2003	Robyn	708421	78.24	5.67	0.79	
3	21	2		2003	Robyn	1114872	77.78	5.79	0.71	
3	21	2		2004	Navels	1274532	78.14	6.81	0.61	
3	21	2		2004	Navels	899867	78.62	5.72	0.68	
3	21	2		2004	Robyn	1341432	82.16	6.64	0.64	
3	21	2		2005	Navels	623921	78.45	6.41	0.53	
3	21	2		2005	Navels	745149	81.87	6.54	0.52	
3	21	2		2005	Robyn	1213470	78.64	5.16	0.49	
3	22	2		2003	Navels	649775	79.79	7.19	0.60	
3	22	2		2003	Navels	61540	84.03	8.67	0.59	
3	22	2		2003	Robyn	268920	79.86	7.46	0.68	
3	22	2		2003	Robyn	47980	78.14	5.96	0.74	
3	22	2		2004	Navels	619801	77.88	6.05	0.56	
3	22	2		2004	Robyn	342480	77.92	6.62	0.53	
3	22	2		2005	Navels	295121	80.78	7.94	0.27	
3	22	2		2005	Robyn	224775	80.45	6.54	0.22	
3	23	2		2003	Navels	487660	76.20	5.63	0.59	
3	23	2		2003	Robyn	248276	76.95	4.10	0.66	
3	23	2		2004	Navels	644200	82.41	7.63	0.62	
3	23	2		2004	Robyn	241647	82.12	7.36	0.58	
3	23	2		2005	Navels	189725	85.38	7.34	0.31	
3	23	2		2005	Navels	417610	86.06	7.52	0.35	
3	24	2		2003	Navels	115607	70.81	3.59	0.71	
3	24	2		2003	Navels	33698	70.12	3.34	0.54	
3	24	2		2003	Robyn	31992	80.48	8.14	0.85	
3	24	2		2004	Navels	48788	76.11	4.61	0.81	
3	24	2		2004	Robyn	155484	84.61	6.19	0.67	
3	24	2		2005	Navels	151381	84.42	7.61	0.41	
3	24	2		2005	Robyn	127884	89.97	5.77	0.60	
3	25	2		2004	Navels	68679	75.40	4.08	0.53	
3	25	2		2005	Navels	880176	82.41	6.60	0.60	
3	25	2		2005	Robyn	64610	81.27	5.78	0.54	
4	27	2	5	2005	Navels	197176	82.15	8.17	0.64	0.02
4	27	2	4	2004	Navels	213349	79.88	6.73	0.43	0.02
4	27	2	6	2005	Navels	56902	83.87	6.17	0.35	
4	27	2	2	2005	Navels	107452	80.65	6.40	0.68	0.05
4	27	2	6	2005	Navels	107929	82.32	6.20	0.64	0.07
4	27	2	7	2005	Navels	43687	88.21	7.12	0.58	
4	27	2	6	2005	Navels	111775	84.44	7.77	0.59	0.02
4	27	2	11	2005	Navels	81215	80.50	7.22	0.71	0.03
4	27	2	6	2005	Navels	41725	82.59	7.85	0.52	
4	27	2	6	2005	Navels	249945	82.28	6.48	0.59	0.00
4	27	2	7	2005	Robyn	103322	78.13	5.08	0.66	
4	27	2	7	2005	Navels	49060	84.04	6.99	0.42	
4	27	2	8	2005	Navels	69020	77.90	4.98	0.62	0.05
4	27	2	8	2005	Valencia	141718	81.31	8.63	0.72	0.00
4	27	2	6	2005	Navels	71616	89.91	6.58	0.32	0.02
4	27	2	5	2005	Navels	209814	80.72	7.14	0.56	0.07
4	27	2	7	2005	Navels	105798	85.18	8.07	0.50	
4	27	2	5	2005	Navels	302747	77.89	6.11	0.54	0.10
4	27	2	6	2005	Navels	75492	82.84	7.65	0.42	

Data Group	Producer	Area	Month	Year	Fruit	Total kgs	Average Size (mm)	Std Dev Size (mm)	Proportion Grade 1	Proportion Green
4	27	2	5	2005	Navels	177710	79.56	6.35	0.63	0.02
4	27	2	8	2005	Valencia	207586	75.14	7.99	0.78	0.02
4	27	2	6	2005	Navels	11366	81.12	6.53	0.27	
5	31	3	5	2005	Navels	44530	81.00	8.36	0.20	
5	32	3	5	2005	Navels	90225	87.03	6.85	0.42	
5	32	3	6	2005	Navels	124465	89.34	4.75	0.44	
5	33	3	5	2005	Navels	97644	87.19	6.69	0.43	
5	33	3	5	2005	Navels	92671	82.50	8.00	0.47	
5	33	3	5	2005	Navels	106580	80.74	7.99	0.54	
5	34	3	5	2005	Navels	50005	82.06	7.92	0.60	
5	34	3	5	2005	Navels	127385	81.71	8.32	0.53	
5	35	3	5	2005	Navels	162352	89.30	6.60	0.45	
5	35	3	5	2005	Navels	94535	88.64	6.79	0.45	
6	26	2		2005	Valencia	208420	83.49	6.23	0.82	
6	23	2		2005	Valencia	96280	83.56	8.69	0.54	
6	23	2		2005	Valencia	216935	75.39	5.65	0.54	
6	24	2		2005	Valencia	109200	83.55	7.16	0.87	
6	26	2		2004	Valencia	256360	82.08	6.62	0.74	
6	23	2		2004	Valencia	158860	80.46	8.41	0.69	
6	24	2		2004	Valencia	122970	81.87	6.41	0.82	
6	23	2		2004	Valencia	231080	76.36	6.08	0.76	
6	23	2		2003	Valencia	118340	80.13	7.00	0.75	
6	26	2		2003	Valencia	221948	75.28	4.52	0.83	
6	23	2		2003	Valencia	224240	75.34	5.81	0.73	

Data groups, producers and *areas* have been assigned numbers to depict the various sources.
This was done to maintain the confidentiality of the data.

APPENDIX E

FRUIT SIZE BETA DISTRIBUTION FIT

In the tables below the proportion of fruit in each fruit size category is displayed for the captured data as well as the data distribution. Data of all 179 production runs was used for the fitting of the Beta distribution to the fruit size. The α and β, as well as the absolute lower and upper fruit size limits, were calculated using the *Microsoft Excel Add-In Solver*, which was set to minimizing the ***Error %***, which represents the number of fruit that is incorrectly described by die Beta distribution. In the α and β columns the fitted parameters for each production run is shown. *Solver* was able to decrease the percentage of fruit incorrectly represented by the Beta distributions to 1.3%.

Size Categories										**Size Categories**														
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**					
144	**125**	**105**	**88**	**72**	**64**	**56**	**48**	**40**	**36**	**144**	**125**	**105**	**88**	**72**	**64**	**56**	**48**	**40**	**36**	**Count**				
Diameter (mm)										**Diameter (mm)**														
62.0	65.0	69.0	73.0	77.0	81.0	86.0	90.0	95.0	**∞**	62.0	65.0	69.0	73.0	77.0	81.0	86.0	90.0	95.0	**97.0**	**Upper**				
0	62.0	65.0	69.0	73.0	77.0	81.0	86.0	90.0	95.0	**56.0**	62.0	65.0	69.0	73.0	77.0	81.0	86.0	90.0	95.0	**Lower**			**Error %:**	**0.0129**
??	63.5	67.0	71.0	75.0	79.0	83.5	88.0	92.5	**??**	**59.0**	63.5	67.0	71.0	75.0	79.0	83.5	88.0	92.5	**96.0**	**Average**		**SUM:**	**150953153**	**1951944**
Proportion in each size category										**Beta proportion in each size category**										α	β	**Error Sum**	**Number of fruit**	**Fruit Error**
0.00	0.01	0.03	0.07	0.15	0.22	0.28	0.15	0.08	0.02	0.00	0.00	0.03	0.08	0.15	0.22	0.29	0.16	0.06	0.00	**5.91**	**3.77**	0.02	103370	2021
0.01	0.01	0.04	0.10	0.17	0.21	0.24	0.13	0.07	0.02	0.00	0.01	0.05	0.11	0.17	0.21	0.25	0.14	0.06	0.00	**4.47**	**3.24**	0.02	115742	2202
0.00	0.01	0.03	0.08	0.16	0.23	0.28	0.14	0.07	0.02	0.00	0.01	0.03	0.09	0.16	0.22	0.28	0.15	0.06	0.00	**5.67**	**3.80**	0.02	246458	4255
0.00	0.01	0.07	0.19	0.29	0.25	0.15	0.03	0.00	0.00	0.00	0.01	0.07	0.19	0.28	0.25	0.16	0.03	0.00	0.00	**7.20**	**7.45**	0.01	111264	840
0.00	0.02	0.08	0.19	0.28	0.25	0.14	0.03	0.00	0.00	0.00	0.01	0.08	0.20	0.28	0.25	0.15	0.03	0.00	0.00	**6.93**	**7.26**	0.01	84738	671
0.00	0.00	0.01	0.04	0.12	0.22	0.33	0.18	0.09	0.02	0.00	0.00	0.01	0.05	0.12	0.21	0.33	0.20	0.08	0.00	**7.04**	**3.93**	0.02	372749	6459
0.00	0.00	0.01	0.06	0.15	0.26	0.32	0.14	0.05	0.01	0.00	0.00	0.02	0.07	0.16	0.26	0.32	0.14	0.03	0.00	**7.73**	**5.12**	0.01	399506	5773
0.00	0.01	0.03	0.09	0.17	0.23	0.26	0.13	0.06	0.02	0.00	0.01	0.04	0.09	0.17	0.23	0.28	0.14	0.05	0.00	**5.56**	**3.87**	0.02	630916	10665
0.00	0.01	0.03	0.09	0.16	0.21	0.26	0.14	0.08	0.02	0.00	0.01	0.04	0.09	0.16	0.21	0.26	0.15	0.07	0.00	**4.82**	**3.27**	0.02	209666	4005
0.01	0.01	0.06	0.13	0.20	0.23	0.23	0.09	0.04	0.01	0.00	0.01	0.06	0.13	0.20	0.23	0.24	0.10	0.03	0.00	**5.13**	**4.27**	0.01	156892	2131
0.04	0.04	0.09	0.15	0.19	0.19	0.18	0.08	0.04	0.01	0.02	0.04	0.10	0.15	0.18	0.19	0.19	0.09	0.04	0.00	**3.31**	**3.10**	0.02	195758	3762
0.04	0.05	0.11	0.17	0.20	0.19	0.16	0.06	0.03	0.01	0.02	0.05	0.12	0.17	0.20	0.19	0.17	0.07	0.02	0.00	**3.48**	**3.71**	0.02	149126	2595
0.05	0.05	0.10	0.15	0.18	0.17	0.16	0.07	0.04	0.02	0.03	0.06	0.12	0.15	0.17	0.17	0.17	0.09	0.04	0.00	**2.73**	**2.78**	0.02	40547	913
0.03	0.04	0.10	0.15	0.19	0.19	0.17	0.07	0.04	0.01	0.02	0.04	0.10	0.15	0.18	0.18	0.19	0.09	0.04	0.00	**3.27**	**3.15**	0.02	17048	337
0.04	0.06	0.14	0.22	0.23	0.17	0.11	0.03	0.01	0.00	0.02	0.06	0.16	0.22	0.23	0.18	0.11	0.03	0.00	0.00	**4.14**	**5.30**	0.01	112215	1581
0.01	0.02	0.08	0.17	0.25	0.24	0.17	0.05	0.01	0.00	0.00	0.02	0.08	0.18	0.25	0.24	0.18	0.05	0.01	0.00	**5.78**	**5.70**	0.01	419646	4009
0.00	0.01	0.05	0.14	0.24	0.26	0.21	0.06	0.02	0.00	0.00	0.01	0.06	0.15	0.24	0.26	0.22	0.06	0.01	0.00	**6.39**	**5.68**	0.01	119369	1087
0.01	0.02	0.06	0.14	0.22	0.23	0.21	0.08	0.03	0.00	0.00	0.02	0.07	0.15	0.22	0.23	0.22	0.08	0.02	0.00	**5.23**	**4.64**	0.01	375969	4388
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...

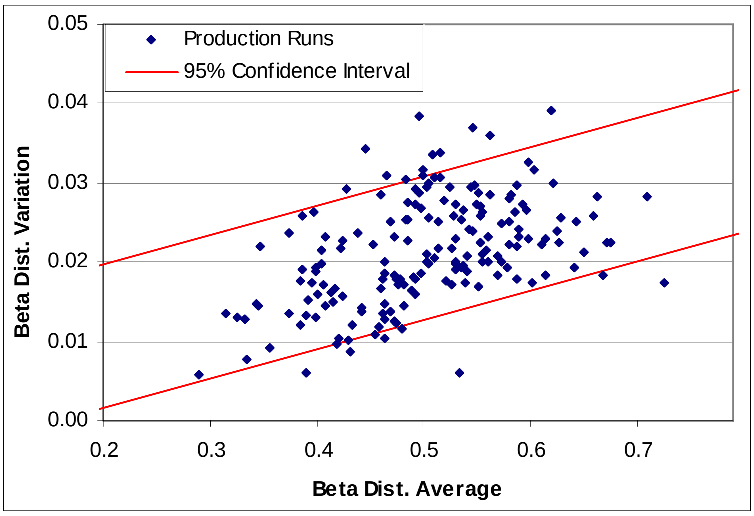
After fitting the Beta distribution to every one of the 179 production runs, an attempt was made to describe the α and β parameters by only specifying the average fruit size.

α	β	Mean	Var	Error of Variance
5.91	3.77	0.61	0.02	0.00
4.47	3.24	0.58	0.03	0.00
5.67	3.80	0.60	0.02	0.00
7.20	7.45	0.49	0.02	0.00
6.93	7.26	0.49	0.02	0.00
7.04	3.93	0.64	0.02	0.01
7.73	5.12	0.60	0.02	0.01
5.56	3.87	0.59	0.02	0.00
4.82	3.27	0.60	0.03	0.00
5.13	4.27	0.55	0.02	0.00
3.31	3.10	0.52	0.03	0.01
3.48	3.71	0.48	0.03	0.01
2.73	2.78	0.50	0.04	0.02
3.27	3.15	0.51	0.03	0.01
4.14	5.30	0.44	0.02	0.01
5.78	5.70	0.50	0.02	0.00
6.39	5.68	0.53	0.02	0.00
6.07	5.36	0.53	0.02	0.00
5.53	4.46	0.55	0.02	0.00
5.23	4.64	0.53	0.02	0.00
3.81	3.87	0.50	0.03	0.01
...	...	...	...	...

The mean and variance of the fitted distributions were calculated with the following equations:

$$mean = \mu = \frac{\alpha}{\alpha+\beta} \qquad variance = \sigma^2 = \frac{\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)}$$

The calculated mean and variance of the fitted Beta distributions are shown in the figure below.



Statistica© was used to analyse the relationship between the mean and the variance of the fitted Beta distributions (StatSoft, Inc., 2005). The results of regression analysis indicated that the effect of the average fruit size on the variance was statistically significant with a p-value of 0.000. However the equation is valid only for a specific range of the mean, as shown in the equation below. From the results of the regression analysis the following relationship between the variance and the mean was established:

$$variance = \sigma^2 = 0.0357\mu + 0.0039 \pm 0.0119 \qquad 0.318 < \mu < 0.677$$

The equation above can be interpreted logically as the following:

- The larger the fruit diameter, the more the variance (0.0357)
- There is a standard variance that can be expected (0.0039)
- The fruit size distribution can be either peaked (low σ^2 0.357μ+0.0039-0.0119) or flat (high σ^2 0.357μ+0.0039+0.0119)

As an estimation of the variance has been established, the limits of the α and β parameters can be determined using the following equations:

$$\alpha = \mu\left(\frac{\mu(1-\mu)}{\sigma^2} - 1\right) \qquad \beta = (1-\mu)\left(\frac{\mu(1-\mu)}{\sigma^2} - 1\right)$$

Using the upper and lower values of the variance with the mean two sets of α and β values are calculated, one set represents a peaked distribution and the other a flat one.

APPENDIX F

FRUIT CHARACTERISTIC FORECASTING

The calculations of the fruit statistic prediction method are shown below. Data from 2003 and 2004 was used to predict the data of 2005 (which was also known). Three fruit statistics from individual producers were targeted: Crop yield (kilograms), Average fruit size (mm) and quality (proportion of Grade 1 fruit). Using the inverse of the method described in Section 4.3 (p.61), with the ε coefficient set as a variable, the weight assigned to the two years were calculated by minimising the error in predicting the third years actual data.

CROP YIELD							Coefficient ε	Error
Fruit & Producer	Mass (kg)			Proportion			0.8887	1.084
	2003	2004	2005	2003	2004	2005	2005 – Predicted	Abs error
Navels 21	3977807	3315831	2582539	2.62	2.49	2.21	2.50	0.29
Navels 22	1063674	1087961	779956	0.70	0.82	0.67	0.80	0.14
Navels 23	1038811	977907	849656	0.68	0.73	0.73	0.73	0.00
Navels 24	301296	326827	360570	0.20	0.25	0.31	0.24	0.07
Navels 25	1206075	951459	1257676	0.79	0.71	1.08	0.72	0.36
Total	**1517533**	**1331997**	**1166079**					
Valencia 21	1457923	1817920	1009050	1.62	1.65	1.53	1.64	0.12
Valencia 23	342580	389940	313215	0.38	0.35	0.47	0.36	0.12
Total	**900252**	**1103930**	**661133**					

FRUIT SIZE							Coefficient ε	Error
Fruit & Producer	Diameter (mm)			Proportion			0.7389	0.157
	2003	2004	2005	2003	2004	2005	2005 – Predicted	Abs error
Navels 21	75.54	79.64	79.65	0.99	1.00	0.96	0.99	0.03
Navels 22	80.88	79.19	82.43	1.06	0.99	1.00	1.01	0.01
Navels 23	76.62	83.20	85.54	1.00	1.04	1.03	1.03	0.00
Navels 24	73.82	79.00	83.06	0.97	0.99	1.00	0.98	0.02
Navels 25	75.10	78.95	82.63	0.98	0.99	1.00	0.99	0.01
Total	**76.39**	**79.99**	**82.66**					
Valencia 21	75.40	73.90	81.35	0.98	0.97	1.01	0.97	0.04
Valencia 23	77.75	78.39	79.48	1.02	1.03	0.99	1.03	0.04
Total	**76.58**	**76.14**	**80.41**					

FRUIT QUALITY							Coefficient ε	Error
Fruit & Producer	Proportion Grade 1			Proportion			0.8431	0.255
	2003	2004	2005	2003	2004	2005	2005 – Predicted	Abs error
Navels 21	0.72	0.73	0.62	1.01	1.05	1.06	1.05	0.02
Navels 22	0.73	0.63	0.48	1.03	0.90	0.82	0.92	0.10
Navels 23	0.62	0.68	0.55	0.87	0.97	0.94	0.96	0.01
Navels 24	0.81	0.79	0.65	1.14	1.14	1.12	1.14	0.02
Navels 25	0.68	0.65	0.61	0.96	0.93	1.05	0.94	0.11
Total	**0.71**	**0.70**	**0.58**					

APPENDIX G

FRUIT PACKAGING TIME STUDY

A study was conducted at GHC to estimate the time it takes to pack fruit into cartons. The results are presented in Section 5.6.1 (p.85), and the *observed data* and analysis are presented below.

		Average	**Std Dev**	**95% range** **Upper**	**Lower**	**±**	
Average of time/fruit	**Unwrapped**	**0.631**	0.078	0.477	0.785	**0.154**	*seconds/fruit*
0.746 *seconds/fruit*	**Wrapped**	**0.855**	0.112	0.636	1.075	**0.220**	*seconds/fruit*

OBSERVED DATA						**Time/fruit**			
Per layer	**Fruit Count**	**Wrapped**	**Person**	**Layer**	**Seconds**	*seconds /fruit*	**Person Average**	**Person Deviation**	**Time/fruit minus deviation**
21	105	0	1	2	13	0.619			0.698
21	105	0	1	4	10	0.476			0.555
21	105	0	1	2	12	0.571			0.650
21	105	1	1	3	17	0.810			0.888
21	105	1	1	5	15	0.714			0.793
21	105	1	1	1	17	0.810	0.667	-0.079	0.888
21	105	0	2	2	21	1.000			0.584
21	105	0	2	4	18	0.857			0.441
21	105	1	2	1	33	1.571			1.155
21	105	1	2	3	27	1.286			0.869
21	105	1	2	5	23	1.095	1.162	0.416	0.679
21	105	0	3	4	12	0.571			0.492
21	105	1	3	3	18	0.857			0.777
21	105	1	3	5	22	1.048	0.825	0.080	0.968
16	64	0	4	1	11	0.688			0.766
16	64	0	4	3	8	0.500			0.579
16	64	1	4	2	13	0.813	0.667	-0.079	0.891
16	64	0	5	1	11	0.688			0.673
16	64	0	5	3	8	0.500			0.485
16	64	0	5	1	11	0.688			0.673
16	64	1	5	2	15	0.938			0.923
16	64	1	5	4	14	0.875			0.860
16	64	1	5	2	14	0.875	0.760	0.015	0.860
16	64	0	6	1	13	0.813			0.621
16	64	0	6	3	13	0.813			0.621
16	64	1	6	4	20	1.250			1.058
16	64	1	6	2	14	0.875			0.683
16	64	1	6	4	15	0.938	0.938	0.192	0.746
16	64	0	7	1	9	0.563			0.631
16	64	0	7	3	10	0.625			0.694
16	64	0	7	1	10	0.625			0.694
16	64	1	7	2	11	0.688			0.756
16	64	1	7	4	13	0.813			0.881
16	64	1	7	2	12	0.750	0.677	-0.069	0.819
18	72	0	8	1	9	0.500			0.704
18	72	0	8	3	8	0.444			0.648
18	72	1	8	2	12	0.667			0.871
18	72	1	8	4	10	0.556	0.542	-0.204	0.759
18	72	0	9	1	8	0.444			0.634
18	72	0	9	3	9	0.500			0.690
18	72	0	9	1	8	0.444			0.634
18	72	1	9	2	11	0.611			0.801
18	72	1	9	4	14	0.778	0.556	-0.190	0.968
18	72	0	10	1	10	0.556			0.676
18	72	0	10	3	10	0.556			0.676
18	72	1	10	2	11	0.611			0.732
18	72	1	10	4	14	0.778	0.625	-0.121	0.898

APPENDIX H

CAPESPAN CARTON & PALLET GUIDE

4. CARTON LIST

Code	External dimensions (mm)	Brand	Carton colour	Colour of printing	Cartons/palle
Telescopic cartons					
A07C	400 x 300 x 150	Outspan	kraft	Blue & orange	130
A07C	400 x 300 x 150	Goldland (lemons)	kraft	Green & yellow	130
A10C	400 x 300 x 194	Cali	white	Blue, yellow, orange & green	100
A15C	400 x 300 x 270	Outspan	kraft	Blue & orange	70
A15C	400 x 300 x 270	Bella Nova	white	Green & blue	70
A15C	400 x 300 x 270	Thandi	Kraft	Yellow, Orange & black	70
A15C	400 x 300 x 270	Goldland (lemons)	Kraft	Green & yellow	70
A15C	400 x 300 x 270	Goldland (oranges)	kraft	Blue & orange	70
A15C	400 x 300 x 270	Goldland (generic)	kraft	Blue & orange	70
E10C	500 x 300 x 174	Outspan	kraft	Blue & orange	88
D15C	600 x 400 x 160	Outspan	kraft	Blue & orange	60
D15C	600 x 400 x 160	Goldland (generic)	kraft	Blue & orange	60
E15C	600 x 400 x 170	Outspan	kraft	Blue & orange	55
G15C	600 x 400 x 215	Outspan	kraft	Blue & orange	45
G15C	600 x 400 x 215	Goldland (generic)	kraft	Blue & orange	45
Display cartons					
E02I	296 x 244 x 102	Outspan	kraft	Blue & orange	304
A02S	297 x 197 x 111	Outspan	Brown "wood colour"	Blue & orange	360
B05D	500 x 300 x 100	Outspan	kraft	Blue & orange	152
E10D	500 x 300 x 170	Outspan	kraft	Blue & orange	88
E10D	500 x 300 x 170	Goldland	kraft	Blue & orange	88
A06D	600 x 400 x 100	Outspan	kraft	Blue & orange	100
C15D	600 x 400 x 146	Outspan	kraft	Blue & orange	65
C15D	600 x 400 x 146	Rico	white	Green, yellow & black	65
C15D	600 x 400 x 146	Ica	Kraft	Black & red	65
C15D	600 x 400 x 146	Thandi	Kraft	Yellow, Orange & black	65
C15D	600 x 400 x 146	-	Green	Kraft	65
C15D	600 x 400 x 146	-	Black	Kraft	65
D15D	600 x 400 x 160	Outspan	Kraft	Green & blue	60
D15D	600 x 400 x 160	Bella Nova	White	Blue & orange	60
D15D	600 x 400 x 160	Thandi	Kraft	Yellow, Orange & black	60
E15D	600 x 400 x 170	Outspan	kraft	Blue & orange	55
E15D	600 x 400 x 170	Goldland	kraft	Blue & orange	55
E15D	600 x 400 x 170	Bella Nova	White	Green & blue	55
E15D	600 x 400 x 170	Rico	White	Green, yellow & black	55
E15D	600 x 400 x 170	Naturally Tasty	Green	Green	55
E15D	600 x 400 x 170	Thandi	Kraft	Yellow, Orange & black	55
E15D	600 x 400 x 170	Cevita	White	Orange, green & blue	55
E15D	600 x 400 x 170	Ica	Kraft	Black & Red	55
E15D	600 x 400 x 170	-	Black	Kraft	55
E15D	600 x 400 x 170	-	Green	Kraft	55
G15D	600 x 400 x 170	Outspan	kraft	Blue & orange	45
G15D	600 x 400 x 170	Goldland (generic)	kraft	Blue & orange	45

Bins & Crates

Code	Description	External dimensions (mm)	Nett. mass	Bins/crates per pallet
J38B	carton bin	1210 x 1010 x 750	380kg	3
J50B	carton bin	1210 x 1010 x 1050	500kg	2

APPENDIX I

TESTING OF FLOW CONTROL ALGORITHM

To assign packing tables to the multiple incoming flows of a flow control unit an algorithm was described in Section 5.7 on p.89. The algorithm was tested three times by comparing the results of the assignment algorithm to that of the Excel Add-in *What's Best!® version 7.0* from Lindo Systems Inc. The results of the first test are presented below. For each test the *input flows* $\mathbf{I}$, the values of the *allowable assignment matrix* $\mathbf{C}$ and the *table capacity per flow matrix* $\mathbf{R}$ were varied. It was found that the assignment algorithm and *What's Best!* made identical assignments.

Input j		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Total**	**Unit**
Input Flows i		**3.40**	**4.40**	**10.80**	**11.60**	**18.45**	**15.40**	**4.80**	**1.50**	**70.35**	*fruit/second*
Packing Table i	**1**	0	1	0	1	0	1	1	0		0/1
	2	1	0	1	0	1	0	0	1		0/1
	3	1	1	0	1	1	1	1	1		0/1
	4	0	1	0	1	0	1	0	1		0/1
	5	1	0	1	0	1	0	1	0		0/1
	6	1	1	0	1	0	1	0	1		0/1
	7	0	0	1	0	1	0	1	0		0/1
Matrix *C* Allowable assignments	**8**	1	1	0	1	0	1	0	1		0/1
	9	0	0	1	0	1	0	1	1		0/1
	10	1	1	0	1	0	1	1	0		0/1
	11	0	1	1	1	0	1	1	1		0/1
	12	1	0	1	1	1	0	1	0		0/1
	13	1	0	0	1	1	0	1	0		0/1
	14	1	0	1	0	0	1	1	1		0/1
	15	0	1	0	1	1	1	0	0		0/1
Packing Table i	**1**	0.00	5.97	0.00	5.43	0.00	5.01	4.74	0.00		*fruit/second*
	2	6.19	0.00	5.73	0.00	5.24	0.00	0.00	4.41		*fruit/second*
	3	6.19	5.97	0.00	5.43	5.24	5.01	4.74	4.41		*fruit/second*
	4	0.00	5.97	0.00	5.43	0.00	5.01	0.00	4.41		*fruit/second*
	5	6.19	0.00	5.73	0.00	5.24	0.00	4.74	0.00		*fruit/second*
	6	6.19	5.97	0.00	5.43	0.00	5.01	0.00	4.41		*fruit/second*
	7	0.00	0.00	15.29	0.00	13.97	0.00	12.64	0.00		*fruit/second*
Matrix *R* Table capacity per flow	**8**	10.32	9.95	0.00	9.05	0.00	8.35	0.00	7.35		*fruit/second*
	9	0.00	0.00	9.56	0.00	8.73	0.00	7.90	7.35		*fruit/second*
	10	10.32	9.95	0.00	9.05	0.00	8.35	7.90	0.00		*fruit/second*
	11	0.00	9.95	9.56	9.05	0.00	8.35	7.90	7.35		*fruit/second*
	12	10.32	0.00	9.56	9.05	8.73	0.00	7.90	0.00		*fruit/second*
	13	10.32	0.00	0.00	9.05	8.73	0.00	7.90	0.00		*fruit/second*
	14	10.32	0.00	9.56	0.00	0.00	8.35	7.90	7.35		*fruit/second*
	15	0.00	9.95	0.00	9.05	8.73	8.35	0.00	0.00		*fruit/second*
Packing Table i	**1**	0	0	0	1	0	0	0	0	**1**	0/1
	2	0	0	1	0	0	0	0	0	**1**	0/1
	3	0	0	0	0	1	0	0	0	**1**	0/1
	4	0	1	0	0	0	0	0	0	**1**	0/1
	5	0	0	1	0	0	0	0	0	**1**	0/1
	6	1	0	0	0	0	0	0	0	**1**	0/1
	7	0	0	0	0	1	0	0	0	**1**	0/1
Matrix x Table assignments	**8**	0	0	0	0	0	1	0	0	**1**	0/1
	9	0	0	0	0	0	0	0	1	**1**	0/1
	10	0	0	0	0	0	1	0	0	**1**	0/1
	11	0	0	0	1	0	0	0	0	**1**	0/1
	12	0	0	0	0	0	0	1	0	**1**	0/1
	13	0	0	0	0	0	0	0	0	**0**	0/1
	14	0	0	0	0	0	0	0	0	**0**	0/1
	15	0	0	0	0	0	0	0	0	**0**	0/1
Allocated capacity		**6.19**	**5.97**	**11.47**	**14.48**	**19.21**	**16.71**	**7.90**	**7.35**	**89.27**	*fruit/second*
Overalloc. capacity		**2.79**	**1.57**	**0.67**	**2.88**	**0.76**	**1.31**	**3.10**	**5.85**	**18.92**	*fruit/second*

APPENDIX J

TABLES OF THE COMPUTER MODEL

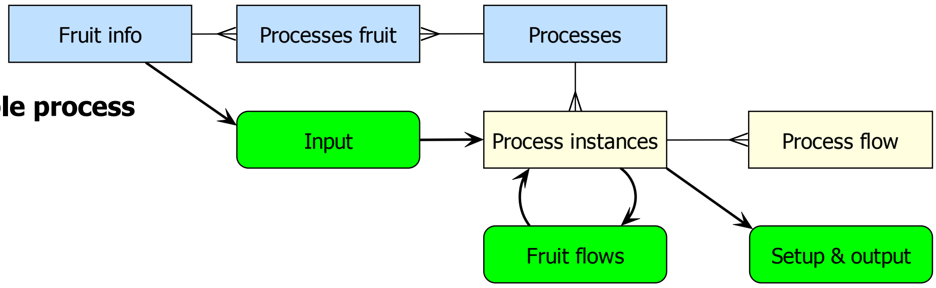
FRUIT INFO: For each fruit type

Parameters of size and quality distribution

Volume filling parameters (ρ_{AKV})

Roller filling correction

Conveyor belt area filling factor



PROCESSES: For every possible process

Generic process type

Capacity calculation parameters

PROCESSES FRUIT: For each *process-fruit* combination

Compatible?

Allowable processing speed/time

Required processing speed/time

PROCESS INSTANCES: All *processes* found in a specific packing line

Process ID

Capacity Parameters

Setup possibilities

Number of Inputs/Outputs

PROCESS FLOW: Linking all *process instances*

Input Process ID

Output Process ID

Output Number

INPUT: Production run specific

Number of containers

Estimation of fruit distributions (Colour, size, quality)

FRUIT FLOWS: For each *process instance* – Production run specific

Process ID

Number of fruit (Max & Min)

Estimation of fruit distributions (Colour, size, quality)

SETUP & OUTPUT: For each *process instance* and Production run specific

Setup of each process instance

Recommended feed rate