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An Integrated Approach to Waste and Energy Minimization in the Wine Industry: A Knowledge-Based Decision Methodology

by

Ndeke Musee

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Promoters:

Professor L. Lorenzen　　Professor C. Aldrich

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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.

Ndeke Musee 20th, September, 2004

Synopsis

The importance of waste management is growing rapidly for several reasons. These reasons include the escalating cost of wastewater treatment and cleaning chemicals, an emerging trend of onerous regulatory regime regarding effluent disposal from governments, rising public awareness on the adverse effects of industrial waste as well as drastic reduction in water resources in the winegrowing regions. In addition, owing to the large energy demand for refrigeration purposes for high quality wine production and rapidly increasing energy costs, the challenges of energy management in the wine industry were also investigated.

In order to address these challenges adequately, the solutions were derived via the integration of two disciplines: environmental science (waste and energy management) and computer science (applications of artificial intelligence). Therefore, the findings reported from this study seek to advance knowledge through the construction of decision support systems for waste and energy management in circumstances where conventional mathematical formalisms are inadequate. In that sense, the dissertation constitutes interdisciplinary research on the application of integrated artificial intelligence technologies (expert systems and fuzzy logic) in designing and developing decision tools for waste and energy management in the wine industry.

The dissertation first presents the domain of interest, where the scope and breadth of the problems it addresses are clearly defined. Critical examination of the domain databases revealed that data, information, and knowledge for waste and energy management in the wine industry are generally incomplete and lack structure overall. Owing to these characteristics, a hybrid system approach was proposed for the development of decision support systems based on fuzzy logic. The integrated decision support systems were developed based on an object-oriented architecture. This approach facilitated the flexible design required for waste and energy management-related complex problem-solving.

To illustrate the applicability of the off-line decision tools developed, several case studies mirroring on actual industrial practices were considered. These systems were found to be robust and yielded results that were in accordance with actual industrial practices in the wine industry. Furthermore, they provided intelligent suggestions in scenarios where there was minimal information, and under certain instances they offered feasible suggestions in circumstances where a human novice could have problems in making the right decisions.

Oorsig

Die belangrikheid van afvalbestuur neem om verskeie redes vinnig toe. Die redes sluit in die eskalerende koste van afvalwaterbehandeling en skoonmaakmiddels, streng regulatoriese vereistes van regeringskant met betrekking tot die verwydering van uitvloeisels, toenemende openbare bewustheid van die nadelinge effekte van nywerheidsafval, sowel as die drastiese afname in waterbronne in wynproduserende omgewings. Daarby, a.g.v. die groot energieverbruik wat deur die verkoeling van hokwaliteitwyn vereis word en die snelgroeiende energiekoste, is die uitdagings van energiebestuur in die wynbedryf ook ondersoek.

Ten einde die uitdagings die hoof te kon bied, is oplossings gevind deur die integrasie van twee disciplines: omgewingswetenskap (afval- en energiebestuur) en rekenaarwetenskap (toepassings van kunsmatige intelligensie). Gevolglik is daar deur die bevindinge van die studie gepoog om kennis te bevorder deur die konstruksie van besluitnemingsondersteuningstelsels vir afval- en energiebestuur onder omstandighede waar konvensionele wiskundige algoritmes ontoereikend sou wees. In die opsig verteenwoordig die proefskrif interdissiplinre navorsing in die toepassing van gentegreerde kunsmatige intelligensietegnologie (kundige stelsels en wasige logika) in die ontwerp en ontwikkeling van besluitnemingshulpmiddels vir afval- en energiebestuur in die wynindustrie.

Die proefskrif baken eers die probleemgebied af, waarna die bestek en omvang van die probleme waarop die werk gemik is duidelik gedefinieer word. Kritiese ondersoek van die databasisse in die domein het getoon dat die data, informasie en kennis oor afval- en energiebestuur in die wynbedryf in die algemeen onvolledig en gebrekkig gestruktureer is. A.g.v. di eienskappe, is 'n hibriede stelselbeandering voorgestel vir die ontwikkeling van besluitnemingstelsels gegrond op wasige logika. Die gentegreerde besluitnemingsondersteuningstelsels is ontwikkel op 'n objek-georinteerde argitektuur. Die benadering het die daarstelling van 'n buigsame ontwerp wat benodig word vir komplekse probleemoplossing in afval- en energiebestuur vergemaklik.

Om die toepaslikheid van die aflynige besluitnemingshulpmiddels wat ontwerp is, te illustreer, is verskeie gevallestudies wat werklike industrile praktyk uitbeeld beskou. Die

stelsels was robuust en het resultate gelewer wat in ooreenstemming was met werklike industrile praktyke in die wynnywerheid. Die kundige stelsels het verder intelligente voorstelle gemaak in scenarios waar daar minimale informasie beskikbaar was, en onder sekere omstandighede het hulle realistiese oplossings voorgestel waar 'n onkundige persoon probleme sou gehad he tom die regte besluite te kon neem.

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Acknowledgments

This work is a participatory enterprise as much as the knowledge domain it examines. As such, a highly integrated network of various components has immensely contributed and played unique roles whose end product is the research findings reported in this dissertation.

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To my wife Ngina and daughter Kathini... your love and support is invaluable. In memory of my dearest parents: Kathini and Musee.

Chapter 1

Introduction

1.1 Study Motivation

The progress in human development is becoming increasingly dependent on the surrounding natural environment and may be restricted by its future deterioration. The increasing rhythm of industrialization, urbanization and population growth, which our planet has faced in the last phase of the 20^{th} century, has forced society to consider whether human beings are changing the very conditions essential to life on earth (Thomson, 1997). The environmental degradation associated with such growth has a multiplicity of negative effects on the quality of water, air and soil and hence plant, animal and human life (El-Swaify and Yakowitz, 1998).

This paradigm shift has generated growing environmental concerns from communities, civil societies, governments, business fraternities, judiciaries, and other stakeholders, posing new challenges to the process industries including the wine industry. However, in recognizing the need to meet these challenges, achieve industrial production goals, and protect the environment from negative impacts of excessive industrial effluent, sustainable development (WCED, 1987; Bakshi and Fiksel, 2003; Sikdar, 2003a; Sikdar, 2003b; MacNeil, 1989; Ruckelshaus,1989) has been proposed as the way forward. The rallying wisdom behind sustainable development is to restrain the high rate of raw material use and nonrenewable energy consumption now, so as to reserve sufficient quantities for many future generations to fulfill their own ambitions of living standards.

Secondly, another significant challenge facing the process industry is an increasingly onerous regulatory regime from governments regarding environmental issues. In the recent past, a number of countries (e.g. South Africa (Müller, 1999), Greece (Katsiri and Dalou, 1994) and France (Massette, 1994)) have promulgated new legislation governing waste management particularly in the wine industry. The introduction of stringent environmental legislation has compounded the complex twin problem of wine production and the protection of the environment from winery effluents and emissions.

Over the years, end-of-pipe (additive) technologies, notably treatment and disposal techniques have been the core waste management approaches widely practiced in the wine industry (Recault, 1998; Marais, 2001; Shepherd, 1998; Shepherd and Grismer,1999). However, recent trends are rendering these approaches unattractive owing to the high capital investment required for land acquisition, actual waste treatment plant construction, and operational and managerial costs for waste treatment and consequent disposal. Besides these huge non-profitable expenses, global markets are becoming exceedingly competitive with a rising demand on products that are environmentally friendly. In this sense, both manufacturing processes and final products are expected to impart minimal footprints to the environment (Wackernagel and Rees, 1996). This paradigm has consequently generated constraints to wine makers in their endeavor to achieve what is currently regarded as the "triple bottom line", namely economic development, sound environmental stewardship, and societal equity (Elkinfton, 1997).

Winetech (Wine Industry Network for Expertise and Technology), the research structure of the wine industry in South Africa, in collaboration with the Center for Process Engineering at the University of Stellenbosch, Nietvoorbij Center for Wine and Vine, Institute for Agricultural Engineering and Prolor Techpros (Pty) Ltd, mounted a multidisciplinary research group to develop appropriate strategies to address several challenges facing the wine industry. The primary objective of the group was to investigate possible alternative strategies that have the potential to improve waste and energy management in the wine industry and meet current and future global environmental principles.

For the research group to achieve its objective, a Winetech Environmental Management Program was launched and some of its findings have been documented by Lorenzen and co-workers (Lorenzen, et al., 2000; Bezuidenhout et al., 2000). It is from the findings of the multidisciplinary research work, that the need for the development of a decision support system for the waste management in the wine industry was identified. Thus, the results acquired from the multidisciplinary study through data collection and experiments formed a reasonable part of the data, information and knowledge that was used in the design and development of a knowledge-based decision support system reported in this dissertation.

Based on the research findings mentioned above, valuable knowledge, information and expertise in waste and energy management in the South African wine industry was acquired. Initially, attempts were made to analyze the data using classical models in pursuit of developing decision support systems (DSSs) for the wine industry.

However, although there was to a certain degree success in manipulating the data bases for individual plants using classical approaches, critical limitations were apparent. In particular, classical approaches were incapable of dealing with qualitative data and information adequately as the wine industry environmental knowledge domain is highly unstructured. In addition, the data and information in this domain contained numerous uncertainties which classical data processing approaches are ill-designed to handle effectively. Some of the limitations for classical approaches in designing decision support tools for the environmental management domains can briefly be summarized as follows:

- Most data and information in the environmental domain contains qualitative features which are essential for problem solving. However, classical mathematical algorithms are ill-equipped to represent such data and information in decision making scenarios.
- The classical mechanistic models can only be valid when applied appropriately to a particular plant. In this case, findings are difficult to transfer to other plants owing to the unforeseen circumstances or differences arising from operational practices, which are a fundamental feature in the wine industry (winemaking practices vary as widely as there are wineries).
- The classical models are not easy to develop and in many cases they are inaccurate and overly simplistic representations of reality.
- A high degree of continuously changing operational conditions in the wine industry throughout the year in any given winery, renders classical models inadequate as they

require steady state conditions. This is because the vinification process consists of batch or semi-batch operations, which experience wide control variations, that occur instantaneously resulting in wastes that exhibit both temporal and spatial variations.

- One unique characteristic of the winemaking process is that it is considered by some practitioners to be an art and therefore quantitative data and process control are not a primary production goal in monitoring process progression, which is in striking contrast to that of the chemical industry. This renders the application of quantitative data driven decision support system approaches very difficult to implement in this domain.
- Environmental problems are ill-structured, where the data contains numerous non-statistical uncertainties which are difficult to handle using classical models. Besides, such models require on-line logging systems (e.g. sensors and actuators) for the timely generation of the required input and output data for their effective functionality. However, in most wineries such gadgets for data acquisition are lacking. This is because they are expensive and secondly, on-line data logging systems would require long period of time to adequately analyze some of the key important effluent variables[1]. This diminishes the usefulness of such models as the time delay requirement reduces their suitability in the wine industry.

In an endeavor to utilize the expertise gained from the collaborative Winetech research findings, and taking into account the nature of data, information and knowledge available in this domain, the knowledge-based systems (KBS) approach was chosen as a viable alternative for addressing some of the challenges stated above. KBS is an artificial intelligence (AI) technology that assimilates and reasons with knowledge obtained from experts with a view to solving problem(s) and giving advice in a specific domain.

The KBS have shown promising results due to its capabilities in representing heuristic reasoning and working with large amounts of symbolic, uncertain, inexact data and qualitative information which human users (e.g. operators, decision-makers) are able to comprehend. In contrast, classical approaches (quantitative modeling) lack the capability

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[1] Some data determination requires hours or even several days to synthesize e.g. carbon oxygen demand (COD) and biological oxygen demand (BOD), which are critical in evaluating the quality of effluent generated.

to deal with such tasks adequately and, in many cases, managers and other decision makers do not understand the complicated formulas used in them, and thus do not believe in them (Chen and Gorla, 1998).

The KBS is comprised of expert systems (ES) and fuzzy logic (FL) technologies. Both technologies permit the implementation of human-like reasoning strategies, which have hitherto defied solution by any of the quantitative mathematical approaches whose prime desiderata are precision, rigor, and certainty. Moreover, the KBS technologies allows taking advantage of the knowledge gained by the operators and experts through experience over the years to derive robust solutions in ill-defined domains, such as the case with environmental problems, particularly in the wine industry. Therefore, the successful development of decision making tools reported in this dissertation can be attributed to the KBS capability to use linguistic rules or conditional statements elicited from human experts and other sources (e.g. textbooks, journals, plant manuals). The acquired knowledge was coded into knowledge base and was crucial in deriving conclusions or generating new solutions based on the inputs specified by the user.

This dissertation therefore presents the design and implementation of two off-line knowledge-based decision support systems to enhance decision making processes in the wine production industry with regard to waste and energy management. The approach has several advantages. Firstly, it provides expertise to the users enhanced through the integration of large knowledge data bases from wide ranging disciplines (e.g. engineering, environmental science, mathematics, oenology, etc.). Secondly, the system does not require large computational power to arrive at the solutions. Thirdly, the KBS provides intelligence and thus, can derive decisions (solutions) and/or elicit alternatives to the problem owing to its inherent reasoning capabilities. Fourthly, the decision-making software model developed can also be used as a training tool for wine industry personnel on aspects of waste and energy management.

In the wine industry, other successful computer-based decision support systems using AI have been developed to address various specific problems. Some examples of AI based applications in this domain include:

- Classification of aged wine distillates using neurofuzzy (Raptis et al., 2000) and fuzzy logic (Tsekouras et al., 2002) technologies.

- Optimization of wine fermentation processes using artificial neural networks (ANN) (Vlassides, 1998; Vlassides et al., 2001; Cleran et al., 1991).

- Application of fuzzy logic control in:
  (i) white wine fermentation kinetics (Martinez et al., 1999) and,
  (ii) anaerobic digestion of winery distillery wastewater treatment (Estaben et al., 1997; Polit et al., 2001; Genovesi et al., 1999).

- On-line diagnostic detection and analysis of abnormalities using a hybrid fuzzy neural network in a fluidized bed reactor for the treatment of wine distillery wastewater (Steyer et al., 1997).

- An expert system (ES) for the management of *Botrytis cinerea* disease (Ellison et al., 1998; Ellison et al. 1998) and anntelligent decision model for the simulation of winery operations (Nievere et al., 1994).

On the other hand, several cases have been reported in the literature, where classical approaches have been employed in the wine industry. Some of the reported cases in this domain are as follows:

- Simulation of wine production using linear programming (Tower, 1979).

- Identification of the most effective strategies for waste management, with a software package developed by Balsari and Airoldi (1998).

- Use of a mathematical empirical model to predict heat-generation kinetics during fermentation processes (Lopez and Scanell, 1992).

- An empirical mathematical model for the prediction of production and environmental costs based on input resource consumption (Sheridan, 2003).

No previous attempts have been reported in the wine industry literature where the KBS approach has been employed to address waste and energy challenges in the vinification processes. The thrust of this research was to develop an integrated intelligent decision support systems for waste and energy management in the wine industry by using KBS technologies. ES and FL technologies were used to capture, represent, and provide decision-algorithm for the data and knowledge in this domain.

The ES enhanced the systematic methodology of capturing and representing the data and knowledge in a hierarchical structure in the knowledge base, thus making the system highly flexible. However, most data and knowledge in this domain are highly qualitative or at best, very difficult to define quantitatively. Thus, FL was found to be a suitable platform as a reasoning mechanism for the knowledge base, which has the capability to represent both quantitative and qualitative data and manipulate it appropriately. As a result, the combined technologies yielded a flexible and an integrated knowledge base reasoning system, having the capability to take into account qualitative linguistic variables in the decision making process.

1.2 Study Objectives

The main objective of this dissertation is to report on the development of intelligent decision support systems for enhancing waste and energy management during vinification processes. This entailed the development, implementation and evaluation of each intelligent decision support system. Other specific *sub*-objectives of this dissertation are:

- To review the work carried out by the Winetech research group in waste and energy management and to identify any existing gaps. The identified gaps were to be filled via knowledge elicitation techniques such as interviews and literature reviews. This should lead to the representation of consistent data and knowledge in a manner amenable for automation of waste and energy management in the wine industry.

- To consider the applicability of KBS approaches to waste and energy management in the wine industry through the development of a conceptual system framework and consequent construction of decision support tools using operational knowledge including the experience of personnel (experts and operators).

- To contribute to the study and development of decision tools for waste and energy management with a view to improve productivity, product quality, and the reduction of the environmental burden from winery operations.

- To integrate ES and FL technologies in order to develop a robust diagnostic system with enhanced flexibility and reliability in decision making. This was aimed to ensure robust systems were developed that effectively captured the knowledge adequately in this domain of study.

- To validate the intelligent system through; (i) justification of its suitability for application in vinification processes. (ii) systematically examine the logic and integrity of system's rule base and (iii) verification and evaluation of the system's performance by ascertaining how well it accomplishes the intended role in actual practice in terms of performance levels, usefulness, flexibility and efficiency.

1.3 Structure of Dissertation

This dissertation is structured as follows:

- Chapter 2 deals with standard vinification processes and the most significant processes are reviewed in the first part. A case study is discussed with respect to generic information on inputs and outputs, effluent characteristics, and environmental legislations for a number of countries. Parts two and three briefly summarize waste management approaches and energy management strategies in order to lay the foundations for the choice of scope and breadth of the problem addressed in this dissertation. The chapter closes with a discussion on the significance of defining the system problem boundaries to avoid ambiguities during validation and evaluation of the knowledge bases.

- Chapter 3 provides an overview of AI based technologies that are used for the development and implementation of decision support systems reported in this dissertation. The salient features each technology type possesses, its capabilities and consequent suitability for deployment in the wine industry to solve the energy and waste management challenges are explored. Integration of KBS and FL is explained and the merits of a hybrid system as candidate of choice in implementing automated decision support systems for environmental problems is presented.

- Chapter 4 examines plant-wide waste minimization in a winery through the development of a conceptual framework based on an input/output model. A systematic methodology for deriving possible alternative strategies to waste problems in the wine industry is discussed. The methodology is applied to the wine industry and strategies with potential to minimize or prevent product and byproduct loss, waste generation or offer possibilities for recycling and reuse are presented. The results are presented in tabular format to enhance their suitability to automation during the processes of designing and developing a decision support system for waste minimization in the wine industry.

- Chapter 5 presents a waste minimization index developed for screening and ranking of the alternative strategies derived and discussed in chapter 4. The following sections focus on the development of the knowledge base and the inference mechanism. A case study is presented for the design and development of a fuzzy expert system for waste minimization in the wine industry. The prototype is tested, and the results are presented and discussed based on several possible industrial operational scenarios.

- Chapter 6 is concerned with a case study on energy management at the maceration stage of the vinification process. Factors influencing energy consumption are summarized and alternatives to mitigate against high energy usage are explored. Using the acquired data and knowledge, an intelligent decision support system for energy minimization diagnosis is designed and developed. To illustrate the functionality of the developed system, four worked examples are presented and their results discussed.

- Chapter 7 provides a summary of the main contributions of this work and recommendations for further work.

- Chapter 8 presents the cited literature that provided several fundamentals both in terms of knowledge and tools applied in this study.

The project outline at various stages of its conceptualization, development and implementation are presented in Figure 1.1. The most dominant phases that characterized the development of the knowledge based decision support systems are the intelligence

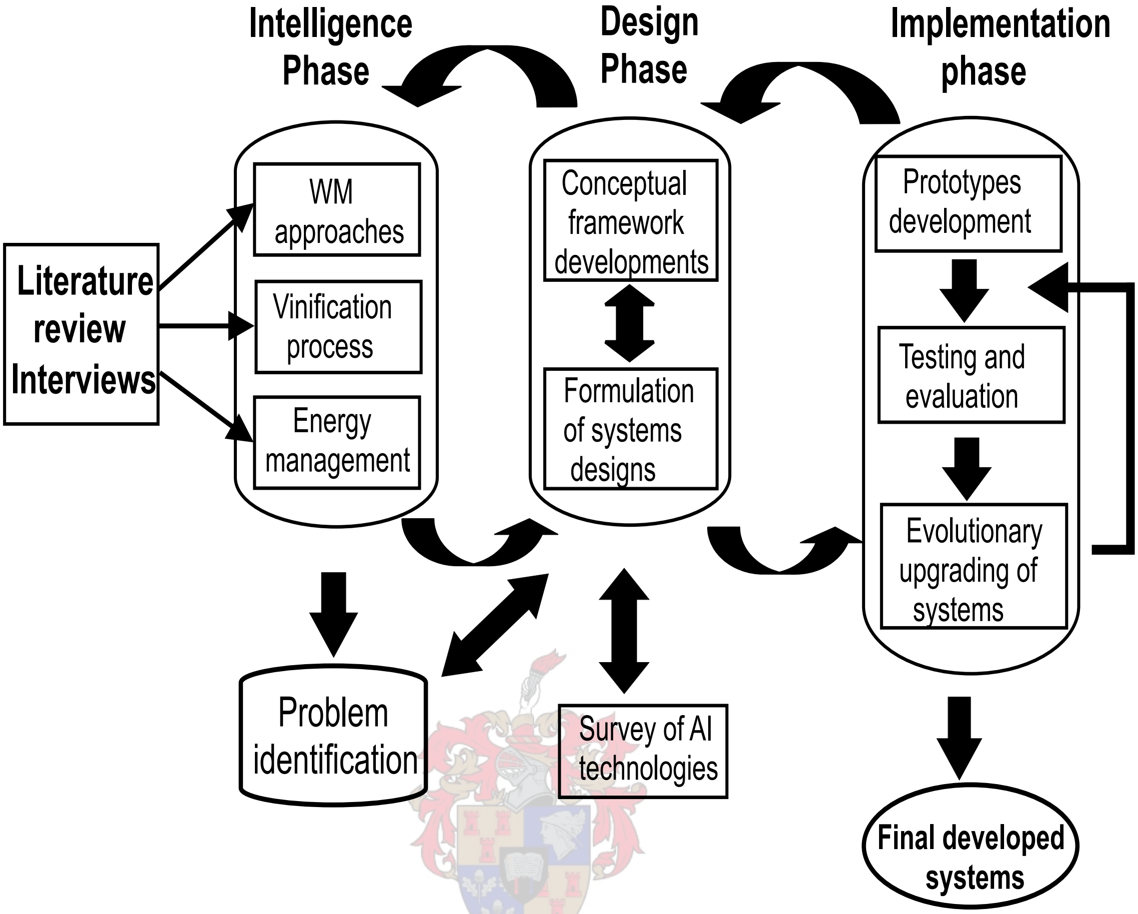

Figure 1.1: Schematic representation of the cyclic project framework.

phase, the design phase and the implementation phase. The intelligence phase focused on the processes that aided in knowledge elicitation from various sources such as the documented literature, waste management experts and the personnel working in the wine industry. This lend to the conceptualization of the challenges to be addressed taking into account the data and knowledge features characterizing the waste and energy management domains in the wine industry.

The second phase entailed the development of various conceptual frameworks that were crucial in analyzing and understanding the acquired data and knowledge. This resulted in a systematic classification of data and knowledge into various entities. Entities in this sense included all sources of wastes, waste causes, different cooling loads, knowledge types, feasible mitigating strategies, among other aspects that were identified as significant in terms of influencing waste and energy management in the wine industry. This objective was accomplished through the identification of all the elements in each problem domain and their features. It is at this phase where feasible artificial intelligence technologies having the capability to address the challenges in the wine industry adequately became explicitly clear.

The first two phases provided a sound foundation for the actual development of the decision support systems softwares. In ensuring robustness and consistency of the knowledge contained in each knowledge base, a modular approach was adopted that facilitated rapid prototyping of the decision support systems. To ensure that all the critical aspects of waste and energy management were sufficiently covered by the developed prototypes, rigorous testing and system evaluations were carried out in each module and stage of the system development. As a result, a cyclic evolutionary pathway approach in developing the knowledge based decision support systems emerged and its framework is schematically illustrated in Figure 1.1.

Chapter 2

Literature Review: The Vinification Process, Waste and Energy Management

A critical review of areas that inform decision making process particularly with respect to waste and energy management during the standard vinification process is essential. Most profoundly this improves the understanding and appreciation of the knowledge domain under investigation in this study. In pursuance of this objective, three broad areas are reviewed. The first part presents the standard vinification process. The basic unit operations and processes of the vinification process are discussed and their contributions with regard to waste generation and energy consumption are highlighted.

The second part is devoted to reviewing waste management approaches developed over the years to address environmental challenges. These approaches are broadly classified as macroscale, mesoscale and operational concepts with respect to their scope and breath in the context of addressing environmental challenges as presently practiced in the wine industry.

The last part discusses energy sources and use in the wine industry, and the integrated approach in finding solutions to the challenge of high energy consumption, high volumes of water released to the environment and the generation of other emissions to air and water, specifically as a result of the cooling processes. The chapter closes by discussing the significance of defining the system problem boundaries in order to derive feasible alternatives and in validating the systems for both energy and waste management.

Part I: Industrial Vinification Process

2.1 Process Description

Wine is an alcoholic beverage produced by the fermentation of sugars in grape juices. Different wine-end products such as still table wines, sparkling wines, desert wines, sweet table wines, and brandy are produced. These grape end-products are a function of the chemicals added during vinification, the procedure used in processing a particular batch of grape inputs, the chemical composition of the processed grapes, grape cultivar type, quality of the grapes and the desired level of alcohol content in the final product.

In the literature (Rankine, 1989; Boulten et al.,1998; USEPA, 1995, Ribéreau-Gayon et al., 1999), detailed descriptions of the standard winemaking process has been presented. However, in this case, only basic generic wine production processes are described and an attempt is made to identify wastes generated and energy consumption with respect to these processes. The main vinification processes for both white and red wines are shown in Figure 2.1. The basic vinification process stages include several processes as described in the following paragraphs:

2.1.1 Harvesting

Grape harvesting is the initial stage of the vinification process. Harvesting of grapes is often done during the cooler periods of the day to prevent or retard heat buildup in the grape. Harvesting time depends on the ripeness of the grapes which should be in the range of 19^o-24^o Balling[1], and is, to a large extent, a function of cultivar type, and the wine type to be produced. Depending on the grape temperature, the grapes should be cooled as soon as they are harvested and transportated to the winery to prevent flavor deterioration during crushing and reduce the refrigeration load at the first cooling process.

During the harvesting process, which is either done with the use of machines or hand picking, some grapes are bruised, resulting in the release of the juice. To avoid the oxidative degradation of the juice, which leads to growth of yeast or bacteria, sulphur based compounds (e.g. potassium or sodium metabisulphite) are added to the grapes as

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[1] Balling refers to the number of grams of cane or beet sugar in 100 grams of water at 15.6^{o}C (Rankine, 1989).

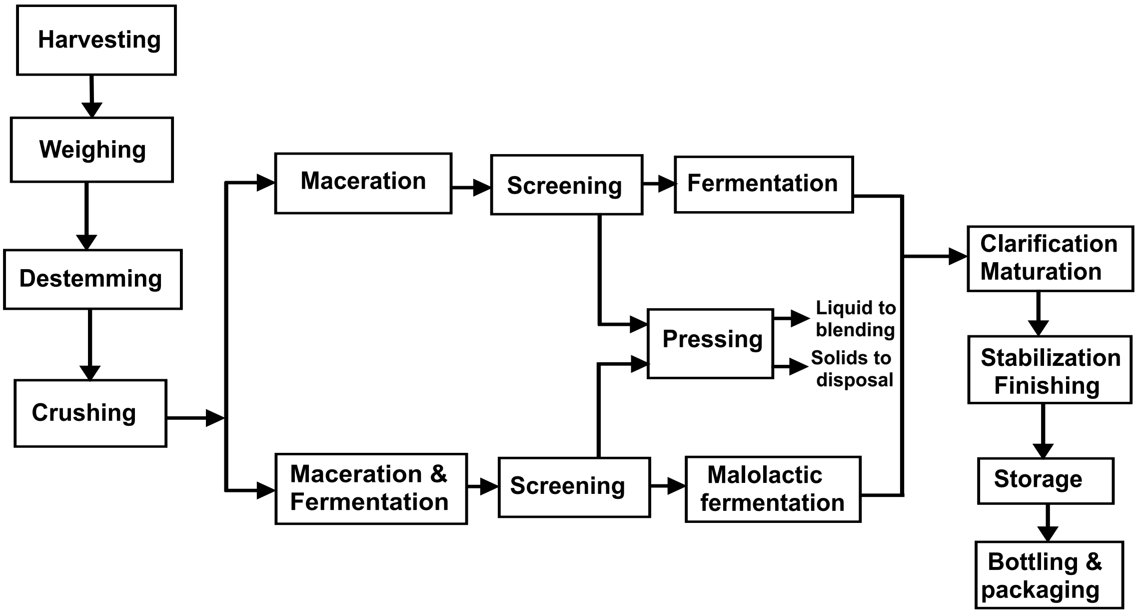

Figure 2.1: Schematic representation of industrial vinification process for both white and red wine.

soon as possible after harvest.

Waste generation: Inevitable wastes resulting from the harvesting process includes stems, skins, leaves, and in some special cases cardboards[2].

Energy consumption: Temperature of the grapes at harvesting time, influences the quantity of refrigeration load for the grape juice and wine. For instance, the higher the temperature of the mash, the higher the required cooling load in the first cooling process at the maceration stage.

2.1.2 Destemming and Crushing

The grapes are immediately destemmed and crushed after harvesting. The destemming process entails the removal of stems, leaves, and stalks prior to crushing. This controls the production of undesirable compounds in the wine during the subsequent production steps. Destemming occurs in a perforated cylinder that rotates in such a manner that it prevents the passage of stems, stalks and leaves but allows the grapes to pass through. The grapes fall immediately into the crusher.

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[2] Cardboards are used for grape transportation as a means of temperature control (to prevent grape heat load increase owing to the heat absorption from the surroundings during transportation).

Crushing of grapes after the destemming process may permit the fermentation to commence as soon as possible and limit microbial contamination although in certin cases the juice is kept overnight for settling and cold soaking. In practice, there are three most common crushing procedures. These are: (i) the pressing of grapes against a perforated wall; (ii) passing grapes through a set of rollers and (iii) by use of centrifugal force.

The basic principle in crushing is to ensure that the grapes are opened to release the juice but avoid breaking the seeds, which can cause harsh characteristics in the wine. For reasons of efficiency and convenience, currently destemming and crushing are often performed at the same time using a crusher-stemmer (a combined unit for the formerly single equipment). At this stage, liquefied sulphur dioxide is added to the crushed grape mass to control wine oxidation, growth of wild yeasts, and spoilage of wine quality through bacterial activity.

Waste generation: Operations linked to the destemming and crushing processes generates wastes such as greenhouse gases (e.g. sulphur dioxide) and solids such as stalks, stems, and leaves.

Energy consumption: At this stage of production, energy consumption can be very high as a result of using of old and inefficient equipment, operating under capacity, lack of good energy housekeeping practices such as turning off equipment when not in use or through lack of preventive and regular maintenance of electrical motors in destemming and crushing machines.

2.1.3 Maceration

With the use of pumps and the piping networks, the juice resulting from the crushing process is transfered to various types of tanks for the maceration process to commence. Maceration involves the breaking down of grape solids and release of phenolics following crushing. The maceration occurs through two mechanisms namely; the mechanical crushing process which is predominant and a small portion as a result of enzymatic breakdown of solids.

It should be noted that in the red wine production, the grape juice is not separated from the skins, seeds, and pulp, and in certain wineries it marks the beginning of the fermentation process. The reason for allowing the skins in red wine during the maceration and fermentation processes is to allow the extraction of red color, tannins and flavor characteristics to the wine for quality enhancement.

However, in the case of white wine production, the grape juice is immediately separated from the skins, pulp, and seeds through draining and pressing processes. The clear juice is inoculated with selected yeast to better control the rate of the fermentation process.

At maceration stage, temperature control and duration of the cooling process are very critical with respect to the quality of wine produced. These factors greatly influence the degree of compound extractions and types of compounds released, hence determining the end product from a given batch of juice from the grapes. In white wine, reductive conditions are maintained through the addition of sulphur dioxide to avoid the oxidation of wine. The temperature ranges maintained for the white and red wine are between 10^oC to 18^oC, and 15^oC and 28^oC, respectively.

Waste generation: Greenhouse gases (carbon dioxide, sulphur dioxide) and organic matter residues (grape colloid) are produced during white wine production. For the red wine, carbon dioxide, ethanol and other volatile organic compounds[3] are released to the atmosphere. An aqueous residue of yeast cells is collected after the fermentation process is complete. High organic pollution loading from the unit operations in this process are also possible due to spills, wine transfers and mishandling of aqueous residues in vessels for both in white and red wine production.

Energy consumption: The maceration process entails temperature control of wine juice and must. The quantity of energy consumed is a function of: temperature of the grapes at the time of delivery and heat load from the surroundings and pumps and the efficiency of the cooling heat exchanger used.

2.1.4 Pressing

The pressing process aids in the extraction of juice from the mash. In certain facilities, both press and de-juicers are used. The de-juicers commonly use the gravity flow technique in the separation process, after which the remaining juice in the pomace (skins

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[3] Also the VOC are released in white fermentation, but due to cooling in much smaller quantities.

and seeds left after the draining of wine juice) is extracted with the use of a press. Both de-juicers and presses are of many types and designs and as such have a direct impact on the quantities of water and chemicals consumed during their cleaning and sanitation processes.

The dejuicing process takes place after the introduction of mash into the tank and the juice flows through a perforated basket into a receiving tank. Due to the weight of pomace, some of the juice is forced into the receiving tank. After the dejuicing process is complete, the pomace is discharged into the press. Through the application of sufficient force the remaining juice in the pomace is extracted and the dry pomace cake is periodically discharged through the lower end of the cylinder.

Waste generation: Pressing operations are a source of pollution discharges with high organic content, such as the solids (pulp, skins and seeds) and the wine juice (for white wine) or wine (red).

Energy consumption: This can be assumed to be the same as discussed in the case of destemming and crushing processes.

2.1.5 Fermentation

The alcoholic fermentation process is a chemical reaction where sugars (glucose and fructose) are converted into ethyl alcohol and carbon dioxide. It may occur naturally or be induced by innoculating a yeast culture. Under natural conditions, the juice is exposed to ambient temperatures and oxygen conditions to promote the rapid growth of natural yeasts found in the vineyards to initiate fermentation. However, in many cases the fermentation is initiated through the inoculation of selected yeast to the juice. The rate of fermentation is strongly temperature dependant, hence the need for its effective control. Fermentation lasts for 7 to 21 days for white wine at a temperature range of 10^oC to 16^oC, while for red wine, the process can last for 4 to 14 days at between 15^oC to 30^oC.

The fermentation process takes place in tanks, barrels and vats of great variety in terms of shape, material, size, and design. Tank materials are mainly stainless steel, epoxy (fiber glass) and lined with concrete. Owing to their differences in surface finishing and surface volume ratio, quantities of water and chemicals for cleaning and sanitation vary greatly. The material properties of the containers also affect energy demand during the cooling process. In most cases, stainless steel tanks are prefered due to their rapid heat transfer. Note that since the fermentation process is exothermic, in certain instances the wine spills over due to overfilling of tanks. It is thus crucial to fill the tanks appropriately and monitor the progress of the process through the installation of sensors to avoid product loss and an increase in organic load in the wastewater stream.

After the completion of sugar metabolism in the wine, the yeast cells die and settle at the bottom of tanks, barrels or vats and are refereed to as yeast lees. The wine is racked to other vessels and the lees is left at the bottom of the fermentors (tanks, barrels, etc.). Care should be taken in handling of lees, bitartrates and other aqueous residues in the base of the tanks after completion of wine racking. Diversion of these process residues into the wastewater stream impacts negatively on the effluent quality.

In certain instances and mostly in red wine processing, a secondary fermentation is performed and its called malolactic fermentation (MLF). The principal effect of MLF is to reduce the acidity and increase the pH of the fermented wine through the conversion of malic acid into lactic acid. MLF is carried out by use by lactic acid bacteria essentially and improves the sensory characteristics of wine.

Waste generation: Spills from the overflowing wine from tanks during fermentation leads to product loss, and is a source of high organic content in the wastewater stream. Racking process in various fermenting and settling vessels causes significant pollution if organic residues are poorly handled or if the must and residue wine are not effectively recovered before disposal. Spills and leakages are other causes of pollution during the racking process after the completion of the fermentation process.

Energy consumption: The total refrigeration load required during the fermentation process is dependant on the following factors: the initial temperature of the grapes, the efficiency of the heat exchangers used for cooling, the rate of fermentation heat load generation (heat load due to the fermentation process), thermal properties of the wine holding vessel, and quantities of heat load gains from pumps (function of pump efficiency) and surroundings (the effectiveness of insulation) and whether the tanks are inside or outside the winery buildings.

2.1.6 Clarification, Maturation and Stabilization

Clarification of wine is essential to remove particles present in the wine after fermentation. The particles consists of spent yeast cells, different types of bacteria, grape cells, precipitated tannins, proteins and tartrate crystals. The clarification can be achieved by the aid of gravity so that particles settle at the bottom of the vessels or through the addition of fining agents.

Commonly used fining agents include bentonite, gelatin, silica soil, albumen, to mention but a few. The separation is achieved through a racking process where the wine is transfered from one vessel to another. The process is done manually or by use of automated transfer systems. It should be noted that during wine transfers or filtering, chances of wine loss is high and results in increasing the organic content in the wastewater stream.

The maturation process involves the precipitation of particulate and colloidal material from the wine as well as a complex range of physical, chemical and biological changes occuring in the wine itself. The core purpose of this process is to maintain and improve the sensory characteristics of the wine. The main wine adjustments at this stage are; acidity modification, sweetening, dealcoholization, color adjustment and blending.

Stabilization is a process aimed at producing wine which is permanently bright (wine with no flavor faults). This means that the wine produced is stable under both hot and cold environments without resulting to turbidity or developing crystalline particles as a result of exposure to temperatures extremes. Due to increased handling of large quantities of wine, great care is required to avoid spills and leakages. Different types of equipment are used for the filtration process and this results in different levels of wine loss and quality (depending on whether oxidation occurs during the numerous transfer processes).

Waste generation: During clarification, the use of filter media in alluvial filtration techniques acts as a source of organic pollution loading during the cleaning cycle. The filtration media produces suspended solids likely to impair the transfer of effluent by plugging or blocking of pipes. Other sources of wastes are as a result of racking process discussed in section 2.1.5.

Energy consumption: In all cases, energy is used for cooling, filtering or transfer of wine. The quantities of energy used are a function of numerous factors such as the efficiency of equipments used, length of transfer lines, and implementation of sound energy housekeeping practices.

2.1.7 Bottling and Packaging

This is the final stage of the vinification process. The key issue in this process is to minimize contact of wine with air during filling and hence reducing oxidation. This is achieved by flushing the bottles with inert gas before filling or flushing the head space with inert gas after filling. To protect the wine against microbial spoilage, and to limit oxidation, about 50 mg/L of sulphur dioxide is added to the wine. In certain instances, bottles are replaced by bag-in-box, expecially in case of low quality, high volume wines. In other facilities, there is no bottling and the wine is sold in bulk to other companies.

Waste generation: During bottling and packaging processes, many forms of waste are generated. These includes used cartons, broken bottles, spilled glue and wine, and used labeling paper.

Energy generation: Some of the energy uses entail the movement of bottles and filling of bottles with wine.

2.1.8 Winery Sanitation

The wine industry is governed by the health act which stipulates the hygienic requirements for food and beverage processing industries. In pursuit of meeting these legal and hygienic requirements, large quantities of potable water and sanitizers are used in the wine industry. The highest water demand is recorded during the vintage season. The main purpose of water use is for the cleaning and sanitization of processing equipments and surfaces, that get in contact with wine. Other water consumers are cooling towers, and earth filtering process.

The quantity and quality of wastewater generated, amounts of sanitizers, and detergents used for cleaning are a function of complex factors. Several principal factors taken into consideration in evaluating the mentioned variables are:

1. The type of technology used. This refers to both the cleaning equipment and the nature of surfaces and equipments to be cleaned. Where the facilities employ modern technologies in processing and sanitization processes, the consumption of resources is low[4].
2. Levels of environmental consciousness of the personnel at all levels of the winery workforce in a given facility. In facilities where environmental concerns on resource consumption are high, remarkably conscious steps to assess the high consumption rates exists. The vice versa scenario is also true.
3. The ease of assessing all parts of the various equipment during cleaning and sanitization processes. This is a function of facility layout and is determined at the design stage. In wineries where environmental concerns were incorporated at the design stage, resource consumption is low.
4. The properties of chemicals used for process and utility purposes (this addresses the question of hazardousness and toxicity properties of the chemical solvents used).
5. The leverage of a given facility to adopt reuse and recycling of high quality wastewater before it is disposed to the storage tanks.

2.2 Case Study

2.2.1 General

In South Africa, the Western and Northern Cape Provinces have viticulture as the predominant agricultural activity covering a total land area of approximately 1.08×10^5 hectares. The main wine growing regions in South Africa are shown in Figure 2.2. According to South Africa Wine Information and Systems (SAWIS, 2003) annual report, during the 2002 vintage season, approximately 1.0799×10^6 tonnes of grapes were produced, and yielded 8.34×10^8 liters of wine. There are over 500 registered grape-based processing

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[4] Resource consumption in this section refers to the usage of water and chemicals.

Figure 2.2: Wine growing regions in South Africa.

wineries in South Africa, ranging from small, medium to large scale with respect to size and annual production throughput.

The waste streams generated from winery operations are liquid wastes (wastewater, stillage bottle washings, cooling waters), spent cleaning solvents, solid wastes (pomace, lees) and gases (CO_2, SO_2, VOC's etc.). Wastewater is the major waste stream, and was given significant attention in this study. The trend over the recent years indicates that freshwater demand has increased tremendously for the winery operations. For instance, an average of 3 to 8 liters of water is required for every liter of wine produced (Lorenzen et al., 2000) in South African vinification process. Such high intensive water use in certain cases has resulted in excessive pumping of water resources from freshwater aquifers or has caused sharp increases in water costs for the wineries sourcing it from the municipal water supplies.

From the view point of the current trends on water usage and failure to implement sound mitigating strategies, threatened water resources and acute water shortages are possible in the long term. Thus, a sustainable approach to water management such as conservation of water or reutilization of wastewater is proposed to offset shortages and stabilize water supplies in the winery operations as a long term feasible alternative.

On the other hand, in circumstances where the effluent is disposed into the ecosystem without careful handling, several negative environmental impacts are possible. Examples of such impacts are eutrophication of water reservoirs, suffocation of aquatic life, pollution of ground water resources and the creation of anaerobic conditions which generate offensive odors, just to mention a few (see details in Appendix A).

2.2.2 Waste Characterization

In order to focus on mitigation and preventative measures on waste reduction successfully, it is crucial to understand the characteristics of the waste streams generated. Some of the recent reviews on wastewater characterization from different regions globally have been presented by Marais (2001) and Grismer et al. (1998, 1999).

In characterizing wastewater its physical, chemical, and biological compositions are determined. Table 2.1 presents some of the descriptors that constitute the wastewater from a typical wine making operations. It is significant to note that the wastewater generated is characterized by variable flow rates that are season dependent, and mainly of high volume. For instance, on the basis of studies on wine wastewater characterization (Malandra et al., 2003; Petroccioli et al., 2000; Torrijos and Molleta, 1997) from different vintage regions globally there is an indication of high content of organic matter, extreme pH levels, and high conductivity.

In a practical sense, however, not all the parameters presented in Table 2.1 are measured or can be directly determined experimentally in any given treatment plant or in circumstances where the wastewater is examined to ascertain its suitability for irrigational purposes. In several reported cases the most determined parameters are chemical

Table 2.1: Classification of physical, chemical, and biological descriptors of wastewater.

Physical	**Chemical**	**Biological**
Temperature	*Organic*	*Algae*
Odor	Proteins	Molds
Color	Carbohydrates	Protozoa
Suspended solids	Phenols	Fungi
	Fats, oils	*Pathogenic organisms*
	Volatile organic compounds	Viruses
	Inorganic	Bacteria
	Alkalinity	Helmiths
	pH	
	Oxygen	
	Sodium	
	Magnesium	
	Calcium	
	Potassium	
	Phosphate	
	Electrical Conductivity	

oxygen demand (COD)[5], suspended solids (SS), electrical conductivity, pH, magnesium, sodium, potassium, calcium, biological oxygen demand (BOD)[6], and total coliform (bacteria, faecal, *E. coli*). The last two measures attempt to measure the presence of protists or pathogens in the wastewater, while COD and BOD values provides indirect determination of organic matter quantities in the effluent. Typical effluent characteristics from a winery for some of the measured parameters are depicted in Table 2.2.

Pomace is the predominant solid waste from the winery operations and its analysis is given in Table 2.3 based on the findings of Tofflemire (1972). In the wine industry, no characterization of gaseous wastes has been reported yet. In fact, data and information on the quantities of VOC emissions are not readily available in the literature either.

In all cases presented by numerous researchers, the main thrust of characterizing the effluent was to form a basis in designing a treatment technique or plant for the purpose of treating the wine effluent to satisfy stringent regulatory legislations. However, in retrorespect to the case of designing a decision support tool for waste minimization in the wine industry presented in this dissertation, such data and information reported in the

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[5] COD is a measure of oxygen equivalent to the organic matter that can be oxidized using a strong chemical oxidizing agent in an acidic medium.

[6] BOD is a measure of dissolved oxygen depletion due to the biochemical oxidation of organic matter.

Table 2.2: Typical wastewater characteristics from a winery operations depicting wide variations of concentrations of various components. The data extends over a period of 8 days from 7th February, 2001 to 13th February, 2001.

No.	**pH**	**C**^{a} **(mS/m)**	**COD (mg/l)**	**TDS (mg/l)**	**TSS (mg/l)**	**K (mg/l)**	**Na (mg/l)**	**Mg (mg/l)**	**Ca (mg/l)**
1.	3.58	55.70	2,975	1,800	3,148	174.54	3.77	1.56	4.22
2.	3.55	56.40	4,085	1,588	14,164	143.77	3.95	1.86	3.55
3.	3.62	50.20	1,970	884	8,292	77.48	3.48	0.09	1.91
4.	3.66	30.00	980	524	444	34.19	2.46	0.00	0.51
5.	3.72	20.20	2,720	1,132	588	126.26	3.78	0.90	2.85
6.	3.80	314.00	189,000	37,224	15,776	11.92	0.00	16.78	4.58
7.	3.49	36.40	3,180	724	300	966.29	20.96	52.45	41.83
8.	3.89	119.90	18,800	3,592	1,952	0.00	3.52	0.00	0.36
9.	3.91	91.90	13,800	2,740	1,592	532.00	7.76	7.16	8.39
10.	3.95	98.10	14,800	3,444	1,868	365.36	6.62	4.48	6.28
11.	4.01	57.70	9,100	1,640	964	240.39	4.55	2.85	4.49
12.	4.08	20.40	3,200	640	600	14.22	4.08	1.02	2.89
13.	3.97	83.20	11,900	2,064	1,192	47.60	3.68	0.00	1.28
Avg. value	3.79	79.55	21,270	4,466	3,914	220.23	5.28	6.86	6.40

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[a] C: Conductivity

literature provided some key insights. These are as follows:

1. The values from one operation to the next for any measured component(s) showed wide variations in any given facility (see variations as shown in Table 2.2). Thus, it was clear that the effluent quality was a function of the operational practices and technologies in any given facility. As these analysis results are from the same winery, they indicate wide spatial and temporal variations of wastewater properties. The variations are thus seen as a function of the operating practices and the vinification processes undertaken in this period.

Table 2.3: Characterization results for the analysis of pomace waste from winery operations (adapted from Tofflemire 1972).

Component	**Component Percentage Range (%)**
Protein	11.0 - 12.0
Oil	3.3 - 7.4
Ash	4.7 - 8.1
Fiber	26.0 - 41.0
Starch	7.4 - 7.9

2. The figures reported by all researchers from different wine growing regions globally were for wastewater generated after a set of operation(s). On the basis of the measured values, the possibility of finding a relationship between the practices during production operations and cleaning processes with the resulting wastewater matrix became apparent. Such data and information was useful in analyzing the problem upstream in order to derive waste minimization strategies to abate both treatment costs and possible adverse environmental impacts (see Appendix A for brief discussion of the wastewater impacts on the environment) when the effluent enters the ecosystem untreated.

3. Since both wastewater quality and quantity cannot substantially be altered without extensive treatment after its generation, the most probable effluent minimization strategies should attempt to ensure effective management through appropriate use of equipment as well as other factors that influence these variables before or during its generation period. It thus became apparent that a multidisciplinary approach has an edge in providing reasonable results in addressing the waste minimization problem in the wine industry. The experience of managers and operators was found critical in achieving this objective.

4. In view of the observations presented in 1 to 3 and acknowledging that the wine making process is more of an art than a finite science, a strong case for solving the waste minimization problem in this domain by using a qualitative reasoning approach was presented. The qualitative approach depends heavily on heuristics that have been developed over the years through experience and in circumstances where the quantitative data is scarce, vague and characterized by nonstatistical uncertainties. The data and knowledge in the wine industry meets these characteristics explicitly.

5. Wastewater characterization can be viewed to a certain extent as a measure on how effective waste minimization strategies have been adopted in a given facility. For instance, in circumstances where the SS, COD and BOD values are found to be extremely high, it points to a number of possibilities that may have caused such a scenario. On the one hand, it may imply that the techniques to isolate different waste

streams are ineffectively or poorly done. On the other hand, irregular maintenance of facilities which leads to equipment leakages or spillages and accidental spillages can also be another possible reason that account for such high values, which is supported by the wastewater containing high organic matter. However, in instances where the reported values are low, it can be inferred that the waste streams (solids and liquids) were effectively segregated before the wet cleaning process commenced, and through regular check ups and effective control of spillages and leakages.

2.2.3 Environmental Legislation

In the pursuit of ensuring that the process industries incorporate sound waste management into their production activities, governments worldwide have or are in the process of setting up legislative frameworks targeting waste generators in different industrial sectors. The wine industry is no exception and in the recent past, governments in Greece, France, South Africa, USA and Australia have passed laws that govern waste management with respect to the vinification process (three legislative case samples are presented at Appendix B).

It should, however, be pointed out that the wide differences in legislative requirement for wine makers specified by a given state environmental law is largely influenced by the type of wine processing, type of grapes processed, the type of products processed, climate, type of soils, and immediate ecological and environmental neighborhood which are unique and specific in each case.

Part II: The Environmental Management Hierarchy

2.3 Review of Waste Management Approaches

As early as 1950's and 60's, the industrial waste problems, resulting from rapid industrialization had been acknowledged. In an endeavor to solve these new challenges, numerous technical concepts and approaches proliferated in the literature over the years aimed in protecting and/or improving the environmental media. However, for most of these terms (e.g. sustainable development, pollution prevention, cleaner production, waste minimiza-

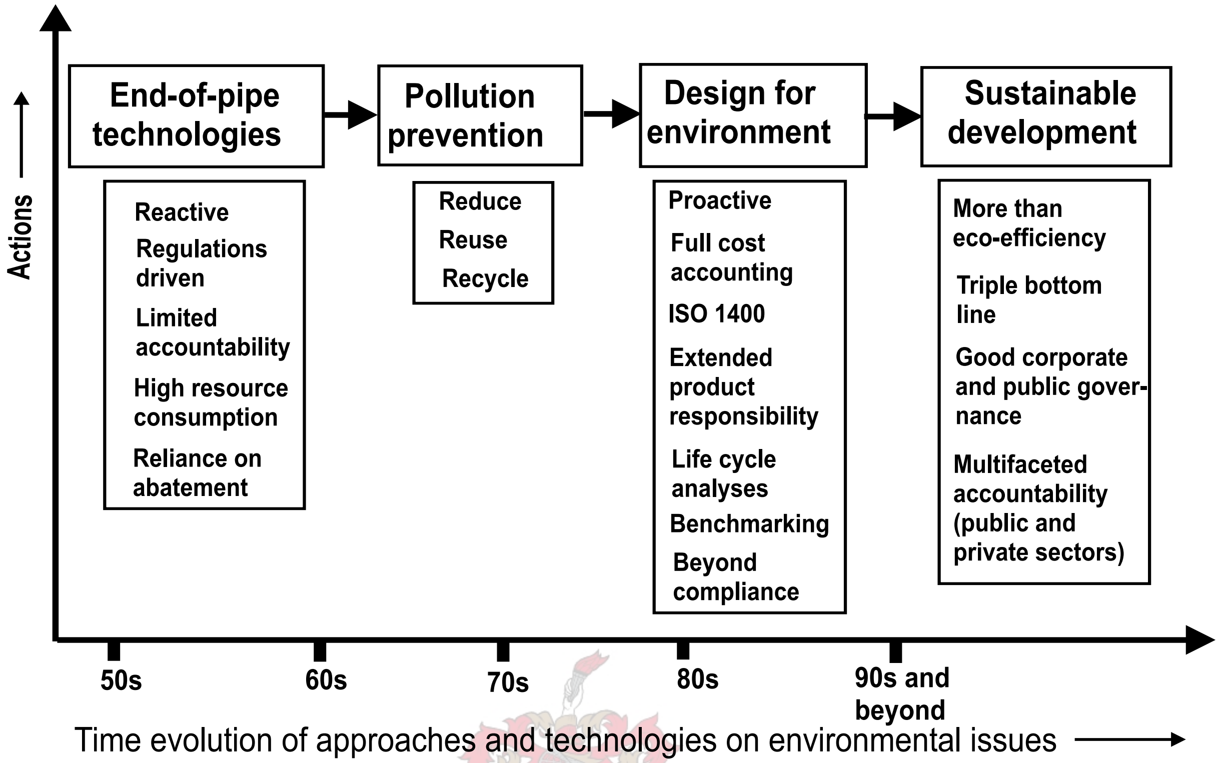

Figure 2.3: Environmental issues evolution from treatment perspective through green engineering to sustainable science and engineering (adapted from Mihelcic et al., 2003).

tion, etc.), the drawback lay in the ambiguity of their definitions, scope, breadth, misinterpretation, applications and evolutionary nature.

The evolution of these approaches and technologies aimed at addressing waste management are presented in Figure 2.3. Primarily, the goal of these concepts and terms is to inspire changes in industrial behavior and technology used in order to reduce negative environmental impacts from industrial effluent and remarkably reduce the extraction of natural resources as raw materials. The majority of these approaches and technologies are based on the premise commonly known as the precautionary principle also known by the old saying "an ounce of prevention is worth a pound of cure".

Debate over the semantics of various waste management approaches and their application has attracted a lot of attention in academia, governments, and corporate circles (Freeman et al., 1992; Hamner, 2003; Hilson, 2003). In solving the waste problem in the wine industry, the question of which approach is suitable to employ in knowledge engineering is a critical issue. This is owing to the fact that some of the concepts are long term goals with complex relationships in terms of practices, philosophy, objectives among other. Moreover, they are ongoing concerns that are unsuitable to address specific problems such as waste generation and mitigation, and particularly with regard to the development of a decision support system to aid decision-making.

Therefore, in this study various concepts were classified based on factors such as their philosophy, objective, time frame for their implementation and breadth of scope. The three broad levels of conceptualizing environmental management are macroscale, mesoscale, and operational concepts.

The macroscale concept addresses the complex interrelationship web of interactive forces beyond the boundaries of a manufacturing company, but which contributes to the state of the environment. In this category a broad holistic view is adopted in finding the synergies over wide ranging fields such as raw material sources, other companies, social institutions, the public, governments, and the environment itself in finding solutions to the waste problem. The approaches mainly attempt to establish the material flows from natural source extraction to consumer, and then finally to the product disposal.

The scope of each concept is presented using a shell model as depicted in Figure 2.4. The key question here is, how does each interactive force influence the state of the environment as the world struggles to meet the needs of a rapidly growing population and of a wasteful lifestyles from an industrial economic point of view? This question can only be answered adequately when the waste problem and resource availability are addressed based on the concepts of sustainable development and industrial ecology. However, such concepts are goal oriented and hence difficult to model as a base-concept to develop a decision support system, particularly in the wine industry. This is because the decision making model based on such concept will require a large knowledge base, hence rendering it impracticable for use in a winery setup with regard to waste generation.

On the other hand, mesoscale concepts can be said to have meanings and applications which are plant-wide to the extent that any attempt to develop a decision support tool based on their philosophy in solving waste management problem yields large data bases. Such decision tool will not only be inefficient to use but very difficult to validate, especially

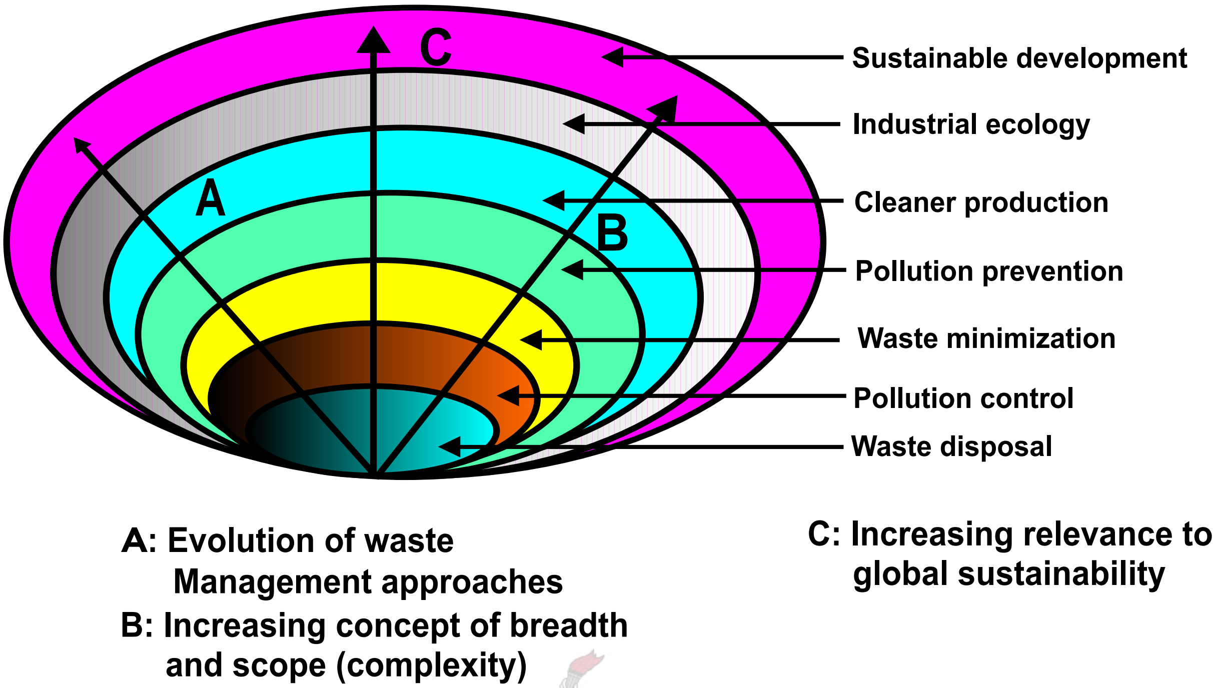

Figure 2.4: The scope and breadth of waste management approaches from waste disposal perspective to sustainable development concept.

if the system knowledge base contains data, information and knowledge from diverse fields of specialization. These concepts are mainly ingrained on the management philosophies and practices of the manufacturing industry. The waste management concepts in this category are cleaner production and pollution prevention.

The operational concepts address specific functions of the manufacturing process. They are ideal candidates for developing decision tools in solving waste management challenges. This can be attributed to the specificity of these approaches and the breadth of their scope as opposed to the cases in macroscale and mesoscale. The waste management approaches in this category are waste minimization, pollution control and waste disposal. This forms the core of the aspects considered in this work. However, since the last two approaches only deal with waste after it has been generated and with no reference to reducing it at the point of production, they were not considered in the process of developing the management decision tool reported in this dissertation.

The interrelationships for the scope of each concept or term with respect to others is illustrated using a shell model depicted in Figure 2.4. The outer concepts are of higher scope than those at the core of the shell, and hence difficult to model in pursuit of developing a decision support system. Secondly, the two inner core shells were first attempts in mitigating environmental degradation due to the industrial wastes.

These approaches were predominant in the 1950's, 60's and 70's in addressing waste management problems. However, owing to their inherent limitations, more holistic and higher order approaches were required and this gave rise to the increment of the shell as the world community searched for long lasting solutions to the complex environmental problems. Currently, at the pinnacle of this evolution is sustainable development, but the shell is expected to grow with time. This can be attributed to new knowledge becoming available from the research community as they pursue effective strategies of solving environmentally-oriented problems. The basic principles of each concept are briefly reviewed in the following sections.

2.3.1 Sustainable Development

Sustainable development (SD) concept requires a macroscale consideration of the economic, sociological, cultural, regulatory, environmental and ecological aspects, making it very difficult to define explicitly. Numerous definitions have been developed over the years and the commonly used version adopted here is based on the World Commission on Environment and Development Report (WCED, 1987). It states thus: SD is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

The definition is beyond the scope of individual firms to implement single handedly, and presents great complexities which are difficult to model using knowledge based decision tools. Sustainability is a goal, and is time dependent (Clift, 2000; Rucklelshaus, 1989). This makes it unsuitable for modeling a decision tool to address the waste problem in the wine industry. However, the decision tool reported in this work can be viewed as one of the means in pursuing the global goal of achieving SD in the wine manufacturing industry. This is true because the nascent nature of sustainability is based on the principle that, economic growth and development must take place and be maintained over time. However, this should be done within the limits set by ecology in the broadest sense, taking into account the interrelations of human beings and their works and the biosphere and the laws governing their interaction (Rucklelshaus, 1989).

The philosophy of sustainable development has been extensively covered by various authors (MacNeil, 1989; Ruckelshaus,1989) and recently, sustainability measurement performance indicators have been developed and reported by Bakshi and Fiksel, 2003; AIChE, 2003; IChemE, 2003; and Sikdar, 2003.

2.3.2 Industrial Ecology

Industrial ecology (IE) is based on the premise of waste exchange between industries. Many definitions (Frosch and Gallopoulos, 1989; Allenby, 1992; Seager and Theis, 2002; Socolow et al., 1994) among others have been proposed. The commonly used definition is by Graedel and Allenby (1995), where IE is seen as the means by which humanity can deliberately and rationally approach and maintain a desirable carrying capacity, given continued economic, cultural and technological evolution.

The concept requires that an industrial system be viewed not in isolation from its surrounding systems, but in conjuction with them. It is a systems view in which one seeks to optimize the total materials cycle from virgin material, to finished material, to component, to product, to obsolete product, and to ultimate disposal. Factors to be optimized includes; resources, energy, and capital. From such definition, IE can be viewed as a component of SD. Again the concept is very broad and indeed a goal in which companies should endevour to pursue to improve their environmental performance.

Current preventive environmental management practices of industries that can make possible contributions to achieve the goals of IE are practices such as Pollution Prevention (P2) (US Congress, 1990), Design for Environment (DfE) (USEPA, 2000; Graedel and Allenby, 1996), Toxics Use Reduction (TUR) (Freeman et al., 1992; Roy and Dillard; 1990), and Waste Minimization (WM) (USEPA, 1986; USEPA, 1988). Owing to the wide scope of the IE concept, it might be almost impossible to develop a viable decision tool for the wine industry.

2.3.3 Cleaner Production

Cleaner production (CP) concept addresses aspects of inputs, production, products, practices, services, and management styles in a firm (either for manufacturing or service), and impacts of all, including their design, and utilization of raw materials and energy. It thus incorporates attitudes such as management philosophies and business practices. The term CP originated from the United Nations (UN), and is defined as a continuous application of an integrated preventive environmental strategy to processes and products to reduce risks to humans and the environment (UNEP, 1996). It should be noted that in most countries the term CP is used as opposed to pollution prevention which is primarily used in the USA (Hilson, 2003).

The broad nature of the CP concept renders it to have a wider breadth of scope over pollution prevention. The most remarkable difference is the inclusion of product design and use, which is beyond the scope of pollution prevention (Hamner, 1996). Besides being a broad concept, it also addresses the question of product design. The problem reported in this dissertation for the wineries, does not include design alternatives to minimize waste at project conceptual stage. However, it focuses on finding retrofitting strategies to minimize and/ or eliminate high waste generation in existing wineries. Therefore, the suitability of CP concept as a platform to address this problem, became unattainable.

2.3.4 Pollution Prevention

The term pollution prevention (P2) is widely used in the USA[7], and has markedly different definitions from one state to another (Foecke, 1992). The differences in definition results mainly from the activities a given state chooses to place emphasis on. Many closely related competing terms and concepts have proliferated over the years and which are also difficult to define explicitly as reported by Allen and Rosselot (1997), Van Weenen (1990), and Foecke (1992). Among the numerous P2 definitions, the most popularly used and adopted in this study was codified by the US congress in the Pollution Prevention Act of 1990.

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[7] P2 was developed in the late 1970's as the manufacturing community became more environmentally conscious from the view point of the potential impact of their processes, operations, and products into the environment.

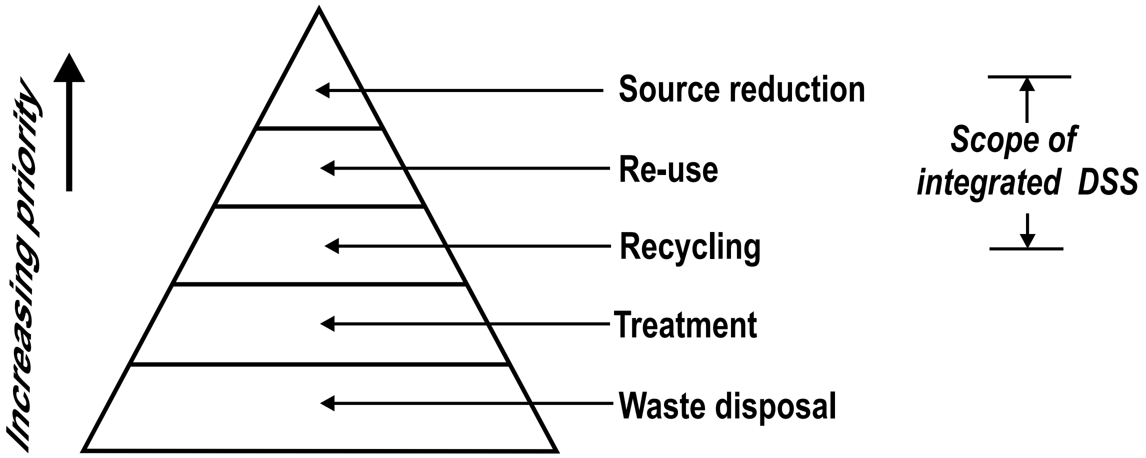

Figure 2.5: The pollution prevention hierarchy (after Pollution Prevention Act of 1990 (1990)).

The P2 is defined as the use of materials, processes or practices that reduce or eliminate the creation of pollutants or wastes at source. It includes practices that reduce the use of hazardous materials, energy, water, or other resources and practices that protect the natural resources through conservation or more efficient use (US Congress, 1990).

By scrutinizing the definition, there is an inclusion of waste recycling (on-site and off-site), recovery, treatment and waste disposal which agrees with an interpretation reported by the Chemical Manufacturers Association (1994). From the federal state definition of P2, taking into account the nature of the wine industry wastes generated and the vinification manufacturing process itself, the inclusion of the implied aspects were adopted in this study. The P2 hierarchy used in this work in deciding the scope of the knowledge domain of the developed decision support tool is depicted in Figure 2.5.

Two key issues should be noted regarding the P2 hierarchy. First, at the top of the hierarchy is source reduction which encourages avoidance or reduction of waste generation at source point as far as practically feasible. Secondly, the placing of waste treatment and disposal at the bottom of the hierarchy is an admission that, in a manufacturing process, some form of waste will be generated and requires appropriate attention to prevent its potential damage to the ecosystem. However, the wide scope and breadth of P2 (as it integrates many constituent parts) and the many interpretations of what it entails, made it difficult to implement as the base concept of developing a decision support system reported in this dissertation.

2.3.5 Waste Minimization

The most widely applied concept in addressing the question of waste management for specific industrial manufacturing process(es) is waste minimization (WM). This can be explained on the bases of its scope and operability. In this respect, it is safe to argue that WM concept defines the scope that solve numerous environmental problems explicitly and adequately.

According to the United States of America Environmental Protection Agency (USEPA), waste minimization is defined as the reduction, to the extent feasible, of hazardous waste that is generated or subsequently treated, sorted or disposed. It includes any source reduction or recycling activity undertaken by a generator that results in either; (1) the reduction of total volume or quantity of hazardous waste or both, or (2) the reduction of toxicity of hazardous waste, or both, so long as the reduction is consistent with the goal of minimizing recent and future threats to human health and the environment (USEPA, 1986).

The core of WM term was for industries to determine ways on how hazardous wastes can be minimized and therefore, the recycling techniques were implied in this definition. This attracted a lot of critics questioning how broad the term can be useful in addressing other wastes as well as the inclusion of recycling which could make the industrialists abandon source reduction options (US Congress, 1986). However, the approach has been widely applied in the process industry and good results have been reported (Allan and Rossiter, 1997; Hillson and Murck, 2001; Viguri et al. 2002; Petek and Glavič, 1996) .

Owing to the extensive understanding of the WM concept both in academia and corporate circles, it has been a base concept for the development and implementation of numerous decision support systems with respect to environmental problems where the domain is poorly structured. A number of such systems have been proposed and reported in the literature by authors Edgar and Huang (1992); Ferrada and Rodgers (1992); Palaniappan et al. (2002); Huang et al. (1991); Huang and Fan (1993, 1995); Luo and Huang (1997); and Halim and Srinivasan (2002a,b).

Besides the ongoing debates and numerous definitions being advanced in the literature with respect to WM concept, a concensus is emerging that WM mainly comprises of source reduction and recycling (USEPA, 1993). Therefore, for any strategy to qualify for inclusion in the knowledge base of the decision support system reported in this dissertation, the criteria used was to determine whether it falls under source reduction or recycling techniques that are applicable particularly to the wine industry. The scope of the integrated decision support system developed is shown in Figure 2.5

As environmental concepts have a wide range of interpretations, the following paragraphs explain the terms source reduction and recycling as employed in this work.

I: Source Reduction

The term source reduction entails eliminating and/or reducing (minimizing) the generation of waste at source in any given process. The basic premise is that, strategies should be put in place which yields avoidance or minimization of waste quantities or toxicity or both of what can be regarded as a waste from a given process. In the context of the vinification process, waste generation can be avoided for instance by ensuring no wine spillages or leakages from various equipments and transfer systems occurs. As a result, there will be minimal or no product or byproduct loss and the organic component in the effluent stream will be low.

For instance, to minimize waste generation during the vinification process, quantities of the input materials should be monitored through an inventory control. A case here is the control of quantities of cleaning solvents and other process chemicals through accurate inventory management. Other alternative of minimizing waste toxicity is through the substitution of hazardous chemicals with environmentally benign substitutes. For instance, chlorine which is used for cleaning and sanitization of equipments can be substituted with hydrogen peroxide, ozone or hot steam, hence eliminating its negative environmental impacts and potential inherent safety threat to the personnel. The methods that can achieve source reduction are broadly classified as:

1. *Good operating practices*: These are administrative, procedural or institutional measures aimed in minimizing of waste generation in a company. Most of the measures

are relatively easy to implement at minimal or no costs. These practices have a plant-wide application in areas such as production, maintenance of equipments, handling of raw materials and product among other. Good operating practices include the following: management and personnel practices, material handling and inventory practices, loss prevention, waste segregation, production scheduling and good environmental cost accounting practices.

2. *Technological modifications*: Technological changes are aimed in modifying both the processes and equipment to optimize production and reduce waste generated per unit throughput. The degree of technological changes varies from simple alterations to intensive re-engineering work that completely changes the processes. In cases where large scale technological modifications are carried out, huge capital layout is required. Examples of such changes include the introduction of new equipment which is more efficient, the automation of process(es) control, and the redesign and retroffiting of equipment and alteration of process conditions or setting.

3. *Input material substitution*: The premise here is to find alternative input materials that generate less waste or are environmentally benign. In the vinification process, material substitution is commonly considered with respect to the use of chemicals in cleaning, sanitization, prevention of wine oxidation and microbial growth inhibition. It also arises in cases where the chemical-phase determines how hazardous or wasteful it can be, in the course of its application. Some examples entail the replacement of chlorine cleaning agents with non-chlorinated solvents and the substitution of gaseous sulphur dioxide with liquefied or solid pellets of sulphur dioxide.

II: Recycling and Reuse

The term is used to describe the activities that attempts to recover waste materials created from the production processes before treatment and disposal options are considered. These activities can comprise but are not limited to:

1. Use of waste material from a given process or unit operation to another process as a raw material either on-site or off-site process or both.

2. Reuse of the waste material to the originating process as a substitute for the virgin input material(s).

3. Reclaim the by-products (secondary materials) for separate end use through the segregation of effluent characterized by different concentrations. The reclaimed material can become a raw material, product or a by-product in its own right, although purification may be required to derive the desired specifications.

Note that recycling can be carried out on-site (closed-loop) or off-site (open-loop). The option(s) to be implemented in any given company depends on many factors and the decision to undertake recycling can be dictated by one or a combination of these factors. These factors includes (i) the question of safety and hazardous nature of the waste generated, (ii) quantities of the waste generated to determine the cost-effectives in setting up an on-site recycling facility, (iii) feasibility of the waste material reuse in the manufacturing process and possible environmental and cost implications of the residue wastes generated from the first waste, (iv) liability risks during transportation of the waste to the off-site recycling facility.

In the wine industry a good example is the recovery of lees, tartrates,protein feed, diatomaceous earth, skins, pips and other organic materials for the manufacture of fertilizer and compost. Since the waste quantities from individual wineries are insufficient for industrial recycling scale production, they are often re-processed in a central place. The second factor supporting this decision is the low risk involved in transporting these wastes to a central processing plant as none is toxic or hazardous.

Although in certain circumstances off-site recycling has been argued to be a form of waste disposal for the industries creating the wastes, but for the wine industry this point of view can be challenged. This is because the wastes generated are neither hazardous nor toxic and can be reprocessed to recover tartrates or for the manufacturing of fertilizer and compost. The new products (fertilizer and compost) are useful in the vineyards for improving soil structure and crop yield. As such, the vinification outputs apart from the product wine, help in completing the ecological cycle as they support the creation of the primary raw materials, which in this case are grapes.

Another case is the reuse of high quality wastewater (where the organic content is as low as possible) mostly final rinse water from a given equipment as a first rinse in cleaning the next equipment in the cleaning-cycle. In this manner of practice, quantities of water used for the cleaning process are reduced and the risk of cross contamination is minimal as the water reuse is strictly undertaken in the first round of the next cleaning-cycle.

2.3.6 Pollution Control

The industrial revolution, in pursuit of meeting human needs and profitability, has created a parallel exponential growth of pollution in the biosphere. Such trends of unchecked ecosystem burdens resulting from industrial effluent have been found to be unsustainable. Since the 1950's, this has forced numerous companies to start putting in place mechanisms of controlling both quality and quantity of wastes reaching the environment. This approach is popularly referred to in the literature with terms such as "end-of-pipe techniques/technologies, additive technologies or pollution control (P1)".

The premise of this approach is to ensure the wastes generated from both domestic and industrial sources are rendered benign before entering the environmental media. The P1 concept is very expensive in comparison to other approaches discussed in previous paragraphs because waste treatment and final disposal do not add value to the company, but are undertaken as a mandatory measure to meet legal requirements with respect to waste handling and disposal.

The P1 approach can be viewed as a passive mechanism of encouraging inefficiency of the production processes as the waste treatment or control investment can be made to operate under capacity if waste generation is effectively reduced at source or through recycling. Thus, pollution control alternatives should only be considered when all the outer shell concepts (see Figure 2.4) have been exhaustively investigated.

Pollution control is achieved through effective waste treatment. Treatment of waste is any method, technique or process, designed to change the physical, chemical, biological character or composition of any hazardous/harmful waste so as to neutralize such a waste. The motivation is to recover energy, render waste less or non hazardous, or safer for transportation to disposal sites, or recover valuable materials, or transform the waste to forms amenable for storage, or reduce its volume among other. The significance of establishing what P1 entails was to ensure that the strategies that fall under this category were excluded from the data or knowledge to be included in the knowledge base reported in this dissertation. The reason being that they do not target waste reduction at the source point but encourage and justify the establishment of waste treatment facilities.

As the largest percentage of the wine industry waste is wastewater, numerous traditional pollution control approaches have been developed over the years to render it benign before its release to the environment. Examples of some of these treatment strategies are: constructed wetlands (Shepherd, et al., 2001; Shepherd, 1998), woodlot irrigation (Marais, 2001; Chapman et al., 2001), anaerobic digestion systems (Calderon et al., 1998; Bernet et al., 1998; Danfonchio et al., 1998), aerobic digestion systems (Petruccioli et al., 2000; Petruccioli et al., 2002), evaporation ponds (Rankine, 1989), irrigation paddocks (Rankine, 1989), rotating biological contractor (Malandra et al., 2003; Muller, 1994).

Owing to the large body of knowledge in reference to effluent treatment techniques for the winery effluent, and specifically for the wastewater generated as a result of diverse water uses in the winery, vast knowledge and information has been acquired in this domain. As a result, several artificial intelligence applications have been reported in the literature by Estaben et al., 1997; Polit et al., 2001; Genovesi et al., 1999; and Steyer et al., 1997. In striking contrast, there has been no attempt to date in addressing waste management in the wine industry at the WM level specifically with respect to application of knowledge-based techniques, which thus forms the core of the work reported in this dissertation.

2.3.7 Waste Disposal

Waste disposal refers to the means of discharging, depositing, injecting, dumping, spilling, leaking or placing any waste (solid, liquid or gaseous) into the environment. From the perspective of an integrated waste management approach the concept of waste disposal should be viewed as the last result under inevitable circumstances. However, if it has to be carried out, it should be done responsibly to avoid cross media waste transfer e.g. from the liquid phase (water) to solid phase (soil).

In the wine industry, wastewater accrued from various vinification processes is either disposed in rivers, streams or used for irrigation of vineyards or pastures. Nevertheless, in disposing the wastewater or solids (especially skins, lees or sludge), the waste should be benign to the receiving environment. For example, wastewater and sludge disposal through irrigation and spreading on the land respectively, should be carried at the agronomic rates. This ensures that the organic components of the applied waste to the soils is consumed by microbial activities and therefore causing minimal or no adverse effects to the soil, crops or underground water resources.

Other ways of disposing the wastewater is through municipal sewers while the solids are used for land filling[8]. However, waste disposal costs are high and the processes do not accrue any returns to the companies. Thus they should only be considered if all other waste management options are found infeasible after being screened using multi-criterion such as costs, technological requirements, safety and hazards, ease of implementation, availability of the technology, period of payback, among other.

Several negative impacts associated with improper disposal of the wine industry wastes are, but not limited to eutrophication of water reservoirs, suffocation of aquatic life, pollution of groundwater resources, creation of anaerobic conditions leading to odor generation, sodicity and salinity in soils. A full summary of possible environmental impacts has been presented in Appendix A.

Part III: Energy Management

2.4 Energy Usage in the Vinification Processes

Although copious literature exists addressing several subjects on industrial vinification process such as waste management, winemaking processes, wine tasting, marketing of wine, and effect of temperature on wine quality, however, energy management in the wine industry has attracted minimal attention from researchers. This can be explained by the fact that energy is an invisible resource whose resultant waste is invisible as well. However, in the case of wet cooling systems (who are the single highest energy consumer in vinification processes), not only is the waste heat emitted to the environment but other

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[8] This method is becoming unpopular as new uses of solids are currently being realized.

wastes such as wastewater, used chemicals, and air emissions are generated. The waste from energy usage is mainly 'waste heat' and has received little attention in the wine industry to date.

Contrary to the lack of energy quantification in the wine industry, water quantification has been done in many different regions over several vintages globally. For instance, in South Africa water intake per unit throughput has been reported as 3-8 liters per liter of wine produced (Lorenzen et al., (2000)). An earlier survey had established the specific water intake (SWI) to be the in the range of 80 to 440 liters per hectoliter of wine during cooling and washing processes (Steffen Robertson and Kirsten Consulting Engineers (SRKCE); 1993).

Figures for the water usage in Canada (Ontario MOE, 1986) were reported as 1200 liters per hectoliter of wine, while in Australia findings showed that 2 - 5 kiloliters of water are consumed for every ton of grapes crushed (National Water Quality Management Strategy, 1995). However, after implementation of water reduction strategies suggested in the National Water Quality Management Strategy (NWQMS) report, the water consumption dropped to 1 - 3 megaliters per 1,000 tonnes of grapes crushed (Chapman et al., 2001). No similar results have been published to date explicitly quantifying energy usage from an integrated energy management perspective in any wine growing region globally.

On the other hand, it is significant to note that energy usage in the wine industry is substantial and for diverse purposes including lighting, wine transfer, pumping of wastewater for irrigation, heating of fermentation tanks, refrigeration (wine cooling), driving heavy machinery (such as crushers, pressers, filters, etc), bottling of wine, air conditioning and humidity control in barrel aging, filtering of juice or wine, and in the cleaning processes[9]. In practice, the refrigeration processes account for more than half of the sector's electricity use and contribute significantly to peak demand loads during grape harvesting season.

The most significant impact of high energy consumption in wine production is largely on production cost. Such an impact should be viewed in the light of shrinking energy resources globally, which in turn dictate both energy prices and availability. Thus, it is important to find strategies that can mitigate against high energy consumption during

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[9] Especially in facilities where pressure guns or clean-in-place (CIP) systems are used for the cleaning purposes.

the cooling processes in the vinification process.

2.4.1 Energy Sources

In South Africa, diverse energy sources exist to meet both domestic and industrial demands. The major energy sources are coal, synthetic fuels, oil, natural gas, and electricity (from coal, nuclear plants, gas turbines and hydroelectric power stations). This diversity brings into play varying magnitudes of the environmental impacts associated with generation of electricity from different energy production sources. Therefore, to reduce the environmental degradation associated with electricity production, it becomes a crucial decision for the energy-end users to be prudent in energy management. Three merits are advanced in support of this view.

First of all, the pressure on the electricity generating sources which are accompanied by huge negative environmental impacts are leveled, or decreased, as the energy demand is curtailed in cases where the energy-end users implement effective energy conservation measures. Secondly, the energy-end users recoup large savings as energy accounts for a high percentage of operational costs especially in the vinification process in the wine industry, and particularly during the cooling processes. And thirdly, the challenge on users to devise strategies to mitigate the potential ecological systems disruption if the wasted heat, emissions to the air and water, and used chemicals (such as biocides) that enters into the environment are greatly minimized or effectively eliminated.

2.4.2 Integrated Energy Management

Wine cooling forms the bulk of the energy demand in the vinification process. In this section, some strategies for reducing the cooling demand are discussed. It should be noted that the cooling demand is highly dependant on several factors and the possibility of prescribing comprehensive energy management strategies applicable to all processes in the vinification process is seemingly an impossible task. Central to this observation is that, cooling demand is largely process-, site- and facility size-specific as are the personnel practices in a given facility with respect to the energy usage. On the other hand, seasonality of the wine production processes play a key role as a principle determinant in governing energy usage, as it introduces wide spatial and temporal variations owing to process- and facility-specificity. It is on the basis of the afore-mentioned constraints that only the most salient features which govern both cooling system efficiency and environmental performance will be treated in this work.

In any facility, the cooling system has to meet both the process requirements and environmental performance without loosing sight of cost-efficiency. Cooling systems are based on thermodynamic principles and designed to promote heat exchange between the process and coolant. Secondly, they facilitate the release of non-recyclable heat into the environment.

Two approaches exists that can improve the cooling process efficiency and minimize or prevent adverse environmental footprints associated with the process namely: technological changes and operationally oriented techniques. Some of the possible technological options involve the change of cooling technology and modification of existing equipment and chemicals used for scale and corrosion prevention. However, technological changes for existing facilities are confronted by serious delimiting factors including: lack of space for expansion, inadequate operating resources, and existing legislative restrictions, which may be fixed and therefore leave few degrees of freedom to allow any meaningful changes. In this study, where the focus is on the existing cooling installations, there is a limit to the degree to which technological modifications feasiblly result in system efficiency improvements and overall environmental performance of the cooling system.

On the basis of the foregoing argument, it is critical to integrate technological modifications with operationally-oriented approaches to achieve optimal results with respect to reductions in energy consumption. The operational techniques improve cooling system performance through good energy housekeeping practices. The operationally-oriented techniques include: maintenance of cooling systems, monitoring of cooling processes, optimization of operations, and control of the cooling system. Maintenance on a regular basis is critical to ensure non-build up of scales and corrosion, while regular monitoring helps to identify leaks and spills for both process and coolant fluids.

In practice, although each approach has inherent merits when employed singularly in a given facility, its limitations prove critical in delimiting it from yielding optimal performance. This is because real world cooling system challenges are too complex to be solved from a linear thinking perspective. Thus, this pitfall can be addressed by adopting the integration of both approaches in order to improve or maintain the cooling system performance with respect to the environment and energy management.

Any operating cooling system has associated environmental aspects. The two key aspects are the overall energy efficiency and emissions to the environmental media. As earlier stated, both energy consumption and emission levels are very site specific and hence very difficult to generalize. Nevertheless, some of the environmental aspects associated with cooling processes are:

1. **Energy consumption**: In any industrial cooling process, the energy requirement can be considered as direct or indirect consumption. Direct consumption refers to the use of energy to operate the cooling system. In this case, the main energy consumers are the pumps and fans. It works on the principle that the higher the resistance that has to be compensated to maintain the required air or water flow, the more energy a cooling system requires. The final quantity of energy consumed will thus be a function of complex factors such as climate, air or water flow rates, pressure differences, the medium to be pumped (gas, liquid or solids), water lift in the case of cooling towers, to mention but a few.

   The direct energy consumption can be reduced by installation of pumps and fans of higher efficiencies. Resistance and pressure drops in the process can be reduced at the design stage of cooling system, however, for the existing installations proper mechanical or chemical cleaning of surfaces maintains low resistance for air or water flow.

   Indirect consumption is the energy consumed by the process to be cooled. This energy consumption is mostly due to sub-optimal cooling performance of the applied cooling configuration. The indirect energy usage can be minimized in two ways. One way is by selecting a cooling configuration with the lowest specific indirect energy consumption or by implementing a design with small approaches[10]. The other option

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[10] Small approaches for a heat exchanger device implies, the temperature difference between the temperature of the process medium leaving the heat exchanger and the temperature of the cooling medium entering the heat exchanger should be small.

is by the reduction of resistance to the heat exchange achievable through maintenance of the cooling system on regular basis.

2. **Water**: The water environmental aspect in the wine industry for cooling systems is as a result of its consumption and consequent emission into the environment. In most cases water is the predominant coolant in wet cooling systems. However, in other cases, quantities of water used for cooling are high and urgent measures are necessary to minimize such consumption owing to the scarcity of water resources especially in a country like South Africa, associated high effluent treatment costs and stringent legislative requirements for effluent disposal. The following strategies have the potential to reduce water consumption and emissions into the environment:

    (a) Replacement of once-through systems with recirculating systems. This not only reduces the quantities of water consumed but also minimizes the emission of chemicals and other wastes from the cooling system to the receiving environmental media.

    (b) For existing recirculating systems, the number of cooling water cycles should be increased before blow-down. This is achievable through the improvement of make-up water quality or by optimizing the reuse of wastewater resources available on site.

    (c) Reduce the need for cooling by ensuring that the grapes are harvested at low ambient temperatures (especially at night or early hours of the day). This practice yields good results in the reduction of cooling process energy demand at the maceration stage of the vinification process.

    (d) Pre-treat the cooling water using techniques such as flocculation, precipitation, filtration or membrane technology to ensure that the number of blow-downs are reduced thus reducing effluent quantities released from the cooling systems to the environment.

3. **Emissions of substances into air and water**: Emissions can either enter into the surface water or air from a cooling system. Most emissions to the air are from the wet cooling towers, however, in this study, the focus is on energy minimization during a cooling

process using the heat exchangers, thus air emissions will not be considered.

The non-benign emissions to the surface water from a cooling system are attributed to one or a combination of the following sources:

(a) Application of cooling water additives and their reactants.

(b) Corrosion products caused by corrosion of the cooling plant equipment.

(c) Leakage or spillage of the wine or wine by-products.

In order to reduce the impact of these emissions into the environment, the following ways have been found to yield good results;

(a) The best way to deal with the need for cooling water conditioning is by reducing the occurrence of fouling and corrosion through regular maintenance and monitoring of the cooling system for existing plants. In certain cases, coatings and paints can be applied to protect the surfaces from corrosion and fouling, resulting in a remarkable reduction in the use of biocides.

(b) Device mechanisms that prevent and reduce the leakage or spillage of wine into the cooling circuit.

(c) Replace the hazardous and toxic cooling water treatment additives (biocides) with environmentally benign chemicals or non-chemicals to minimize and or prevent the emissions impact.

(d) Optimization of biocide applications to the cooling water through effective monitoring and correct dosing. It should be noted that it is a good practice to reduce the input of biocides through targeted dosing in combination with monitoring of the behavior of macrofouling species and using the residence time of the cooling water in the system.

In designing the decision support system for the energy minimization during a cooling process presented in chapter six, an integrated approach in applying the concepts discussed in the foregoing paragraphs was adopted. This was to exploit the synergies achievable through the application of both technological innovations and good energy housekeeping practices with an objective of minimizing energy consumption.

2.5 System Boundary Definition

The critical aspect in finding solutions to a specific domain of knowledge is firstly through unambiguous definition of system boundaries. It follows that the most important step in system design is to establish clear, practical definitions of the function and boundaries of "the system". In other words, to what extent will the system cover the problem domain? The system in this case was defined as the entire vinification processing line consisting of a series of individual processes and operations as depicted in Figure 2.1 when considering the waste management problem.

Definition of boundaries and functions controls the aspects to be addressed in terms of technologies, alternatives to be considered, and the criteria to be used in guiding a systematic evaluation of the alternatives. For instance, waste and energy management alternatives were derived from a systems approach perspective where the unit operations and processes associated with the manufacturing process were considered. This focused on explicit identification of raw material extraction, different manufacturing activities and energy consumption till the final product leaves the production line.

On the other hand, the breadth of the system boundary has a direct impact on the size of the knowledge base, which in turn influences the effectiveness of the decision support system. Clearly this follows from the fact that knowledge contained in the knowledge base determines the usability of the decision support system.

It is from the foregoing discussions in Parts I to III that an attempt was made to address the question of scope and definitions in order to lay the basis for the establishment of concepts employed in this work. On the basis of a well defined systematic approach, the entire manufacturing process was qualitatively optimized to reduce waste generation. However, the problem of energy consumption was only considered from the grape harvesting process stage to the first cooling stage using heat exchangers. The definition of system boundaries is also crucial during the process of evaluation, verification and validation of knowledge authenticity contained in the knowledge base. This is because the scope of a well defined problem can be easily validated by experts to a reasonable degree of accuracy.

Unlike in the chemical manufacturing processes, where the system boundaries are defined based on unit operations, in the food and beverage industry and specifically the wine making process, such a scope and breadth of system boundaries is unattainable. This is because, firstly the processes are batch in nature and seasonally dependent. Secondly, there are inherent wastes from the raw materials that can only be sufficiently handled by other systems or processes outside the vinification process. Choosing global (unlimited boundary to ensure zero environmental impact)[11] system boundaries therefore enhanced the process of deriving comprehensive waste and energy minimization alternatives in this knowledge domain. Thus, by defining expanded plant boundaries, the input wastes[12] and those generated in the course of production can be accounted for in a global waste vector.

As discussed by Cohen and Allen (1992), waste minimization for industrial processes is evolving apparently with at least three generations of activity. The first generation entails good housekeeping, inventory control and minor changes in operating practices. The second generation is concerned with infusion of modern technologies in modifying existing operations and processes to reduce effluent quality and quantity properties. Third generation is envisioned to deal with highly selective separation and reaction technologies, specifically designed for waste minimization applications.

During the design of the decision support system for the wine industry, the first and second phases of waste minimization techniques were adopted in deriving waste management alternatives for existing wine making plants. This approach can be regarded as a retrofitting process which constituted process analysis and waste stream analysis (Mulholland, 2000; Mulholland et al., 2001). A systematic approach investigating feasible waste minimization strategies conducted in the wine industry, revealed a large number of alternatives on ways and means through which waste(s) can be prevented (eliminated), reduced or recycled. The findings of this study are presented in chapter 4. It is thus clear from the foregoing discussion that explicit identification of the problem boundaries has a profound impact on the viability of determining feasible waste and energy minimization solutions in the wine industry.

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[11] It should be noted that the global boundary includes processes or plants outside the vinification process that accept materials that otherwise can be regarded as waste from their original generating process(es) or operation(s). Such widened latitude has a merit of ensuring an effective tracking of materials into the system, specifically inevitable by-products that can be useful feed materials in other processing facilities.

[12] Inherent input wastes implies impurities contained in the raw materials, in this case grapes, which cannot be removed before the vinification process commences (e.g. leaves, stems, skins etc.).

Chapter 3

Tools for the Development of Intelligent Decision Support Systems

A background summary of the tools that were used for the development and implementation of intelligent decision support systems for waste and energy management in the wine industry are presented in this chapter. However, first the characteristics of the databases existing for waste and energy management problem domains in the wine industry are examined. This is for the reason that the type and nature of data accessible in a real-world problem significantly influences the choice of artificial intelligence (AI) tool(s) suitable for the development of a decision support system in a defined domain of knowledge. As a result of diverse data features in a particular problem domain necessitates the development of a hybrid system, that has the ability to deal with such diversity effectively and adequately.

In the process industries and particulary in the wine industry, data and knowledge of the process variables and operations can be described as structured or unstructured, numerical or symbolic, precise or imprecise, complete or incomplete, and certain or uncertain. To use such diverse data and knowledge with an objective of developing an automated decision support tool, integration of multiple artificial intelligence (AI) technologies was essential. Thus, in this study, expert systems (ES) and fuzzy logic (FL), generally referred to as knowledge-based systems (KBS) technologies, were employed for the development of a hybrid intelligent decision support system (IDSS) for the automation of waste and energy minimization analysis in the wine industry. The qualitative reasoning (QR) which is part of the AI domain was also used as a means of representing and making inferences using common-sense regarding possible 'states' of processes, operations or system outputs mostly on the basis of personnel actions/operations and technology employed. Indeed, QR proved crucial in creating numerous problem and solution scenarios that helped in formulating the solution space, which is the core of the work reported in this dissertation.

3.1 Domain Databases

In solving a problem that requires the incorporation of expert knowledge, the characteristics of databases accessible which describe the process variables, play a critical role in determining the choice of tool(s) to implement the expert knowledge. In the development of IDSS for the wine industry, highly fragmented databases were encountered, and in certain instances were unavailable, particularly with respect to waste and energy management.

The available data and information were expressed in several formats: numerical data (e.g. water and chemical measurements, quantities of grapes crushed, wastewater characteristics, temperature ranges during the cooling processes, etc.), qualitative data (perception of process trends by managers and operators, qualitative estimations of the operative variables) and relationships or dependencies among these data. In a nutshell, the databases in the wine production domain can be broadly described as both qualitative and quantitative (see Figure 3.1). Interestingly to note is the fact that the complexity in managing such diverse data types falls within the scope of AI techniques.

3.1.1 Quantitative Data

Although there is limited numerical data available in the wine industry, quantification of its usefulness in decision making towards minimizing raw materials and energy consumption, and resultant waste generated during the vinification process is a Herculean task. Data description and its translation into an executable computer programme of the expert knowledge becomes very difficult or impossible owing to the nature of human descriptions and data obtained from the process. The two main quantitative data sources in this domain are:

1. On-line measurements such as: influent, effluent, and temperature of the wine during

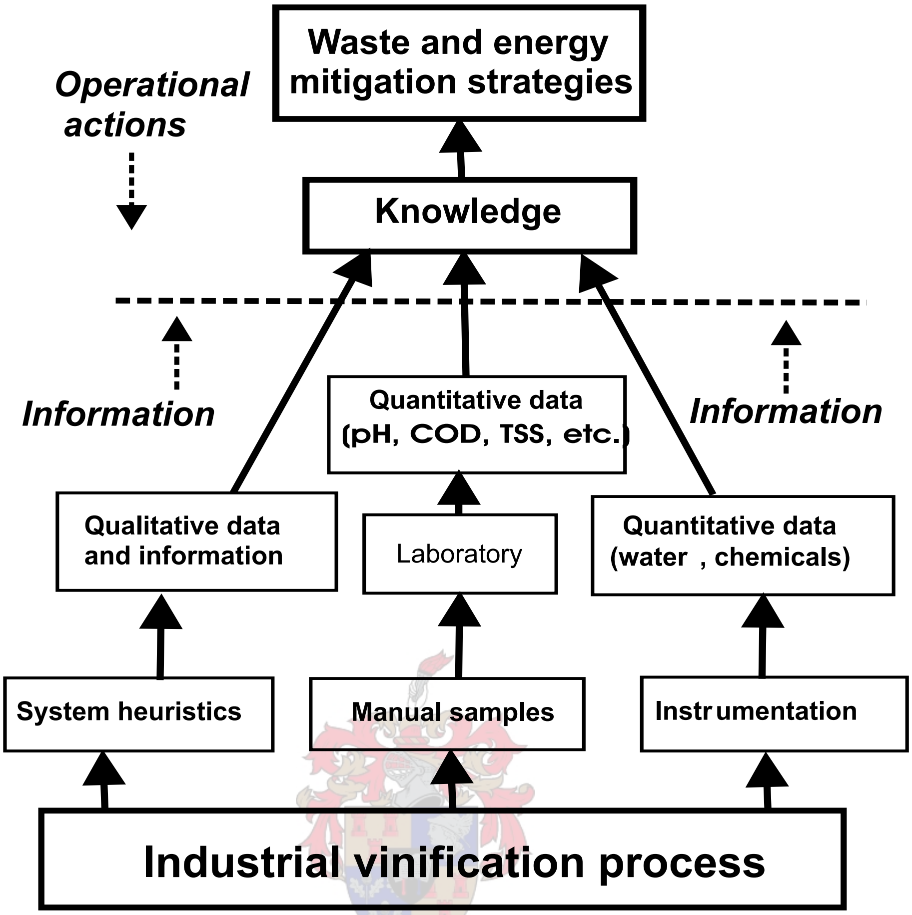

Figure 3.1: Overall data and information structure for the vinification process, exhibiting both qualitative and quantitative features.

the cooling process are obtained. Apart from the temperature measurements, the other variables are not monitored on a daily basis.

2. Owing to the legislative requirement, wastewater effluent characteristics are determined on a weekly basis. The off-line analytical quantitative data from the effluent samples at a specific winery include: organic matter (expressed in terms of COD and BOD values), suspended solids (SS), pH, total dissolved solids (TDS), conductivity, faecal coliforms, and metal ions present (potassium, sodium, calcium and magnesium)[1].

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[1] Determination of magnesium, sodium and calcium concentrations is essential for the computation of sodium adsorption ratio (SAR).

On the basis of the quantitative data obtained from various sources described above, two observations are proper to infer at this stage. First, although some databases have been developed with respect to influent and effluent in certain plants, nevertheless, in most cases they were not used or underused in informed decision making processes that seek solutions with respect to waste prevention and mitigation.

Secondly, investigations on the winemaking operations revealed that off-line data with respect to effluent characteristics is obtained with a significant delay after the wastewater generation. Since the analyzed samples are drawn from the final collection dam, the information they convey becomes impossible to use effectively in targeting specific processes and unit operations that generate part of the final effluent (also taking into account that it is a batch process). Moreover, as the data cannot be accessed in real-time when the particular processes or operations generating the effluent are in progress, it could therefore not support the operators in making instantaneous decisions with regards to formulating possible waste mitigation strategies. In winery unit operations and process settings, the data available at the time decisions need to be made on waste management is usually incomplete and non-quantitative. In this sense, the qualitative reasoning methods (linguistic level reasoning) are more suitable than traditional mathematical methods in building decision-making models.

In spite of the above cited shortcomings in this work, quantitative data was viewed as being significant to a certain degree. The reason being that it provided intuitive insights into a possible spectrum of scenarios that may have lead to the reported statistical data[2] (see the discussion in section 2.2.2). In particular, such data served as a useful guide in constructing "possibility space" for both the quality and quantity of wastewater generated as well as the quantity of the chemicals consumed based on a set of descriptive scenarios of the winery operations using QR.

It is acknowledged that, in certain instances, the numeric data variance and deviations for a given variable (e.g. COD, BOD etc), even on the same winery were so wide that a number of inferences drawn from the data were sometimes highly contradictory. However,

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[2] The validity of this view holds on the assumption that the sampling of the specimens was correctly done. Where the sampling is wrongly undertaken, it introduces errors in the data that may lead to wrong prognosis especially in an attempt to establish the underlying causes of the reported data.

through the construction of a possibility matrix space illustrating how different possible actions and practices may have impacted on the waste output, it was possible to present to the user diverse scenarios of the waste status (in terms of quantity and quality, and quantities of chemicals consumed) and amount of energy consumed in a given process. This was achieved by demonstrating how the variation of operator actions and practices, and management decisions in terms of operating conditions of the equipments, the input materials (in reference to quantity, quality and toxicity) used among other factors, has a direct or indirect impact on resultant waste matrix and resource consumption.

In accomplishing these tasks, all possibilities for a specific action(s), practice(s), operation(s) or condition of the processing equipments were considered. The boundaries in each case were defined ranging from best case scenario to the worst case. This concept will be fully presented in chapters 5 and 6. This was possible by employing the QR technique to model the physical winery systems and the accessible numerical data.

A peculiarity was noted in the wine industry, in that qualitative information on the processes undertaken or process variations arising in a certain process simultaneously were not registered systematically in relation to the numerical data presented (see Table 2.2). Such anomaly evidenced by high (abnormal) data values above the mean or other notable changes in the data made it rather difficult to relate the actions or operations and the quantitative data reported. In fact, the inaccessibility of such critical information rendered the interpretation of data and its consequent application for the development of a decision tool rather difficult. Thus, in certain instances, the link between process operations, processes, and the reported data could not be ascertained.

On the basis of foregoing arguments, the application of AI tools that require quantitative data for their functionality, were rendered unsuitable candidates of choice for the design and development of an intelligent decision support system in the wine industry, particularly with regard to waste and energy management.

3.1.2 Qualitative Data

Interviews with experts and operators in the wine industry reveals that reasonable qualitative data exist although it is not systematically documented with respect to waste and energy management. In an attempt to acquire the qualitative data, the tools provided by the ESs for the extraction of useful information were used, and in this domain, manual knowledge acquisition techniques were found to be most suitable.

Using this technique, the key qualitative variables controlling waste generation and quantities of energy consumed, were identified and captured. Key variables were identified in order to focus attention on the most important issues. The methodology for the identification of the key variables was through an integration of various qualitative techniques of systems analysis such as interpretive structural modeling (ISM) (Warfield, 1973) and fuzzy set theory (Zadeh, 1965; Zadeh, 1996a).

During the interviews with operators and/or experts, they often used examples to present the domain knowledge, which remarkably differed from numeric data, which represented instantaneous sample of measurements, or estimations of the process variables. For instance, in cases where the operator described situations/scenarios or attempted to match the process variables with possible outcomes with regard to its effects on waste or energy management, this was accomplished through using imprecise descriptions of their possible magnitudes. The following example clarifies this argument further:

> "When the organic sources are *effectively* removed from surfaces and equipments before wet cleaning, the final effluent quality is *relatively higher*, the volume of water required for cleaning *decreases* and the demand for the cleaning chemicals is *significantly reduced*".

Such a statement describes an action (*removal of organic sources*) performed by the operator(s) and its corresponding impact on the resultant waste quantity and quality, and resources consumption. The statement is an imprecise description of numerical magnitudes, but interestingly, it's easily interpreted by humans though very difficult to express numerically at any instance during the cleaning process.

On the one hand, some of the qualitative variables were found to be non-ordered (e.g. pre-cleaning of equipments) and it became apparently essential to define their possible categories with quantifiers like: *adequately done, fairly done, poorly done* or *not done*. On the other hand, in order to ease the qualitative ordered variables interpretation (e.g.

equipments used for cleaning such as hose pipes, high pressure cleaners, etc.), it was necessary to divide their interval of possible values into different ranks or modalities. For example, in examining the efficacy of water conservation, the cleaning equipment efficiency was quantized as *very low, low, average, high* or *very high.* Such classifications enhanced the quantification of qualitative data, and offered a transparent modeling technique in expressing complex system interactions through the deduction of linguistic rules without invoking rigorous mathematical formalisms.

On the basis of the observed data features accessible in this problem domain, AI tools with the ability to capture and represent qualitative non-numerical data explicitly, as well as express relationships among imprecise variables taking into account uncertainty and approximate information, became apparent candidates of choice in the building of an intelligent decision support system for waste and energy management in the wine industry. In summary, the tools adopted in this study were able to integrate:

(i) a reasoning mechanism based on the use of linguistic symbols such as; *good management, effective organic matter removal, sufficient recycling* and *reuse*, etc. expressed not on a numerical scale but on a discontinuous scale with reference to a deviation from a set point;

(ii) an uncertainty on variables or influencing factors where they were translated into a precise set of outputs depending on the user responses and;

(iii) outputs which were as a result of an implicit or explicit interpolation between specific states as clearly defined by experts or as reported in the literature.

All the above described tasks were found fundamentally within the scope of AI, particularly by employing qualitative reasoning and modeling techniques where expert system and fuzzy logic technologies offered distinctive merit in building systems whose input data has features described in the preceeding paragraphs. Figure 3.2 depicts some of examples of AI technologies that can be used for the design and development of decision support systems. In this dissertation, the linguistic based approaches were employed.

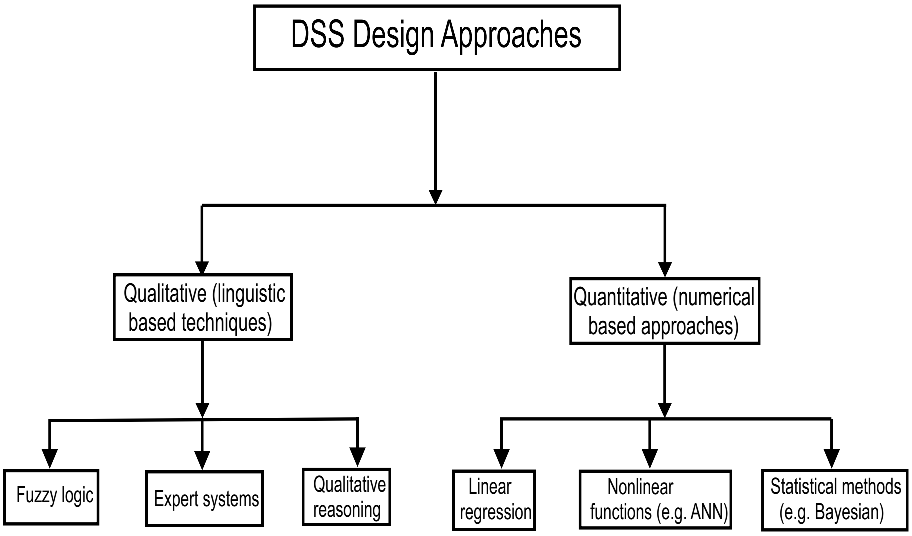

Figure 3.2: Classification of process history based algorithms that treat the integration of expert knowledge in an industrial decision support system.

3.2 Artificial Intelligence

Artificial intelligence (AI) is the structured development of theory and methodology that enable computers to be intelligent through representation and manipulation of data, information or knowledge in a way of approximating or mimicking human results (Fu, 1994; Winston, 1984; Russell and Norvig, 1995). The use of AI in design and development of a decision support system for waste and energy management in the wine industry is borne from its ability to allow the incorporation of interactive, dynamic, uncertain, implicit, and qualitative features of accessible data in this domain, which is amenable to comprehension by both operators and management during decision making process and/or production.

The data, information, and knowledge features in the wine industry display some of the salient problematic and unique environmental attributes as described by Rizzolli and Young (1997), and Guariso and Werthner (1989). In this case, AI tools provided a superior approach in comparison to the most powerful conventional analytical techniques in developing a DSS for waste and energy management in the wine industry. The advantage being that the approach did not require an understanding of the explicit knowledge on both microscopic and macroscopic mechanisms of the process. As a result, the task was accomplished by exploiting the intelligent approaches' ability to deal with available information and knowledge mostly expressed in linguistic rule terms accrued by operators and experts through experience.

In the last quarter of the 20^{th} century, AI technologies applications in industry experienced an exacerbated growth. This growth can be attributed to the flexibility, applicability and versatility of AI tools in diverse knowledge domains. This was also coupled with large financial gains through savings and earnings occasioned by these applications. Examples of domains where AI tools have been applied are business, power generation, engineering, environment, urban planning, medicine, technology management and knowledge management just to mention a few. With such exponential growth on AI applications in diverse disciplines, and in keeping track of the subject progress in various knowledge domains, excellent periodical reviews have been documented by Liao, 2004; Liao, 2003; Wong and Monaco, 1995; Muratet and Bourseau, 1993, Stephanophoulous and Fan 1996; Chan and Huang 2003; Madan and Bollinger 1997. However, AI applications in the food and beverage industry have been few and far apart in different specific domains, as correctly observed by Linko (1998).

The four dominant AI technologies are the (crisp) rule-based or expert systems (ES) (Hayes-Roth et al., 1983; Hunt , 1986; Waterman, 1996, Marakas, 1998), fuzzy logic (FL) (Zadeh, 1965; Yen and Lugari, 1999), artificial neural networks (ANNs) (Haykin, 1998; Bishop, 1999; Hertz et al., 1993) and case-based reasoning systems (CBR) (Kolodner, 1993; Riesbeck and Shank, 1989).

As illustrated in Figure 3.3, although some problem domains can be solved using just one technology (see regions 10, 11, 12, and 13), in numerous cases where complex, non-linear, highly interactive industrial processes and uncertain domains are the target of investigation such as environmental systems, two or more technologies (see regions 1 through 9) are used to enhance the robustness of the decision support. The possible combinations of how this can be achieved is shown in Figure 3.3. In this work, the fuzzy logic system (FLS) and expert systems (ES) (see shaded region 1 in Figure 3.3) were used to implement the expertise on waste and energy minimization during the vinification process as the data available at this stage was not relevant for the application of ANNs and CBSs

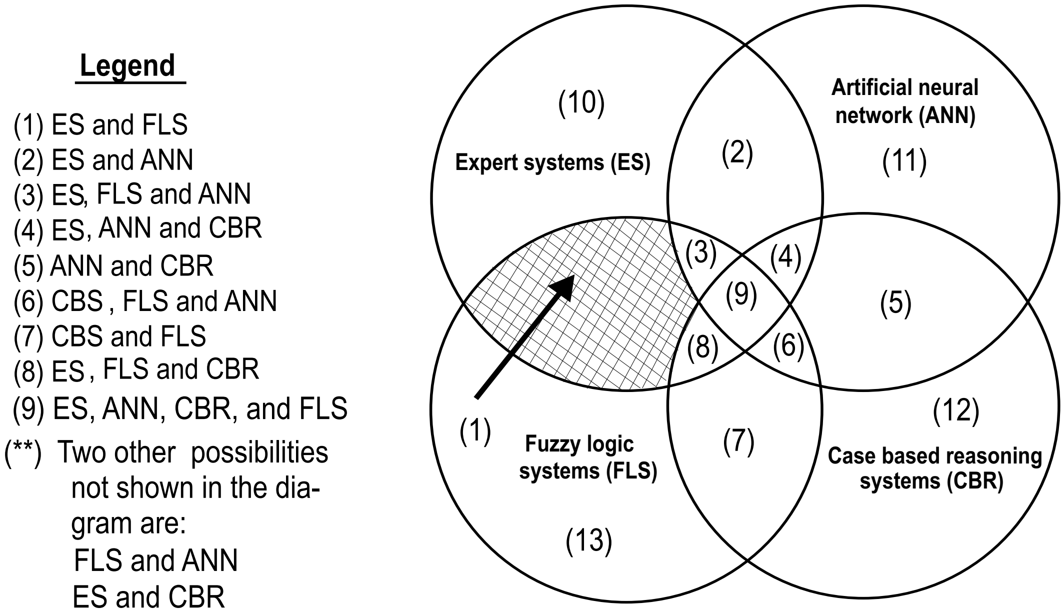

Figure 3.3: The complementarity property of AI technologies in intelligent decision support systems development.

technologies. In the following sections, FLS and ES technologies are treated in detail. Also, QR which was employed to link the ES results with FLS for final system output processing will be briefly discussed as well.

3.2.1 Expert System Approach

Expert systems (ESs) are computational techniques designed to used knowledge and inference procedures to solve problems at the expert level, in a well-specified and narrowly defined domain of expertise (Rich, 1983; Hunt, 1986; Waterman, 1996). These systems are desirable in applications under circumstances where approaches based on convectional software and data processing traditions do not provide an appropriate conceptual framework in representing expertise. By its nature, expertise can exist as structured, unstructured or symbolic knowledge and in certain cases as an abstract of relations between variables. The expert system's capability to integrate both qualitative and quantitative data gives it an edge in confronting complex problems, and particulary where the experience of expert(s) is incorporated in finding solution(s) to a specific problem. Therefore, the portability of software makes the use of expert systems very attractive where human expertise is scarce or costly or is likely to be lost through human resource mobility.

Owing to the uncertain, imprecise and symbolic nature of knowledge in numerous knowledge domains, ESs offer a means of dispensing vital knowledge about a specific task or set of tasks without resulting in application of expensive techniques which require reliable data and information[3]. This is borne out of its capability to deal with data uncertainties and having adequate mechanisms of mimicking the reasoning skill of a human expert in a specified domain.

As depicted in Figure 3.4, an ES consists of two basic components namely the knowledge base and inference engine. These components are made independent of each other to facilitate the update of the knowledge base. The knowledge base and inference engine are further supported by subsystems required for knowledge acquisition, interfacing with the users, explanations of the decisions, a working memory among others.

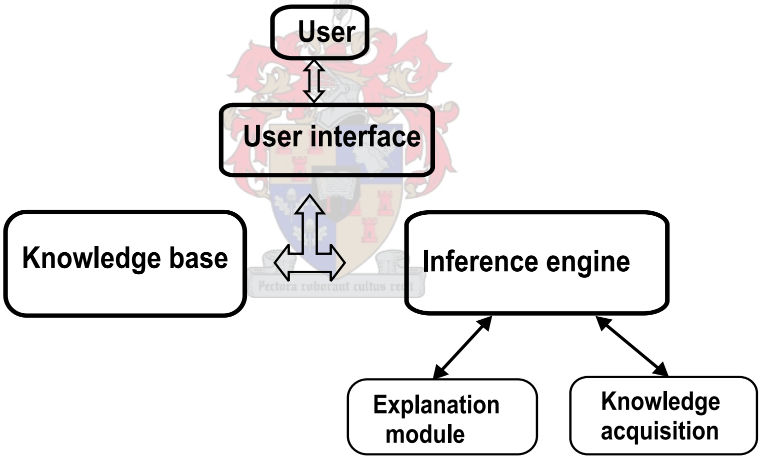

Figure 3.4: A generic expert system architecture.

Knowledge Base

The Knowledge base is the core of the system, and the breadth and quality of knowledge determine the capacity of the system to render useful decision support. In developing the knowledge base, the major tasks are knowledge acquisition and knowledge presentation. The first stage in ES construction is knowledge acquisition where the domain knowledge

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[3] In circumstances where numerical methods are employed for the design of DSSs, highly reliable data is required which is very expensive. This is mainly as a result of extensive installation of sensors, flowmeters and other statistical data acquisition systems, as well as high labor costs on staff for systems administration and data processing.

is extracted, refined and structured in a format amenable for a reasoning process.

The process involves eliciting, analyzing and interpreting the knowledge that experts use to solve a particular problem (Chao et al., 1999; Kidd, 1987) and is the single greatest bottleneck for the development of ES. In this study, conventional knowledge acquisition techniques were used for data and knowledge collection. The knowledge sources used were numerous and are broadly classified as the documented class[4] and the undocumented class [5]. It is significant to note that, in the wine industry there is limited application of sensors and flow rate measurement devices for data logging in most facilities. On the basis of this limitation, automated data acquisition techniques were not applicable to this study.

The second step entails storage of knowledge in the knowledge base. Several modes of knowledge representation in the knowledge base comprise the use of frames, IF-THEN (production) rules, semantic (associative) networks, object-oriented languages, and logic (Quantrille and Liu, 1991; Hayes-Roth et al., 1983). Owing to the simplicity of production systems, the rule-based approach was adopted as means of representing the knowledge because it is closely similar to the natural human language. The rule consists of two parts; an IF clause containing conditions (premise, antecedent, hypothesis) and a THEN clause containing the conclusions (consequent). Each part of the rule can contain one or more clauses which are connected via logical operators like AND, OR, and NOT. The IF-THEN rules are generically of the form:

IF
Before wet cleaning of equipment or surfaces manual organic matter removal is done
AND pre-washing done
AND effluent streams segregated effectively
AND screens were strategically installed along the wastestream
AND an open pipe of small diameter was used for cleaning
THEN

---

[4] Documented sources are based on existing literature for waste and energy management in the wine industry. Under this category, knowledge was obtained from published refereed sources (such as journal articles, reviews, abstracts), books (both text and reference), manuals for operators, magazines, multimedia documents, databases, information from world wide web among other.

[5] This is expertise obtained from experts and operators through a series of structured and unstructured interviews.

MODERATE volume of cleaning water is used
AND effluent of HIGH quality is produced
AND demand for washing detergents decreases

Since the antecedent and consequent parts of the above described rule contains qualitative variables whose values are linguistically expressed, the knowledge manipulation in the inference engine required a system that can deal with such uncertainty. Several mechanisms[6] (see discussions by Hodges, et al., 1999; Kanal and Lemmer, 1986) have been developed to represent and reason with uncertainty arising from the nature of expert knowledge. In this study, fuzzy logic was adopted as a mechanism of choice to deal with such uncertainty.

In the early stages of this study, a method of representing factors and variables as objects, and characterizing each object with a set of attributes that has an associated value, or set of values, was attempted in order to build the rules for the system using decision trees. The waste and energy problem did not lend itself to this method of knowledge representation and reasoning. Secondly, the derived rules were running into hundreds, and many were found to be reductant. In the face of these contrains, it became difficult to evaluate and efficiently validate the high number of rules and a decision was taken to suspend this approach of developing a decision support system.

The ES approach inherently from its systematic characteristic was crucial in identifying numerous factors, processes and operations that had a strong influence on waste and energy management in the wine industry. As such, the approach was essential in integrating knowledge from diverse sources and therefore lead to the design and development of computer-based systems exhibiting both modularity and flexibility properties. Other merits of this approach center on: its ease of development, having a transparent reasoning mechanism and the capability to provide explanations for the solutions provided. In nutshell, the methodologies used in the developement of expert systems proved very useful in this study in extracting expert knowledge from domain experts and other sources.

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[6] Some of these mechanisms includes; Dempster-Shafer (DS) theory, Bayseian networks, certainty factors among others.

3.2.2 Qualitative Reasoning

Qualitative reasoning (QR) also called qualitative physics, is primarily concerned with the application of human common-sense and scientific implications used by engineers and scientists in analysing the environment and situations without invoking mathematics of continously varying quantities and differential equations (Bobrow, 1984; Kleer and Brown, 1984). QR has become an AI domain concerned with means of representing and making inferences using general and physical knowledge about the world. The main goal of QR is to represent common-sense of the physical world, and the underlying abstractions used by engineers and scientists to create quantitative models without turning to rigourous use of mathematical computations.

For instance, we do know that a material becomes hot when heated without requiring to understand its microscopic properties such as specific heat capacity. Given such knowledge and appropriate reasoning methods, the acquired knowledge at the expert system development stage was used to make problem predictions and diagnoses, although the exact quantitative descriptions were unavailable and intractable. Therefore, QR exploits the fact that programs can accept and derive useful inferences from problem statements having much less information than is usually known in traditional mathematics (Hamscher et al., 1995). The crisp numerical outputs generated from QR were fed into the fuzzy logic system as inputs in order to evaluate the overall system outputs[7]. The way QR works without explicitly solving mathematical models is by applying common-sense mathematical rules to the assigned values of the variables (in this case strategies), functions in the model, and the interconnections among these elements, such as constraints.

With the use of qualitative symbolic representations and discrete quantity spaces, modeling of the complex "possible" behaviour of processes and operations on the basis of known knowledge concerning operators' actions and the kind of technology used, turned out to be sufficient to predict process, operations and/or system outputs. The use of a small number of qualitative symbols or values to describe input variables arising from actions of personnel or machines used in wine processing can thus be viewed as the sig-

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[7] What is referred as system outputs in this section are effluent quality and quantity, quantities of chemicals used, quantity of product and byporduct losses, and amount of energy consumption.

nificant contribution of QR in this study.

For instance, in the waste and energy management problem under investigation, QR was used to describe qualitative 'states' attainable with or without implementation of a given strategy aimed in mitigating against waste generation and/or high energy consumption. Thus, a qualitative model was created as our point of departure without involvement of detailed information on implemention of strategies in the winemaking process, or having the necessity of employing traditionalhard-computing whose prime desiderata are precision, certainty and rigor.

Consider for instance the waste minimization strategy the application of counter current method during the cleaning process whose objective is to reduce the quantity of potable water used during a given cleaning process. Using QR, one can predict at least three possible 'states' (which satisfies the condition of using a small number of qualitative values or symbols) after the strategy is applied in a facility. The states were reasoned from casual observations or based on experience from previous measurements where the primary goal was to model the level of the strategy's actual 'effectiveness' after implementation. In this study the reasoning was based on rules of thumb borne out of operators and experts' experience.

The 'effectiveness' of applying a counter current waste minimization strategy in a facility was described by three 'states' namely **effective, partially effective, not effective (applied) at all**. On the basis of knowledge obtained about possible 'states' attainable after implementing or failure to implement an action or strategy during the vinification process, it was possible to predict how a specific strategy impacts the final system output(s). Taking the effluent quantity system output to demonstrate the above concept, and using the knowledge gained from operators and experts on counter current implementation in a facility, a number of possibilities regarding the final effluent quantity can be qualitatively predicted. From QR knowledge, there are three straightforward resultant quantities of effluent predictable from common-sense. These states are: high usage of potable water[8], moderate usage of potable water[9], and low usage of potable water[10]

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[8] It happens on condition that the strategy is poorly or not implemented at all in a facility.

[9] If the strategy is partially efective in terms of implementation in a given facility.

[10] On condition that the said strategy has been effectively implemented in a given facility.

Furthermore, it is significant to note that numerous levels of "effectiveness" are possible in the course of implementing a given strategy. Taking this into account, levels of "effectiveness" that a strategy implementation can generate can safely be described to range from the best case scenario (under proper strategy implementation) to the worst case scenario (under poor or no strategy implementation). In the light of the above observations, the need to increase the predictable states by the envisioned decision support tool arising from the implementation of a single strategy from three to at least five as a way of broadening and increasing the sensitivity of the solution space became clear.

The objective here was to expand the possible states that our system can consider though it is acknowledged that the actual states are infinite. This was achieved through the consideration of uncertainty represented as a degree of belief, or rather level of confidence (CF) the user expresses on a particular response he provides after responding to the questions posed by the system. In this work, only three CF values were presented to the user to chose[11]. The expansion of the possible predictable states was achieved through simple algebraic multiplication of dimesionless scores representing the derived qualitative values of a given strategy by confidence levels (CFs). Therefore, if the qulitative values of a certain strategy are assigned the dimesionless scores x_{i1}, x_{i2}, x_{i3}, and CF values y_1, y_2, y_3, then the possible predictable states from a single strategy or action are given by the model;

$$(x_{i1}, x_{i2}, x_{i3}) \begin{pmatrix} y_1 \\ y_2 \\ y_3 \end{pmatrix} = (x_{i1}y_1, x_{i1}y_2, x_{i1}y_3, x_{i2}y_1, x_{i2}y_2, x_{i2}y_3, x_{i3}y_1, x_{i3}y_2, x_{i3}y_3) \qquad (3.1)$$

where the CF values were fixed at 1.00, 0.75, 0.50 for y_1, y_2, and y_3, respectively and i denotes the strategy under consideration.

Using Equation 3.1, five to nine states of a given strategy representing fuzzy output numbers could be determined. Note that, values $x_{i1}y_1, x_{i2}y_1, x_{i3}y_1$ are equal to the original predictable states from common-sense represented by the values x_{i1}, x_{i2}, x_{i3}.

The challenge associated with integration of diverse strategies or actions characterized by different units of measurement or in certain cases where some were unmeasurable owing to the lack of appropriate instruments was circumvented by assigning each strategy

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[11] This was aimed in reducing the comlexity of the system

or action a qualitative value with a corresponding dimensionless score. The magnitude of the dimensionless score for a given symbolic or qualitative value was a reflection of its potential impact to a specific system output under investigation. In this sense, the scores assigned to a certain strategy with regard to effluent quality were different from those assigned to reflect its impact on the effluent quantity.

To clarify the above assertion, take for instance the case of counter current technique implementation in a facility. The ‘states’ effective, partially effective, and not applied were assigned the scores; 9.00, 4.50, 2.25 when considering effluent quantity while on the other hand in the case of effluent quality, the scores were; 2.25, 4.50, 9.00, respectively. The values assigned are only relevant within a given system output and do not show any interrelationship between the system outputs whatsoever. The assigning of the dimensionless scores was governed by a defined criteria and experts’ opinion in relation to a strategy’s significance measured or rather in comparison against others in a particular category and in the context of a specific system output.

The waste minimization index (WMI) discussed in chapter 5 together with expert’s opinion were employed as a criteria of determining the size of the dimensionless score assigned to a given strategy or action in addressing the waste minimization problem. However, in the case of the energy minimization problem discussed in chapter 6, scores for a specific strategy or action were entirely based on experts’ opinions in the wine industry.

To aggregate outputs from strategies that were viewed to influence a certain variable, where in turn the variable determines the magnitude of a targeted system output, the following arguments formed the basis of the aggregation process. One, that each strategy can only contribute towards waste generation or energy consumption mitigation to a certain degree in a facility. Secondly, no single waste or energy minimization strategy has the capability of solving exhaustively complex environmentally oriented challenges in the wine industry. Therefore, to confront these challenges adequately, it is significant to adopt an integrated approach in implementing the strategies in a winery. Following this line of argument, the magnitude of a specific variable was seen as a function of additions of individual strategies considered to influence the variable. That is, to determine the crisp numerical value of a variable, all scores from strategies influencing that particular variable were summed and normalized. For example, *effluent quality management* variable was found to be a function of several strategies and hence its crisp value was calculated by adding the contribution of each strategy score obtained based on the user's responses in a given winery. The crisp value obtained in this case is a fuzzy number, and was fed into the fuzzy logic system to evaluate a specific system output under investigation, for instance in this case is effluent quality. The principle as discussed in the foregoing paragraphs is schematically illustrated in Figure 3.5.

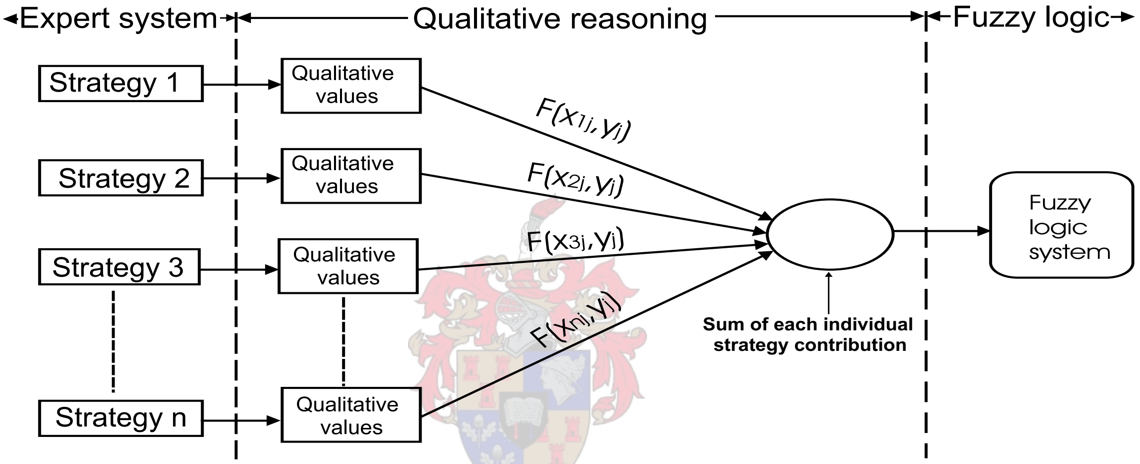

Figure 3.5: Structure of qualitative reasoning during the transformation of qualitative values into fuzzy numbers.

The mathematical representation of a variable (which is in fact the fuzzy logic system input) crisp value is evaluated by the relation:

$$Var_k = \frac{\sum_{i=1}^{n} F(x_{ni}, y_j)}{max \sum_{i=1}^{n} F(x_{ni}, y_j)} \times S_m \tag{3.2}$$

where Var$_k$ is the kth variable under consideration, x$_{ni}$is the dimesionless score assigned to a strategy's qualitative value, y$_j$ is the user's degree of confidence in the response he has provided, n is the total number of strategies that influences the kth variable, j=1, 2, 3 with numerical values 1.00, 0.75, 0.50 respectively and S$_m$ is the mth standardization coefficient where its vaues are 10 for m=1 and 100 for m=2.

To demostrate the significance of the above approach, take the case of effluent quantity system output. The effluent quantity is dependent on three fuzzy input variables namely;

effluent quantity manangement (M_V), equipment efficiency (E_E), and organic matter removal (OMR). Take for instance a situation where M_V depends on 10 strategies. As discussed in this section, each strategy has three qualitative states (descriptors). From a conventional expert system approach, where if-then rules are employed to determine M_V variable by developing decision trees, then a theoretical maximum number of linguistic rules of 3^{10} is required. This obviously gives rise to an impractical situation of attempting to represent the rules in a knowledge base and its clearly unmanageable. However, on the basis of the described procedure, M_V can be dertermined from a minimum of 5^{10} to a maximum of 9^{10} possibility ways stored in a potential state without requiring to codify all the states into the system.

The procedure described above was aimed in addressing the rigidity challenge of a binary system which is a common feature in expert systems. Thus, QR was employed to derive continous granuality of the variables, which is significant in ensuring a smooth transition from one state to the next. The continous granuality of variables and strategies were defined according to the type of reasoning to be performed. For example, temperature qualitative variable is normally described by two states (*low, high*) depending on the temperature of the wine before cooling begins. However, in this study, the temperature variable was defined using *five* qualitative values: *very low, low, moderate, high and very high* to cover more possibility states to enhance decision making regarding the adjustment of energy consumption during the cooling process. The non-linear mappings coupled with abrupt changes of the variables were modeled using fuzzy logic through the use of fuzzy rules and membership functions. Hence, the intent of translating numerical models or relationships into qualitative descriptions was to facilitate the integration of strategies with different units but having an influence on the same variable or by extension the same targeted system output.

3.2.3 Fuzzy Logic

Fuzzy logic is rooted on the concept of fuzzy sets intiated by Zadeh (1965). In an attempt to model and stimulate human linguistic reasoning, Zadeh has demonstrated through numerous articles how humans think in terms of fuzzy sets whose values are words or sentences in a natural or synthetic language (Zadeh, 1965; Zadeh, 1973; Zadeh, 1975; Zadeh, 1994; Zadeh, 1996a; Zadeh, 1997). The fundamentals of fuzzy theory are now well understood and detailed treatment of the subject can be found in specialized literature (Dubois and Prade; 1980, Zimmermann, 1991; Mendel, 1995; Lee, 1990a,b; Yager and Zadeh, 1992; Takagi and Sugeno, 1985; Yen and Lugari, 1999). Since the beginning of the fourth quarter of the 20^{th} century, numerous applications of fuzzy logic have been performed after the first application on the control of model steam engine was reported by Mamdani (1974)[12].

In this section, the fundamental concepts of fuzzy set theory and fuzzy logic required for the design and development of an intelligent decision support system presented in this dissertation are briefly summarized. A complete and detailed discussion can be found in Zadeh (1965); Yen and Lugari (1999); Zimmermann (1991); Kaufmann and Gupta (1985) and Mendel (1995).

Definitions

Let a fuzzy set U be a collection of objects denoted generically by x, which can be discrete or continuous. U is called the universe of discourse and x represents the generic element of U. Suppose a fuzzy set[13] A is subset or class of U characterized by a membership function (MF), $\mu_A(x)$, which takes values in the interval [0, 1], then it can be defined as a set of ordered pairs:

$$A = \{x, \mu_A(x) | x \in U\} \tag{3.3}$$

The MF maps each element of U to a continous membership value (or membership grade) between 0 and 1. Consider A and B be two fuzzy sets in U with membership functions $\mu_A(x)$ and $\mu_B(x)$ respectively. The sets theoretic operations of intersection, union and complement for the fuzzy sets are defined via their membership functions as presented in Equations 3.4, 3.5 and 3.6, respectively;

$$\mu_{A \cap B} = \mu_A(x) \cap \mu_B(x) = \mu_A(x) \oplus \mu_B(x) = min\{\mu_A(x), \mu_B(x)\} \tag{3.4}$$

$$\mu_{A \cup B} = \mu_A(x) \cup \mu_B(x) = \mu_A(x) \otimes \mu_B(x) = max\{\mu_A(x), \mu_B(x)\} \tag{3.5}$$

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[12] By 1995, over 15 000 publications had appeared on theoretical fundamentals and applications of fuzzy set theory since 1965.

[13] A fuzzy set whose support is a single point in U is called a *fuzzy singleton*.

$$\mu_{\bar{A}(x)} = 1 - \mu_A(x) \tag{3.6}$$

The intersection operator corresponds to the fuzzy logic AND operation and is implemented by taking the minimum or the algebraic product (see Equation 3.4), while the union operator represents the fuzzy logic OR operation which is implemented by taking the maximum or the bounded algebraic sum of the two membership functions (see Equation 3.5). It should be noted that, the defined fuzzy logic operations satisfy standard distributivity and associativity properties, thus allowing the application of an operation on more than two fuzzy sets (Zadeh, 1965; Kandel, 1991; Klir and Folger, 1988).

Linguistic Variables

The fuzzy logic systems using fuzzy sets provide a systematic means of manipulating vague and imprecise concepts which are described using natural language. This can be realized by assigning values to the variables in a given domain. In particular, the fuzzy sets are employed to represent the linguistic variables, which are also referred to as membership functions. A linguistic variable can be regarded either as a variable whose value is a fuzzy number or as a variable whose values are defined in linguistic terms (Lee, 1990a). For instance, *Temperature* as a linguistic variable can be decomposed into a set of terms such as *very low, low, moderate, high, very high* within a specified universe of discourse.

Note that each term is a fuzzy set and characterized by a MF, which takes values in the interval [0,1]. Thus, if an element is described by MF that has a value of one (μ=1), then the element belongs completely to that set, if MF is zero (μ=0), then it does not belong to that fuzzy set; and a special case arises when MF value is between zero and one ($0 \leq \mu \leq 1$), then the element partially belongs to the fuzzy set.

To transform a crisp data into a fuzzy set(s) is achieved using a fuzzification operator and the process is called fuzzification. The most commonly used shapes for membership functions to represent fuzzy numbers are triangular, trapezoidal, piecewise linear and Gaussian (Klir and Yuan, 1995; Mendel, 1995).

Fuzzy Rules

The expert knowledge is expressed in conditional form, such that, when the conditions are satisfied then one or more conclusions are inferred. Therefore, the dependence of the fuzzy variables is expressed using the conditional statements of the form:

IF (satisfied set of conditions) **THEN** (a set of consequences can be inferred)

In this case, a fuzzy rule is a fuzzy conditional statement in which the antecedent part is a condition in its application domain and the consequent is a conclusion inferred based on input specifications. Fuzzy rules are quantified using fuzzy implication functions (Klir and Yuan, 1995; Lee, 1990b). The most significant types are three and have been used in this work namely; fuzzy conjuction (AND), fuzzy disjunction (OR) and fuzzy implication (THEN). With the use of logical operators, fuzzy IF-THEN rules can be constructed with one or more antecedent clauses and consequent part of the form:
R1: IF x is A THEN z is C
R2: IF x is A_1 AND y is B_1 THEN z is C_1
R3: IF x is A_2 OR B_2 THEN z is C_2
R4: IF x is NOT A_3 THEN z is C_3
where the subindex of A, B and C indicates different linguistic values of x, y, and z defined by fuzzy sets in the universe of discourse X, Y, and Z respectively.

Fuzzy Decision-Making Algorithm

Fuzzy reasoning, also known as approximate reasoning is an inference mechanism used in deriving conclusions from a set of IF-THEN rules with one or more conditions. The logical operations AND, OR or NOT are applied to the membership functions instead of the input values directly. Though there are several methods of inferencing used in practice, the most popular ones are the so-called MAX-MIN method and MAX-DOT or MAX-PROD method (Lee, 1990b). These methods in practice are expressed as follows:
The MAX-MIN notation;

$$FuzzyAND : \mu_{C1}(z) = min[\mu_{A1}(x), \mu_{B1}(y)] \tag{3.7}$$

$$FuzzyOR : \mu_{C2}(z) = max[\mu_{A2}(x), \mu_{B2}(y)] \tag{3.8}$$

$$FuzzyNOT: \mu_{C3}(z) = 1 - \mu_{A3}(x) \tag{3.9}$$

The PROD-SUM notation;

$$FuzzyAND: \mu_{C1}(z) = \mu_{A1}(x) \bullet \mu_{B1}(y) \tag{3.10}$$

$$FuzzyOR: \mu_{C2}(z) = 1 - \mu_{A2}(x) \bullet \mu_{B2}(y) \tag{3.11}$$

$$FuzzyNOT: \mu_{C3}(z) = 1 - \mu_{A3}(x) \tag{3.12}$$

The MAX-MIN inference algorithm (Mamdani, 1974), which is the most popular was used in the inference process in this study. The degrees of fulfillment of the fuzzy rules in question were computed as the minimum of the corresponding degrees of membership. In rule evaluation, owing to the partial matching attribute of fuzzy control rules and the fact that the preconditions of the rules do overlap, oftenly more than one rule is evaluated at a time for a set of crisp inputs. This occurs when several rules are partially or fully fulfilled by the crisp input values.

For example, consider the following set of rules whose conditions have been partially or fully satisfied when inputs x and y in their respective universes of discourse X and Y are mapped into z in the discourse Z.

Rule 1: IF x is A_1 AND y is B_1 THEN z is C_1
Rule 2: IF x is A_1 AND y is B_2 THEN z is C_2
Rule 3: IF x is A_2 AND y is B_1 THEN z is C_2
Rule 4: IF x is A_2 AND y is B_2 THEN z is C_3

Assuming that each linguistic variable A and B has three fuzzy sets whose values are A_1, A_2, A_3 and B_1, B_2, B_3 respectively, then using the max-min algorithm, resultant output fuzzy set C' can be computed (which in this case, the consequent is: z is C').

The calculation of system output is determined as follows. The crisp input values x and y are fuzzified through discretization process and classified into respective fuzzy sets. The level of discretization of a universe of discourse determines the senstivity of the input variables (Lee, 1990a). The next step is to determine the output of each rule. In this example, the *truth values* for Rule 1 are represented by $\mu_{A1}(x)$ and $\mu_{B1}(y)$ respectively, where μ_{A1} and μ_{B1} represent the membership functions of A_1 and B_1, respectively. Thus, the output strength of Rule 1 is calculated by the expression;

$$\alpha_1 = \mu_{A1}(x) \wedge \mu_{B1}(y) \tag{3.13}$$

where $\wedge$ denotes an intersection (minimum) operator.
Simililarly, the output strength for Rule 2, Rule 3 and Rule 4 are given by the Equations; 3.14, 3.15 and 3.16, respectively;

$$\alpha_2 = \mu_{A1}(x) \wedge \mu_{B2}(y) \tag{3.14}$$

$$\alpha_3 = \mu_{A2}(x) \wedge \mu_{B1}(y) \tag{3.15}$$

$$\alpha_4 = \mu_{A2}(x) \wedge \mu_{B2}(y) \tag{3.16}$$

The output of any rule is calculated using Mamdani's minimum operation rule as a fuzzy implication function. Thus, the strength of the rule output is given by the expression:

$$\mu_{C'i}(\omega) = \alpha_i \wedge \mu_{Ci}(\omega) \tag{3.17}$$

where ω signifies the range of values that the rule conclusions can take.
Applying Equation 3.17 in the rules activated, yields the strength contribution for each rule and in this case are: $\mu_{C'1}(\omega)$, $\mu_{C'2}(\omega)$, $\mu_{C'3}(\omega)$, $\mu_{C'4}(\omega)$ for Rule1, Rule 2, Rule 3 and Rule 4 ,respectively. The aggregated output of the system is determined using the disjunction operator where it yields a pointwise membership function for the combined conclusions of Rule 1, Rule 2, Rule 3, and Rule 4 calculated using Equation 3.18;

$$\mu_C(\omega) = \mu_{C'1}(\omega) \vee \mu_{C'2}(\omega) \vee \mu_{C'3}(\omega)(\omega) \vee \mu_{C'4}(\omega) = [\alpha_1 \wedge \mu_{C1}(\omega)] \vee [\alpha_2 \wedge \mu_{C2}(\omega)] \vee [\alpha_3 \wedge \mu_{C3}(\omega)] \vee [\alpha_4 \wedge \mu_{C4}(\omega)] \tag{3.18}$$

where $\vee$ denotes the union (maximum) operator.

The system output from Equation 3.18 is a fuzzy membership function, specifying a possibility distribution of the output variable and has to be translated into a single value through defuzzification process. Several defuzzification processes have been discussed by Yager and Zadeh (1992); Lee (1990a,b); Berenji and Khedkar (1992), and Mendel, (1995). However, in this work the centroid (the center of area) method had been used because of its sensitivity to the contribution of each rule activated as opposed to other techniques which are strongly biased towards the most dominant rules (rules with higher truth values or firing strengths). The demerit of this method is that, it is computationally complex and slow. The crisp output based on the centroid method is calculated by the expression:

$$z^* = \frac{\sum_{j=1}^{n} \mu_z(w_j)\dot{w}_j}{\sum_{j=1}^{n} \mu_z(w_j)} \tag{3.19}$$

where n is the number of quantization levels of the output[14].

The procedure described above is graphically illustrated in Figure 3.6 where the trapezoidal and triangular membership functions have been employed to represent the fuzzy numbers.

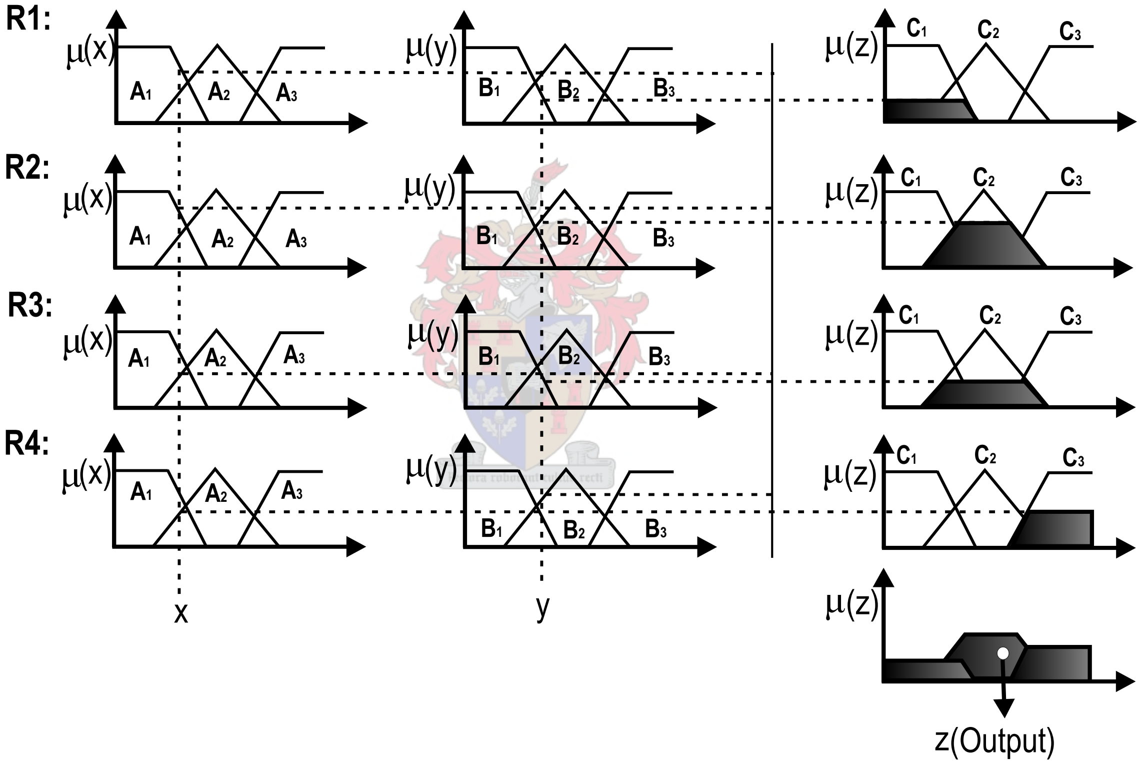

Figure 3.6: Fuzzy inferencing of fuzzy inputs through implicaton, aggregation, and defuzzification processes using the Max-Min gravity method.

Fuzzy Logic System

A fuzzy inference system or fuzzy logic system (FLS) is a computing framework based on the concepts of fuzzy set theory, fuzzy if-then rules, and fuzzy decision-making al-

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[14] If the quantization of the fuzzy sets for the output variable is high, the memory requirement is large and hence the cost to resolute the final crisp value.

gorithm. The basic structure of a fuzzy inference system consists of a rule base, which contains a set of fuzzy rules (from experts and databases), a database defining the membership functions used in the fuzzy rules, and a fuzzy decision-making algorithms that performs the inference procedure upon the fuzzy rules depending on the condition constraints specified to derive a reasonable output or conclusion.

Figure 3.7 depicts the generic components of a FLS. The FLS maps crisp inputs to crisp outputs. It mainly comprises of four components: rules, fuzzifier, inference engine, and defuzzifier. Once the rules have been established, a FLS can be viewed as a mapping from inputs to the outputs. Rules are extracted from experts, numerical data or from reported literature and expressed as a collection of IF-THEN statements. The fuzzifier maps crisp numbers into fuzzy sets. The inference engine via conflict resolution mechanisms deals with the manner in which the rules are to be combined and maps the fuzzy sets into output fuzzy sets. However, in numerous applications, crisp numbers must be obtained at the output of a FLS. Thus, through the defuzzification process the defuzzifier maps the output fuzzy sets into crisp numbers, that are useful in deriving decisions based on the user's responses.

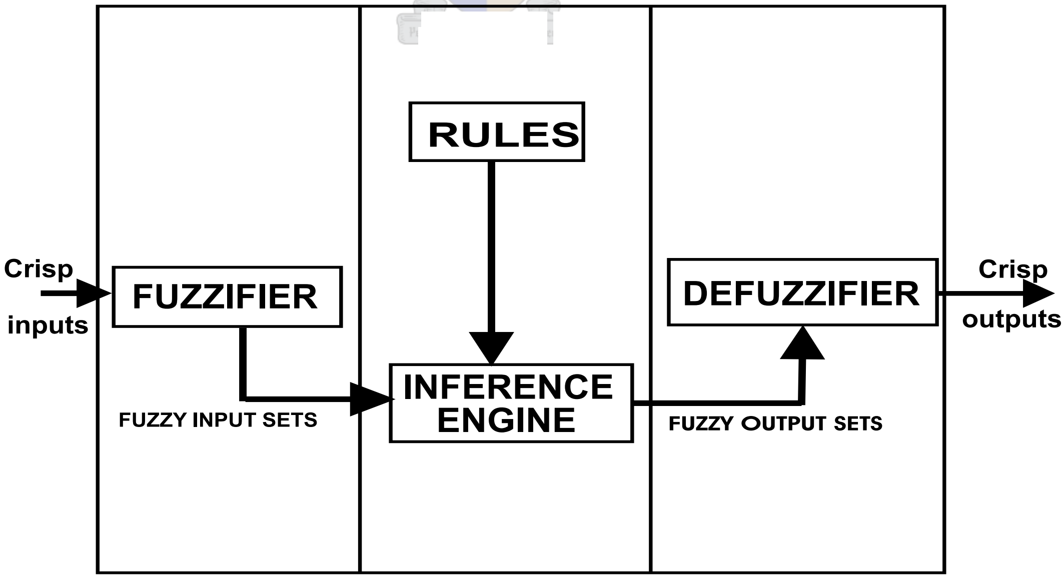

Figure 3.7: Typical scheme of the fuzzy logic system

3.3 Hybrid Intelligent Systems

To derive optimal management solutions in complex systems such as waste and energy management in the wine industry, it became necessary to employ techniques that are adequate and complimentary to each other in several ways. This is because various techniques of computational intelligence have their strong areas but also inherent weaknesses. The techniques and tools of choice had to be adequate in aspects of knowledge acquisition, knowledge representation and efficient in synthesizing the knowledge for decision making under specified operating conditions (both normal and abnormal) besides uncertainty. The overriding objective was to ensure that, the system derives inferences that show a good replica of real world systems to a reasonable extent, or offer a credible criteria for the evaluation of alternatives or/and justifying derived decisions.

On the other hand, this had to be accomplished taking into account the complex and imprecise characteristics exhibited by the environmental domain problems (Guariso and Werthner, 1989; Rizzolli and Young, 1997; Hodges et al., (1999)), which is also true in the wine industry. Thus, hybrid intelligent system development approach was found to be most suited in automating the knowledge for decision making in this domain. This is because the use of a single AI technique for intelligent decision support system is entangled with certain weaknesses that are inherent in their underlying algorithms. For instance the expert system technology has inherent limitations (see full discussion on this subject by Turban and Aronson, 1998 and Marakas, 1999) as well as fuzzy logic theory. In this sense, application of an hybrid approach offered a route of exploiting synergies among the AI technologies and means of complimenting each other's limitations.

Moreover, real world problems are too complex and highly integrated to be handled by an individual AI technology or comprehensively solved from a single point of view. This sort of complexity therefore limits the adequacy of an individual AI technology in satisfying the numerous constraints and challenges poised by such problems. Thus, the application of an hybrid intelligent system in the domain under investigation is seen to be in line with the current global trend in addressing real world problems, and especially in the environmental domain, where integrating diverse tools, techniques and interdisciplinary approaches in problem solving are viewed to offer adequate and sustainable solutions.

In the early stages of this work, the problem was envisioned to be solved through the development of a stand alone expert system. Nevertheless, owing to the brittleness (static knowledge base with no ability to synthesize new knowledge) and the combinatorial explosion[15] of the production rules for the expert system (the production rules were running into thousands), made efficient system evaluation and validation impossible, and this monolithic AI technology approach for decision support development was suspended.

To improve the expert system performance, the knowledge from the expert system-based reasoning was embedded in fuzzy logic, in order to derive a more superior solution, at a lesser computational cost. This was possible because opinions, facts, relations, judgments (both objective and subjective) and heuristics contained in the expert system knowledge base and their varying degrees of imprecision and uncertainty could be qualitatively evaluated and the final weighted crisp outputs be fed into the fuzzy logic system as inputs, to evaluate the system final output based on user's responses.

A graphical illustration of the hybrid system architecture employed in this work is presented in Figure 3.8. Since it is desirable for the intelligent decision support system to be able, just like the human expert, to draw nontrivial inferences from the imprecise data and vague heuristics, the uncertainty for the knowledge contained in the expert system was therefore managed using the fuzzy logic.

Recently, recognition on limitations of a single AI methodology, which affirms the philosophy held on the basis of experience gained from this work, development and implementation of intelligent decision support systems, and precisely in the environmental problem domain, has seen a steady growth in the design and adoption of hybrid systems. An excellent review of such systems in the domain of both small- and large-scale complex environmental problems has been presented by Chan and Huang (2003), and Cortés et al. (2000), and contains an extensive literature review.

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[15] There are different possibilities in representing acquired knowledge such as tables, decision trees, knowledge diagrams and frames. The decision trees were used in this case, where it was attempted to cast all the facts, relations, procedures, judgments etc as a set of decision rules. However, though the translation of knowledge in a branch of a decision tree into a production rule is direct, the rules were numerous and unmanageable as well as many had contradictions and redundancies as there was no numerical dae to assist in portioning the output space.

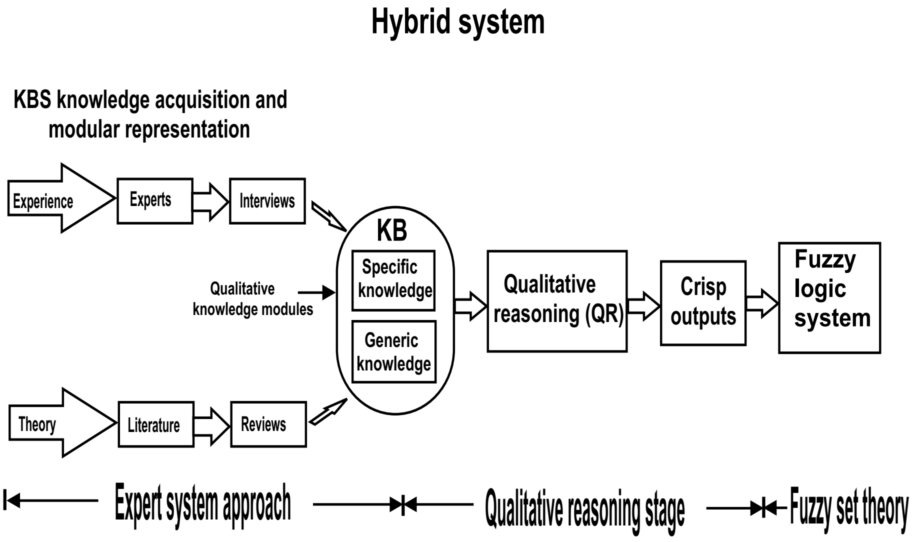

Figure 3.8: The hybrid system structure of the intelligent decision support system (KB: Knowledge base).

3.4 Concluding Remarks

The role of domain databases accessible in the process industry, and specifically in the wine industry has been discussed. The nature and inherent features of data in this domain were found to be a crucial influencing factor in the choice of inferencing mechanisms and knowledge presentation schemes during the process of designing and developing an intelligent decision support system for waste and energy management. Thus, the AI approach(es) chosen to capture and represent expertise knowledge for a certain decision making process, has to sufficiently cater for these different data types; whether numeric, non numeric or symbolic in nature.

In the wine industry, data accessible in the domain of waste and energy management was found to be significantly qualitative and characterized with features such as imprecision, uncertainty, incompleteness, and being highly unstructured. This rendered AI techniques which are quantitative data driven for their functionality of limited application in this domain. The low or non existence of quantitative data was explained to be due to the lack of sensors, flow meters and other statistical data acquisition system installations in many wineries. However, this is expected to change in future as more vinification processes are automated as result of ongoing modernization programme being undertaken by many wineries.

On the basis of salient features of data established to exist in this domain, ES and FLS technologies were proposed as suitable candidates of developing an IDSS for both waste and energy management. For each technology, its core fundamentals have been reviewed and inherent relevancy to the question under investigation discussed. To enhance the flexibility and reliability of the final decision-making model, the synergies and strengths of both technologies was harnessed through their integration via qualitative reasoning that culminated to the design and development of hybrid decision support systems. The choice of these tools can be summed as follows: in winery unit operations and processes setting, the data available at the time decisions needs to be made is usually incomplete and non quantitative. In this sense therefore, the qualitative reasoning methods (linquistic level reasoning) are more suitable than traditional mathematical methods in building decision-making models.

Chapter 4

Waste Minimization Analysis in the Vinification Process – A System Approach

4.1 Background

A brief review of concepts that have proliferated in the literature as a result of waste management evolution has been presented in chapter 2, section 2.3. Waste minimization was identified as the base concept to be employed in this study and the reasons for its choice were concisely stated. In this chapter, the waste minimization concept is employed to help to identify viable waste management strategies that exhibit the potential of eliminating, reducing or minimizing the quantity and quality of effluent streams generated during the vinification process. This is achievable through innovative initiatives that reduce product and byproduct losses and optimizes resource consumption such as water and chemicals.

A conceptual framework was developed to systematically formulate and rank the waste minimization strategies that can yield a reduction in effluent quantity and improve effluent quality of various waste streams generated from the wine industry processes. The primary goal was to eliminate or minimize their potential impacts on the environment. The conceptual framework was developed from a "smart" systems analysis perspective aimed in tracking process material flows, resource consumption, and the generation of waste or byproducts per given throughput at various stages of the vinification unit operations and processes. To this end, the vinification process was decomposed through the transformation of process streams and material flows into various components at the process and/or unit operations level.

This was possible through the use of knowledge on main components, mass balances of processes and utility materials, products, intermediates, byproducts and wastes. The results of the decomposition process offered a window of opportunity to examine the spectrum of possible causes of waste generation at different processes and unit operations. In the last stage of this systematic approach, waste minimization alternative strategies were derived from the results of process decomposition (which generally provided the sources of waste) and causes of waste identified.

4.1.1 Systems Approach

The concept of systems thinking has evolved from a number of intellectual traditions (Sterman, 1994) and has come to mean a multitude of different things. However, in this study, the concept of system thinking is in accordance to the description advanced by Sterman (1994), where it is described as the ability to take a holistic view of the world as a complex system. The significance of applying system analysis concepts for environmental considerations to complex sequential manufacturing processes, lies in its capability to ascertain the material flows, resource consumption, and waste generation, at all times, at the individual process step, manufacturing line, or factory levels, and to provide qualitative process optimization and control from an environmental perspective (Saminathan et al., 1994).

The central issue in meeting these objectives is the need to adopt a new paradigm with respect to the management of resources and equipments during the vinification process. In pursuit of these objective, a systems approach proved effective in evaluating the processes and unit operations methodically. This resulted in explicit identification of linkages among the process variables and ultimately enhanced the understanding of the system behavior over a period of time.

Waste minimization at plant level is highly effective when it is incorporated as an integral part of the production process or facility (Gujer, 1991). To illustrate the importance of this approach, system thinking was found crucial in facilitating the understanding of cause and effect of highly interactive variables such as equipment (various technologies), humans, and the environment as a result of the vinification process.

It should, however, be noted that these variables are complex on their own, and the complexity in fact increases once the interactions between themselves are taken into consideration. In the course of studying the production systems in the wine industry, several constraints were encountered related to scaling mismatches, existence of non-homogeneous information and data, multi-scaled system interactions, non-trivial (complex) management systems, uncertainty in causal relationships of variables, and assessment of trade-offs based on different criterion such as the environment (e.g. pollution prevention, waste reduction possibility, etc), economics, social, technological, and institutional factors.

From the work of Chapman (1996), Chapman et al. (2001), and Lorenzen et al. (2000), a broad road map on a number of possible strategies in minimizing various waste streams resulting from the vinification process have been presented. Nevertheless, both studies failed to present an integrated criteria that can be used as a benchmark to improve management decision-making, and effectively handle the constraints raised above. This chapter presents a systematic methodology for waste minimization analysis focusing on identification and classification of the derived strategies, in a format amenable to a reasoning process during decision-making.

Secondly, to circumvent the challenge posed by the complex constraints, waste minimization index (WMI) was developed to enhance screening and ranking of the derived strategies in order to facilitate decision making (see chapter 5). As a consequence of this chapter's objectives, a knowledge-based fuzzy expert system for waste minimization in the wine industry was designed and developed. Similarly, several case studies (Halim and Srinivasan (2002a); Saminathan et al., (1994); Bellamy et al., (2001); Foxon et al., (2000)), existing in the literature have demonstrated successfully the merits of adopting a system approach in diagnosing complex environmental and resource management problems whose primary objective was to find optimized solutions.

4.1.2 Evaluation Methods

In the literature, two broad approaches have emerged, that are widely applied in synthesizing a process flowsheet in an attempt to identify strategies that are feasible to achieve waste minimization in industrial processes. The techniques are classified as qualitative and quantitative approaches (Allen and Rosselot, 1997). This classification is significantly influenced by data and information features accessible in a given industrial process.

Other factors that play a crucial role in the choice of methods used for the evaluation of alternatives include the nature of problem formulation, the data and information collection techniques chosen, and the defined scope and breadth of the problem under investigation. The qualitative approach was adopted in this work and to establish the effectiveness of each strategy with respect to the waste reduction, the waste minimization index (WMI) presented in chapter 5 was used.

Quantitative Approaches

On the one hand, the quantitative approach to waste minimization is achieved through rigorous application of pinch technology or mathematical (numerical) optimization routines for solving the synthesis problem of water-, heat- and mass-exchange related networks of any given process under consideration. This is particularly true in cases where the accessible data is predominantly quantitative. Typical examples for the application of pinch technology for saving energy through heat-exchange networks (HEN), reduction of waste stream quantities via mass-exchange network (MEN), and minimization and reuse of wastewater using water-pinch technology. These applications have been extensively discussed by Linhoff (1995), El-Halwagi (1997) and Wang and Smith (1994a and 1994b) correspondingly.

Qualitative Approaches

On the other hand, the qualitative approach comprises of methods such as Douglas hierarchical procedure (Douglas, 1992), onion diagram (Smith, 1995, Mizsey, 1994), 3E's[1] (Jackson, 1997) and environmental optimization (ENVOP) (Potter and Isalski, 1993; Isalski, 1995). Other generic qualitative procedures have been published as well aimed in evaluating waste minimization options at industrial scale by the Environmental Protection Agency of USA (USEPA, 1988), United Nations Environmental Programme (UNEP, 1991), and Mulholland and Dyer (2001).

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[1] 3E stands for Energy, Environment and Economy

The qualitative techniques are useful for the identification of possible waste minimization alternatives in domains where the data is highly qualitative (see section 3.1.2). In addition, the qualitative analysis tools offer sound means of evaluating flowsheets of existing processes. The exception is the Douglas hierarchical procedure that can as well be applied at the design stage in domains where not only the numerical data is limited, but also in process industries that produces bulk commodity products. Examples of industries producing bulk products are chemical manufacturing, petroleum refining, mining/ore refining, and food and beverage industry. In this work, the generic qualitative methods reported by USEPA, UNEP, and Mulholland and Dyer were applied in organizing the data and information in the wine industry with respect to waste mitigation, with a view to synthesizing the knowledge into a format leading to the development of a decision support system.

At this point, it is significant to note three key issues. Firstly, neither qualitative nor quantitative approaches presented above, have the ability to comprehensively verify all the waste minimization strategies in any given plant. Therefore, the approach employed for a specific problem domain is strongly influenced by the features of data and information available (see section 3.1). Another influencing factor is the problem objective under investigation and as opposed to the basis of superiority of solutions advanced by a particular approach.

Secondly, most of the data in the wine industry has inextricable features. This is because in many occasions it is verbally communicated and there are no corresponding numerical measurements to provide quantitative data to support the conclusions and actions undertaken. Owing to this prevalent handling approach of data and information in the wine industry, the qualitative approach becomes more attainable in this domain for decision support system design and development. This observation underpins the reason why the knowledge-based decision support system approach was the ideal candidate of choice in deriving problem solutions, as it provides sufficient support in dealing with data having uncertainty while in the process of establishing casual relationships among numerous variables.

Thirdly, as most of the data in this domain are acquired through experience, the techniques that suit synthesizing the process flowsheets for the identification of waste minimization opportunities should adopt a qualitative approach. Such an approach optimizes the heuristics borne out of operators and experts experience. Nevertheless, as better instrumentation of the vinification processes is on the rise, application of integrated qualitative and quantitative techniques are envisioned to become an attractive candidate for derivation of comprehensive solutions in this domain in the future.

The benefits of such advances, where qualitative and quantitative techniques are applied simultaneously in this problem domain, will be manifold. Firstly, it will facilitate automated configuration of rules for the knowledge-based approaches, and hence yield a comprehensive means of validating and verifying the accuracy of the system more rapidly. Secondly, the application of qualitative and quantitative approaches in conjuction with one another will exploit the synergies of each method and offer a more robust solution.

This is because, as the quantitative approaches tend to specify the 'expected results' or rather define the 'intended state' after the implementation of the waste minimization improvement alternatives, the qualitative approach is crucial in specifying the 'means' by which these results can be achieved. This is crucial since all alternatives, both tangible and intangible, qualitatively measurable, and qualitative factors will be considered, screened and ranked based on a defined criterion which includes very significant influencing factors but difficult to numerically quantify such as environmental, impacts on humans, and social-based indicators. Thirdly, combined qualitative and quantitative approaches will allow wineries to establish a comparatively reliable estimate of magnitude of the outstanding waste minimization strategies at minimum cost and effort.

4.1.3 Motivation for Waste Minimization in the Wine Industry

What really motivates the need for waste minimization in the wine industry? A combination of factors plays different crucial roles geared towards waste reduction in the wine industry. Recent rapid expansion of standard wine production and its complimentary products, has seen a parallel exponential growth on the quantities of waste streams resulting from various unit operations and processes during the vinification process. The waste streams consists mainly of organic waste[2], wastewater, inorganic materials (e.g. diatomaceous earth), and greenhouse gases (e.g. carbon dioxide (CO_2), volatile organic gases (VOCs) and sulphur dioxide (SO_2)).

However, while these waste streams are non-hazardous, the high organic component present in the solid and liquid phase waste streams posses high potential of serious environmental damage, in the event of being poorly managed. A list of possible environmental impacts as a result of poor waste management owing to different waste streams from the wine industry are presented in Table A.2 in Appendix A.

A preview of the entire wine industry operations revealed numerous reasons that motivates the adoption of proactive approach towards waste management. A summary of some of the key motivating factors includes the following:

- Initial efforts were concentrated on the management of waste streams through what is commonly referred to as "end-of-pipe (additive) techniques or pollution control (P1)", discussed in sections 2.3.6 and 2.3.7. While this waste management approach through treatment and disposal technology has contributed significantly to the improvements in the reduction of quantities and the concentration of pollutants discharged into the environment, the pollution control approaches have been proven to be costly, inadequate and ultimately unjustifiable business practices (Higgins, 1990).

- There are growing concerns regarding the possibilities of open ended liabilities through health claims from workers and neighboring communities, arising from effluent emissions by the wine making processes. In this respect, wine makers have began to show willingness to adopt proactive strategies, to minimize the probabilities of such occurences through the implementation of proactive waste management strategies such as waste minimization in their facilities.

- As the operational costs increase, e.g. for the raw materials (grapes), and other equally essential auxiliary processing resources like water, energy, chemicals, and labor, the wine industry has began to integrate waste management into its business strategies. The merit of this proactive based approach has the potential to save

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[2] The organic matter consists of solids(stems, stalks), skins, pips, marc, wastewater treatment sludge etc.

millions of dollars that go to waste annually in non profitable undertakings and losses especially with respect to product and byproducts losses, and effluent treatment.

- Recent paradigm on customer demands especially related to foreign markets, require or expect their suppliers to be ISO 14 000 compliant[3]. In light of this new paradigm, ISO 14000 registration, therefore, serves as a guarantee to the customers of sound environmental management by the wine making companies, particularly during the vinification process.

  In response to these customer demands, many companies are beginning to adopt and implement proactive waste management approaches such as waste minimization in their facilities. This will not only help them to maintain their current customer profiles, but have the potential to attract prospective ones as well. It is thus becoming clear that as new trends on market driven demand emerge, measures towards reduced environmental impact and degradation may, in the long term turn, out to be stronger drivers than those arising from cutting down operational costs.

- Since the beginning of the past decade, many governments and environmental protection agencies have adopted an increasingly onerous regulatory regime of legislations[4]. Historically, the wine making companies have been designing reactive policies primarily to meet these regulatory requirements. However, in view of the current ever increasing expenses in pursuit of achieving regulatory requirements, escalating civil and criminal penalties arising from environmental pollution, and the increasing cost and scope of environmental liabilities as new legislations come into force, wine making companies are now engaging to implement proactive measures such as waste minimization in their facilties with a view to addressing some or all of these challenges.

  Closely intertwined to the regulations is the dramatic increase in existing taxes and tariffs on industrial manufacturing waste. Non-compliance with environmental legislations are currently attracting heavy penalties, fines, or imprisonment, and with a potential to tarnish company's public image. The new development has strength-

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[3] It should be noted that, other benefits due to the implementation of ISO 14 000 are; self discipline of employees with respect to waste management, worldwide recognition, improvement of overall competitiveness, enhancement of marketing credibility, serving as a global quality model and creating uniform effluent quality which can be easily treated or reused.

[4] Clearwater and Scanlon (1991) in details have discussed the legal issues that are acting as incentives for corporate establishments to adopt waste minimization in their production processes.

ened the need for the wine producing companies to consider the adoption of waste minimization to be incorporated in their production processes.

Besides the motivating factors pointed out in the foregoing discussion, the waste minimization approach has also been shown to bear other manifold benefits to companies. A number of these additional benefits have been comprehensively discussed by the United States Environmental Protection Agency (USEPA, 1992), Crittenden and Kolaczkowski (1992), Crittenden and Kolaczkowski (1995), and Petek and Glavič (1992) among other. While the benefits of waste minimization in the wine industry are in no doubt numerous, nevertheless, several challenges have been identified that impede many wine producers from realizing them. The following is a brief preview of some of these challenges:

- The wine industry has developed out of an artisanal activity, thus most of its processes were not originally designed form an engineering perspective. Historically, the vinification processes and operations as they are known today, originated as a backyard beverage processing activity and the current processes are scaled from that. This places unique constraints in applying modern technologies to achieve meaningful waste minimization in many wineries.

- The grapes and wine are the raw materials and the desired final product respectively, and both are complex. The indications are that, to a certain extent, the relationship between them is often poorly understood as the raw materials have to undergo numerous processes before the final product is produced. The production chain punctuated by the large spatial and temporal variations, leads to a knowledge gap, which forms a weak foundation for the process optimization especially in relation to the improvement of the production yield. As a result, the wastes that are generated along the numerous web of process pathways can be easily ignored, though they bear a profound impact on production yield and the environment.

- During the processing of the raw materials, which is supported by the use of auxiliary inputs like water and chemicals, large losses of products, byproducts, auxiliary inputs and the primary raw materials are incurred. In many cases these losses are hidden although they have serious environmental impacts, and unfortunately their true costs and impacts draws little or no attention from many wine makers.

- Generically, poor practices are often not classified as poor but as common practice in this industry. For a considerable attitude change to be realized, comprehensive education at all levels of personnel is crucial, especially with regard to waste management.
- In most companies, there is a big gap between the work force and the management.
- The management is often not convinced of the fact that unwanted losses are significant in economic terms and that they can be reduced reasonably by corrective management actions and decisions.
- Most of the variable parameters are not measured on line in a rapid and reliable manner, but are rather estimated subjectively, making it very difficult to know exactly if the grapes are transformed in the most efficient way into the end products. Similarly, this applies to other resources that are required in this process.
- In view of the above factors, the technological drive in this industry has been slow or in certain instances non existent.

While there are no doubts on the benefits that can be obtained from sound waste management in the wine industry, the challenges discussed above require a systematic approach, that can infuse waste minimization as an integral part of the vinification process. In pursuit of this objective, we carried out a systematic study of the vinification process through the systems approach. This was crucial in identifying the existing data and information and filling up the knowledge gaps on possible waste management strategies that can mitigate against waste generation at source or through recycling.

In achieving this goal, a number of activities were conducted for data and information gathering. These activities comprised of extensive literature surved, conducting of interviews with specialists like wine makers, operators, and waste management experts in the wine industry, and actual observation of winery operations. The acquired knowledge was formalized by identifying key factors that govern waste management in the wine industry, that resulted in the development of a decision support system presented in chapter 5.

4.2 Conceptual Framework for Waste Minimization Analysis

The conceptual framework discussed in this section is based on an integrated method of analyzing the vinification process into a format that can facilitate a consistent identification of waste minimization alternatives systematically. The heuristic-based insights from operators, managers and experts, and thermodynamic understanding of processes and unit operations were used to scale down the complexity and size of the solution space. Such an approach was essential as the problem under investigation had no mathematically formulated objective function that could be used in determining the optimal waste minimization solutions through numerically known formalisms.

Thus, as earlier stated, the primary aim of developing a conceptual framework was to have a systematic approach that optimizes the entire manufacturing process from a qualitative perspective aimed in reducing waste generation. The framework entailed a broad range of processes[5], production operations[6], raw materials[7], waste tracking system, and management of inherent complex interactions between them.

The determination of waste minimization solutions for the wine process plants is equivalent to identifying the sources of each material components in the waste stream, establishing their true causes, and finding means to eliminate or reduce them in a given unit operation or process. As many unit operations and processes yield different waste streams characterized by different key pollutants, the first task was to isolate key processes that generate major waste streams on the basis of effluent quality and quantity. The criterion of selection was based on their waste potential impact in the environment. Thermodynamically, such an approach has a merit in that it is unfeasible to completely eliminate all waste streams in any process plant.

The identification and quantification of waste sources was accomplished by the use of inventory tools (Van Berkel, et al., 1997a; Van Berkel, et al., 1997b), where the mass balance and process flow chart methods were used. The mass balance can be in two forms namely, quantitative mass balance and qualitative mass balance. The latter was employed in this study.

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[5] Crushing, filtration, fermentation, etc.

[6] Cleaning, scheduling, storage, etc.

[7] grapes, chemicals, etc.

The next step was to carry out a plant-wide waste analysis through process flowsheets at different unit operations and processes, to understand the principles governing the causes of waste generation in the wine industry. The primary goal at this stage was to establish what can be regarded as the true causes of waste and avoid treating the symptomatic cases of the process upsets.

Once the significant waste streams targeted for waste reduction or elimination had been identified and their true causes ascertained, the focus turned into an overall objective of deriving possible waste minimization strategies that can offer solution(s) to the waste management challenges facing the wine industry. Whereas there are many tools that support the generation of waste minimization options (see for example Van Berkel, et al., 1997a), in this study, a process-oriented tool, referred to as the pollution prevention (PP) techniques (Freeman, et al. 1992) was employed.

4.2.1 Inventory Tools

In this section, a brief review of the inventory tools that were used for the quantification and identification of all possible waste sources are presented. The inventory tools are divided into product-oriented tools[8] and process-oriented tools[9]. In this study, the inventory tools applied were process-oriented; namely the material mass balance and the process flow chart methods.

The process flow chart method is an important inventory tool for the identification of all possible sources of waste generated or excessive material and energy consumption in the whole industrial process (see for example Van Berkel, 1995). The process flow chart begins with the division of the manufacturing process into unit operations. The unit operation refers to an area of the process, or a piece(s) of equipment(s) where materials are input, a function/operation (material transformation) occurs and output materials are identified. Every unit operation or process is drafted as a block. By connecting all the individual unit operations in the form of a diagram, the process flow chart of a given process is obtained. In the case study of the vinification process, the process flow chart developed is schematically illustrated in Figure 4.1.

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[8] Product-oriented inventory tools allocates the material inputs and outputs to functional units of product use.

[9] Process-oriented inventory tools allocates the material inputs and outputs to physical units of production.

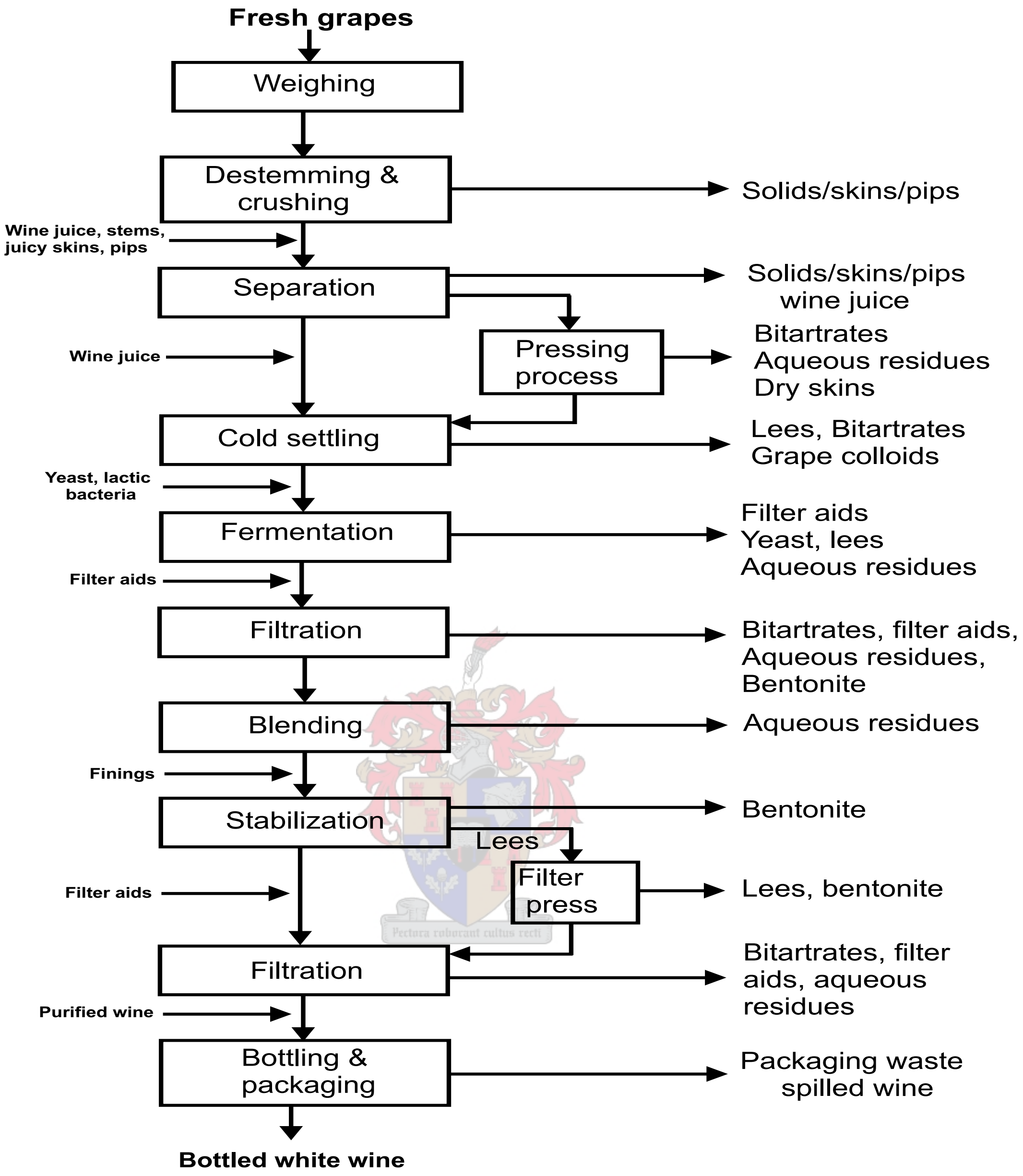

Figure 4.1: Schematic process flow chart representing white wine vinification process.

The qualitative mass balance method was used to find all the materials at the level of each production process or unit operation. This method contributed to the understanding of the relative importance of different causes of waste generation. It also aided in evaluating the relative importance of each of the possible causes of waste. Material balance in the production process clarified the composition of wastewater stream, and thus, the sources of pollutants. Owing to the characteristics of the databases accessible

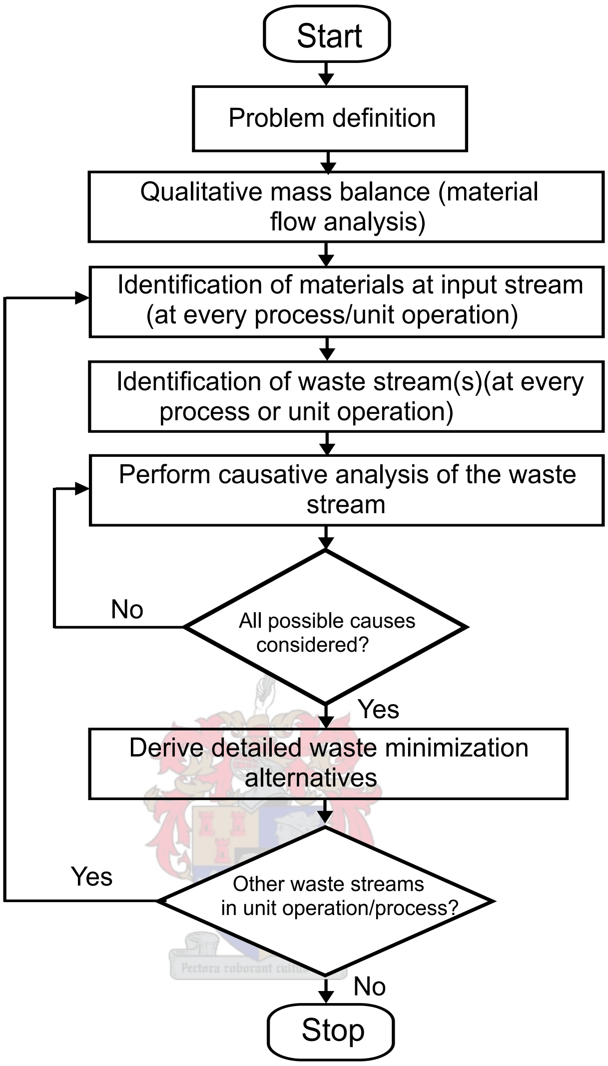

Figure 4.2: Systematic methodology for waste minimization synthesis.

in the wine industry, qualitative mass balance was conducted (see section 3.1).

Figure 4.2 shows the sequential steps beginning with the preliminary work of problem and boundary definition through the application of the qualitative mass balance until the waste minimization alternatives are identified. The materials present in each stream, different processes or unit operations were determined using qualitative simulation of the process flows based on the process knowledge from the heuristics gained by operators through experience, data provided from the plant records and other information sources, and the process flow chart.

While several tools have been developed (Van Berkel et al. 1997a; Van Berkel et al., 1997b) that can support the generation of waste minimization strategies, the conceptual pollution prevention (PP) technique was used in this study. The technique is process-oriented and based on five factors that generally affect volume and composition of waste and emissions streams (Van Berkel, 1995). The factors are product changes[10], technology modification, input material substitution, good operating practices, and recycling and reuse (see section 2.3.5). These five PP techniques indicate in which directions waste mitigation strategies might be generated at the waste minimization conceptual stage.

The option generation is dependent on the information and data acquired from waste identification and causative analysis stages of the conceptual framework. Some of the successful applications of this technique in different industry sectors have been reported by Halim and Srivansan, 2002a; Freeman et al., 1992; Van Berkel, 1995; Crittenden and Kolaczkowski,1992; and Crittenden and Kolaczkowski,1995.

4.2.2 Waste Source Identification

In the context of this dissertation, waste (or byproduct) is defined as any material or energy input into a manufacturing process, that is not incorporated into the desired final finished product or when it is not used to its full potential (Jacobs, 1991; Dijkema et al., 1999; Dijkema et al., 2000)[11]. In the process industry, wastes are classified as intrinsic (process) waste and extrinsic (utility) waste (Douglas, 1988; Berglund and Lawson, 1991; Mulholland and Dyer, 2001). While the process wastes are inherent in the fundamental process configuration, the utility wastes are a function of auxiliary aspects of the operation (Berglund and Lawson, 1991).

Note that, in the context of waste minimization and especially in deriving the reduction strategies based on this classification, the two waste types are not independent of each other. In this sense, care had to be taken to establish the interactions and interconnections between the two types of waste. The focus in this work is on wastes that exist in solid and liquid phases. Examples of solid waste are pips, marc (crushed skins), filtration cakes, and stems; while wastes in the liquid phase are wastewate and used cleaning and sanitizing

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[10] In this study, the product changes were not considered as the problem under investigation is retrofitting and therefore did not entail redesign of the product.

[11] In the literature, there are numerous definitions of waste based on the context of problem under investigation, to account for the unique features in a particular industry or activity.

solvents.

In view of intrinsic waste process sources, the vinification process was broadly divided into four categories as summarized in Table 4.1 as a function of the grouping factors. After the completion of each stage of production, water and other raw materials (e.g. chemicals) are used for a wide range of activities. These activities may include but are not limited to cleaning, cooling, sanitizing of equipments and earth filtering. Using the utility waste as basis of classification, the vinification process was portioned into four categories as presented in Table 4.2.

Table 4.1: General categorization of intrinsic waste sources during the vinification process.

Process category	**Processes**	**Grouping factor**
Grape reception and crushing area	Destemming Crushing	Successive batch operations within the shortest time interval between them.
Transfer systems	Pumping Piping	Waste generation due to wine, juice, and must transfers.
Separations	Screening Pressing Filtration	Product loss via separation of wine and solids.
Tank farm	Fermentation Storage/cooling Clarification Stabilization Blending	Extensive tank usage for process execution.

On the basis of the above described classification for the vinification processes, different waste, byproduct or product loss outputs were identified from various unit operations and/or processes based on process flow path decomposition. A schematic representation of the waste identification summary from specific process or unit operation is illustrated in Figure 4.3. Typical examples of wastes, byproducts or product losses identified in this case study are provided in Table 4.3 and Table 4.4 for the intrinsic and extrinsic wastes respectively. In most cases, the same kind of wastes were generated over different unit operations and/or processes, and therefore in this case study they were labeled with the same symbols. The wastes in solids, liquids and gaseous phases were coded S, L and G, respectively. This was to enhance consistency in identifying viable waste minimization

Table 4.2: General categorization of extrinsic waste sources during the vinification process.

Process category	**Processes**	**Grouping factor**
Wetting	Cleaning Sanitization Cooling Earth filtering	Extensive use of potable water.
Heat transfer	Heating Cooling	Use of energy for product quality enhancement.
Gaseous handling	Sulphication	Gas usage and storage for product quality enhancement.
Packaging/loading	Grape reception Bottling Storage/store rooms	Waste sources from subsidiary support utilities.

options in managing each of them.

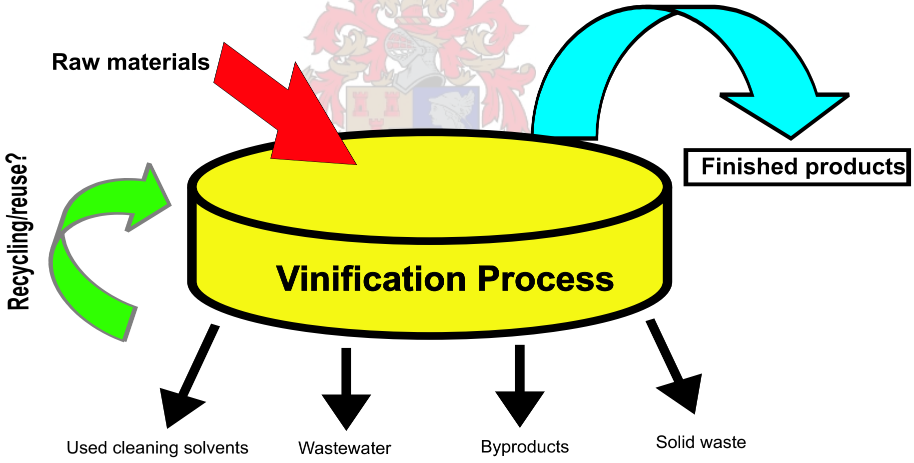

Figure 4.3: Schematic representation of waste source identification.

4.2.3 Causality

In the first stage of the conceptual framework, waste inventories and characterization profiles provided valuable baseline data regarding the nature of pollutants generated. However, before comprehensive strategies for waste reduction or minimization can be formulated, it is important to understand when, how and why different kinds of wastes are generated. It is through causative analysis process that the factors influencing the effluent

Table 4.3: Identification of intrinsic wastes under the phases: G-gas, L-liquid, S-solid.

Process Category	**Raw/Secondary Materials**	**Gaseous wastes**	**Liquid wastes**	**Solid wastes**
Raw material reception and crushing area	Grapes/SO_2/ stalks/leaves	SO_2 (G1)	Spilled wine juice (L1)	Skins/Pips/Solids (S1)
Transfer system	Wine juice/must		Spilled/leaked wine (L1) must,wine juice (L2)	Skins/Pips/Solids (S1)
Separation processes	SO_2/wine/filters/ suspended solids	SO_2 (G1) VOCs (G2)	Splashing wine (L3) Aqueous residue (L4)	Skins/Pips/Solids (S1) Filtration aids (S2) Bitartrates (S3) Filtration cake (S4)
Tank-based processes	Wine juice/yeast	CO_2 (G3) VOCs (G2) Ethanol (G4)	Aqueous residues (L4) Grape colloids (L5) Overflowing wine (L6)	Lees (S5)/Yeast (S6) Bentotites (S7) Bitartrates (S3)

Table 4.4: Identification of extrinsic wastes under the phases: G-gas, L-liquid, S-solid.

Process Category	**Raw/Secondary Materials**	**Gaseous wastes**	**Liquid wastes**	**Solid wastes**
Wetting	Potable water Cleaning chemicals		Wastewater (L7) Used cleaning solution (L8)	Dry skins and Organic dust (S8)
Heat transfer	Cooling water Energy	CFCs (G5) Ammonia (G6)	Cooling water (L9) Ethylene glycol (L10)	
Packaging/loading	Packaging materials Grapes from trucks Sticking glue	VOCs (G2) Ethanol (G4) SO_2 (G1)	Spilled wine (L1) Excessive glue (L11)	Falling grapes (S9) Residual packaging materials (S10)

quantity (in volume, mass or both) and quality (composition matrix), and reasons that lead to the product and byproduct losses, were investigated.

Understanding of the causality formed a sound basis for the design of effective waste minimization strategies that can yield the desired change. Such an undertaking was crucial, as it provided an understanding of the cause-and-effect relationships that govern the vinification operations and processes which are complex and multi-dimensional, and invariably influenced by diverse factors.

Nevertheless, while it is not possible to provide definitive answers on causality and identify the differences that profoundly exist among various causes explicitly, in this model however, the independence of waste generation causes is assumed. Clearly the merit of such an approach makes the causative evaluation process tractable for a given unit operation or process.

To present the waste causes in a format that lends itself to fast derivation of waste minimization options, possible causality categories were broadly classified as technology-oriented, process execution and management-oriented, input material characteristics-oriented, and waste recovery and reuse (recycling)-oriented from a retrofitting perspective. The following paragraphs attempt to establish how each category influences the effluent quantity and quality generated during the vinification process.

(a) Technology-Oriented Category

The technology-oriented category accounts for the waste causes on the basis of technological based factors[12] that influence the quantity or other characteristics of a waste stream as a result of some equipments and/or unit operations changes. For example, when the equipment efficiency is low or the design in a particular unit operation is poor, it generally leads to more waste being produced from that particular equipment. In addition, technology has an effect on the effectiveness of managing and harnessing of useful, but inevitable byproducts generated at various unit operations and processes.

The following two examples are provided to suffice this observation. During the pressing process where skins and wine juice are separated, use of a modern vacuum press reduced wine losses significantly at this stage of production in comparison to the traditional vertical pressing baskets. On the other hand, the efficiency of equipments used for cleaning and the sanitizing process showed a strong correlation to the quantities of potable water and the chemical demand in a given operation. For instance, if open hosepipes were used, water and chemical consumptions were found to be higher than in an operation where high-pressure-low-volume cleaners were used. In Table 4.5, a list of technological-oriented causes are presented and their relative impact on effluent volume,

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[12] Examples are type of material used for equipment design, equipment sizes, piping, equipment efficiency, etc.

effluent quality as well as on the quantities of chemicals required.

Table 4.5: A list of waste causes owing to technological-oriented factors.

	Variables influenced by cause		
Typical waste causes	**Effl.[a] Vol.[b]**	**Effl. Quality**	**Chem.[c] Vol.**
Process design and unit layout	√√[d]	√√√	√
Equipment efficiency (pressers, filters, separators etc)	√√√	√√√	√√
Inadequate/non-existence of recovery installations	√√	√√√	√√
The type of material used for equipment design	√√	√√	√√
The size and number of equipments used	√√	√√	√√
Inefficient/non-existent control and monitoring systems	√	√√	√

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[a] Effl.=effluent

[b] Vol.=Volume

[c] Chem.=Chemicals

[d] The rating on the possible impact of each cause on the variable is based on the scale:
√√√= High to very high impact
√√=Moderate to high impact
√= Low to moderate impact

(b) Process Execution and Management-Oriented Category

In the food and beverage industry, and particularly in the wine industry; procedural, administrative and institutional practices are the key causes of waste generation. These practices mostly referred as good housekeeping practices, significantly determines waste profile in terms of volume, composition and dispersion to other environments. In this study, the lack of or unsatisfactory execution of good practices during the vinification process were viewed as a cause of waste generation.

One distinctive feature of these practices is that they require relatively simple in-plant changes regarding the operating procedures or methods of handling wastes that reduces the quantity of waste stream or the concentration of contaminants in a waste stream. While such measures are not always distinguishable from the technologically oriented process changes, their relatively low-cost, which demands little or no modification to the equipment or process operations, was used as their feature of distinction from the rest.

Numerous waste causing factors fall in this category as can be seen in Table 4.6. Further, most of these factors are generic in nature (e.g. operation efficiency, equipment maintenance, resource management). These causes account for a high percentage of what is regarded as waste in the wine industry. One unique feature on these types of waste causes is the difficulty of ascertaining how a certain “cause” may influence the overall effluent quality and quantity. This is because multiple interactions among different causes lends into a huge combinatorial problem and consequently, it appears very difficult to estimate to what extent the a given single cause has an influence on the effluent characteristics.

For example, inventory control over the raw materials, intermediate products, final products, and the associated waste streams is known to be a significant waste reduction technique. Thus, without doubt, the lack of inventory control can be identified as a waste cause. By taking a close analysis of this ‘cause’, it can be established that, the ‘cause’ stated is also influenced by other factors, whose absence in the facility is termed as cause of waste generation. Some of these includes aspects such as training and motivation of personnel on waste management, improvement on process operations, maintenance levels among other.

(c) Input Material Characteristics-Oriented Category

The feedstock into any process or unit operation possesses certain inherent properties such as toxicity or non-toxicity, hazardousness or non-hazardousness, and tare and other foreign bodies (especially agricultural-based raw materials). On the basis of these properties, the input material may require special handling to mitigate against waste generation or be substituted, in cases where it is toxic or hazardous.

In the wine industry, the key input material are grapes that have neither toxic nor hazardous properties. But, it should be noted that grapes being an industrial agriculturally-based process feedstock, inherently have high organic content and secondly that they can contain tare and foreign bodies (e.g. stalks and leaves), which are unwanted but nevertheless unavoidable input materials. To minimize or eliminate waste generation while dealing with such raw material require proper and effective handling. The same is also true in handling the inevitable byproducts (e.g. stalks, skins, seeds) and the high volumetric fluid product.

In facilities where improper handling of the raw materials, intermediate products,

Table 4.6: A list of waste causes owing to the process execution and management-oriented factors.

	Variables influenced by cause[a][b][c]		
Typical waste causes	**Effl.**[d] **Vol.**[e]	**Effl. Quality**	**Chem.**[f] **Vol.**
Transportation of materials (raw materials, products, and intermediates)	√	√	×
Frequency of cleaning, spillages, leakages and shutdowns	√	√	×
Level of personnel training and motivation on waste management	√	√	√
Maintenance of equipment schedule	×	×	×
Equipment and resources management	×	×	×
Inappropriate filling of vessels (e.g. tanks)	√	√	×
Poor/lack of dosing control on chemicals		×	√
Inadequate/lack of inventory and management of control procedures	×	×	√
Losses owing to process disturbances (e.g. changeovers, malfunctions, pipe blockages)	×	√	×
Communication failures (both written and verbal)	×	×	×

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[a] Note that most 'causes' have no direct link to a certain variable, but if one variable is affected, that may trigger another cause that will make the effect be spread to one or two other variables.

[b] √ Indicates the variable directly affected by the stated waste cause. The effect of the 'cause' on the variable is continuous ranging from lowest to highest, depending on practices in a given winery.

[c] × Indicates the variable is not directly affected by the cause but through a chain of effects ends being impacted.

[d] Effl.=effluent

[e] Vol.=Volume

[f] Chem.=Chemicals

byproducts, and finished products occurs, the effluent composition is characterized by high organic content, high conductivity, and extreme low pH values that are highly disruptive to the receiving environment.

On the other hand, certain cleaning and sanitizing chemicals are not environmentally benign, but are toxic and hazardous. For instance, while chlorine and ammonia solvents are effective cleaning and sanitization materials, because of their toxicity and hazardous properties, in certain wineries they are being substituted with hydrogen peroxide, ozone or hot steam. The former also require higher quantities of rinsing water to ensure that all their traces are effectively removed from the equipment surfaces.

Another example are the sodium-based cleaning agents. Owing to the sodium ability to cause salinity and sodicity conditions in certain soils resulting from using the wastewater for irrigational purposes (on grape farms, grass lawns, woodlots, etc.), such agents are being substituted with potassium-based cleaners. The sodium-based salts render the wastewater useless for irrigation or require costly treatment before being used for agricultural purposes. From the foregoing arguments, the characteristics of the inputs are viewed as a waste cause and can be remedied through substitution or effective handling of the material. A summary of input material waste related causes are presented in Table 4.7.

Table 4.7: Examples of input material with inherent ability to generate wastes.

Process	**Material**	**Waste cause**	**Possible remedial actions**
Crushing and destemming	Grapes	Grape composition (HOM)[a] Tare and foreign bodies	Effective handling all materials with HOM
Cleaning and sanitization	Chlorine/ Ammonia	Inherent toxicity and hazardousness	Substitution of inputs
	Sodium	Its sodicity and salinity causing ability on soils	Substitution of inputs
Filtration	Filter aids	Use of filters (e.g. earth diatomaceous)	Substitute/replace filter requiring filtration techniques

[a] HOM represents high organic matter

(d) Waste Recovery and Reuse (Recycling)-Oriented Category

A study of the wine industry reveals unique waste management constraints that can only be addressed sufficiently through effective reuse, recycling or recovery. The reason being that, grapes possess components (e.g. skins, pulp, and seeds) and inherent foreign materials (impurity) that are not incorporated to the final products, thus generating unavoidable byproducts and wastes. Similarly, this is also the case for potable water and chemicals used for cleaning and sanitization processes. Taking into account this reality, the best alternative is to find a means of either to recycle them, reuse them in other processes or recover them in order to be used as inputs in other industries with the full understanding that these byproducts and wastes cannot be recycled in the process(es) generating them to produce the same product or perform the same function.

Secondly, high health standard requirements for food-based products as stipulated by the industrial food production act, renders byproducts and recyclable wastes not easily reusable in the process(es) generating them. This is attributed to the high degree of uncertainties as one attempts to establish their suitability for reuse, especially owing to the possibilities of microbial contamination of these byproducts and final products.

Thirdly, while the nature of the wine industry waste(s) cannot replace the input streams, e.g. the skin residues from the grape berry cannot be reprocessed to produce table wine, they can be reused for spirits distillation, a process which falls outside the vinification process. Another example is wastewater produced from cleaning of equipments which has been in contact with wine or wine residues cannot be reused in cleaning them again, but can possibly be reused for the cleaning of floor surfaces, grape bins or as a first rinse water in other heavily soiled equipment(s).

The above cited limitations and constraints among many other, gives credibility to the fact that reuse and recycling of waste outside the vinification process "offers an alternative" for waste minimization in the wine industry. Credible evidence indicates that where reuse and recycling is implemented ineffectively, or not practiced at all, high liquid effluent volumes are generated and the solids (such as skins, pips, and lees, etc.) from various processes may result in odors, high organic content in the wastewater stream or catastrophic consequences such as sodicity and salinity when dumped on soils without proper handling (Chapman et al., 2001).

Other examples where recycling and reuse minimizes waste includes the recovery of yeast cells from fermentation and stabilization tanks for sale to pharmaceutical companies or for recycling. Lees, used diatomaceous earth, skins, pips and other recoverable solid organic wastes can be reused as inputs for the manufacture of fertilizers and compost. The wastewater generated during the high peak production period can be stored and reused for irrigating vineyards, grass lawns and trees during dry months. This significantly reduces the quantities of wastewater requiring treatment and subsequent disposal. Skins and pips also find reuse as animal and fish feeds, whereas the grape stalks are used as organic matter in vineyards. Recovery of alcohol, tartrates, and tartaric acid from husks and lees shows potential to reduce the quantity of solids requiring disposal.

It is therefore clear from the examples presented that recovery, recycling, and reuse plays a key role in reducing or eliminating what could be regarded as waste, based on the understanding of the input material and byproducts characteristics. This is becasue there is no possibility of addressing these waste challenges at the source level owing to the characteristics of the input material. In circumstances where recovery, reuse and recycling as discussed, in this dissertation, are not practiced, then lack thereof is regarded as a cause of waste generation.

4.2.4 Identification of Waste Minimization Strategies

The last step of the conceptual framework last step is the development of alternative strategies aimed at eliminating, reducing, controlling the causes of waste generation or segregating useful materials (e.g. products, intermediates, and byproducts) from the waste streams. This becomes apparent once the waste sources have been identified using both waste stream analysis and process analysis and consequently establishing their true causes through a systematic causative analysis. The alternative strategies were formulated using heuristics from personnel expertise, partly on creativity based on facts obtained from waste sources and causes identification stages, and use the of existing technical literature.

It is significant to note that information and knowledge from the causative analysis was used for the identification of viable waste minimization strategies. On the other hand, data and information from waste source identification was crucial in targeting waste sources in unit operations and processes, characterized by features such as high volume, toxicity or hazardousness, which would thus have a potential to trigger a requirement for waste stream treatment.

This is based on the observation that the volumetric flow, organic loading, toxicity and hazardousness strongly influences the end-of-pipe treatment investment and operating costs. And secondly, the end-of-pipe treatment is required only because the waste streams contains components that have to be abated or removed before they are reused or released to the environment.

The derived waste minimization strategies were based on matching true waste causes and the characteristics of the waste generated. Thus, waste minimization alternatives were aimed at ensuring that useful materials were separated from the waste streams and routed to the products stream or reused /recycled to derive other useful product(s) and avoid eventual disposal. Moreover, it was to ensure that all waste streams were reduced at source up to an optimally economical viable levels. Such an approach has the benefit of deriving long-term solutions rather than simply addressing the symptoms. The process of identifying waste minimization strategies followed an hierarchy in which source reduction options were first explored, followed by recycling and reuse options.

To establish a synergistic leverage in deriving waste minimization options from waste causes, the causative categories were grouped (see section 4.2.3) in a manner so as to match a corresponding waste minimization option based on the pollution prevention techniques. As the product modification was not considered in this study, the waste minimization techniques were classified as technological modifications, input substitution, operational practices, and waste/product recovery and reuse/recycling (WPR & RR). Most identified control measures fall in these categories; process execution and management and waste/product recovery and reuse/recycling as opposed to structural facility modifications measures that require high technological innovations with a corresponding huge capital implications. This observation can be attributed to the inherent nature of input materials and the wine industry's operation characteristics.

Some of the minimization strategies derived from this work, and others reported in literature are presented in tabular form and are in no means comprehensive. Note that the strategies derived for a waste stream, operation or process do not imply that they are applicable to every winery, and in certain cases the information and knowledge presented here is beyond some of the current practices in the wine industry. However, such strategies can be viewed as a roadmap to the future possibilities for improving and sustaining sound waste management in the wine industry.

4.3 Case Study: In-Plant Waste Minimization in the Wine Industry

To illustrate the application of the proposed conceptual framework for waste minimization analysis, the industrial vinification process schematically shown in Figure 4.1 serves as our case study. A detailed description of the processes and operations, with a brief summary of waste generating mechanisms at each stage has been presented in sections 2.1.2 to 2.1.8 in chapter 2.

To ease the presentation of waste minimization strategies, the derived strategies were classified as generic or specific. The 'generic' strategy here refers to a waste minimization strategy that is applicable to a different wastes generated at different unit operations or processes. A good example of a generic strategy is the effective recovery of organic matter for reuse as an input for the manufacture of compost or fertilizers. In many instances, these strategies were in the waste minimization techniques category regarded in this study as process execution and management and waste/product recovery and reuse/recycling (WPR & RR).

On the other hand, a specific strategy refers to the unique option(s) that are applicable to a specific unit operation or process. In this sense, it only addresses a waste or byproduct that does not recur elsewhere in the vinification process. In this group of strategies, the dominant waste minimization practices fell under the categories technological and process modifications. A good example in this category is the dedication of crusher lines to a specific grape cultivar type aimed at reducing the number of cleaning cycles and avoidance of cross product contamination.

Using the above established nomenclature and taking the waste type as a unit of classification, three distinctive waste minimization classes were identified:

1. *Strategies for minimizing intrinsic waste. This class was subdivided further into two groups namely, generic and specific strategies for minimization of intrinsic wastes.*
2. *Strategies for minimization of extrinsic waste.*
3. *Strategies for odor elimination and improvement of effluent quality. Note that the strategies derived in the last two classes are generic in nature.*

To ensure consistency in the identification of waste minimization strategies based on the hierarchy; waste elimination or reduction at source, and recycling and reuse, a set of guidewords were used (see for instance in Isalski, 1995). The variables considered and guidewords used are presented in Table 4.8. At each element of pollution prevention technique discussed in section 4.2.4, the guidewords were applied to every unit operation, process, or equipment as a guide to derive the possible waste minimization options.

Table 4.8: Examples of guidewords used for generating waste minimization strategies based on heuristics.

Elements	**Variable**	**Guideword**[a]
Materials	Quality	Reduce
	Impurity	Minimize
	Quantity	Eliminate
	Toxicity	Improve
	Inventory	Change
	Hazardousness	Replace
Technology	Geometry	Modify
	Configuration	Increase
	Flow rate	Decrease
	Efficiency	Segregate
	Size	Install
Operational practices	Stream	Recover
	Operating conditions	Recycle
	Training	Optimize
	Flow rate	Avoid
	Inventory	
WRP & RR	Stream	
	Flow rate	
	Operating procedures	

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[a] The guidewords are applicable to all elements and variables.

4.3.1 Strategies for Minimizing Intrinsic Waste

The intrinsic waste type is the most challenging to eliminate or reduce considerably as it requires a high degree of technologically oriented solutions. This makes it most expensive in terms of implementing waste minimization solutions at any winery. A high capital investment is required for acquisition, installation and operational costs of equipments. However, the merits of reducing the intrinsic waste are numerous with the most profound two being a large reduction of waste generation and an increased yield per unit throughput.

Through the application of the proposed waste minimization conceptual framework discussed in section 4.2, the derived generic waste reduction strategies for the intrinsic wastes are presented in Table 4.9. It can be noted that most common solutions were generic in nature and fall under the ‘operating practices’ category of the pollution prevention techniques.

A batch process comprises of distinctive equipment, unit operations or processes at different stages of the product manufacturing campaign. To address such localized waste generation challenges, specific waste minimization solutions for such equipment, processes or unit operations were derived and the findings are presented in Table 4.10. Most solutions in this class fall under 'technological modifications' technique owing to the significant role played by the technology employed at a particular process or unit operation with respect to quantities of waste generated or effectiveness of handling unavoidable waste.

4.3.2 Strategies for Minimizing Extrinsic Waste

An important waste type mostly overlooked is the extrinsic waste during the vinification process generated from various supportive auxiliary processes such as cleaning, cooling, packaging, etc. However, by investigating the economics of waste handling and treatment in the wine industry, for instance in terms of energy required for cooling purposes and treating large quantities of wastewater, their impact on the environment, no doubt makes this waste type contribution significant towards the winery 'triple bottom line'. Through the application of the conceptual framework discussed in section 4.2, 42 measures for minimizing or eliminating extrinsic waste type as well as improving the wastewater quality were identified. In Table 4.11, the identified measures are presented.

One significant point to note is that the quality of wastewater is dependent on the manner in which the intrinsic waste is handled. That is, if the yield per given batch throughput is high and unavoidable process waste handling is adequate, the quality of wastewater is most likely to be high and with a considerable low volume of effluent generated. Additionally, note the high number of operating practices identified for addressing this type of waste.

4.3.3 Odor Elimination and Improvement of Wastewater Effluent Quality

On the basis of the classification discussed in this dissertation, two problems that are crucial with respect to waste management in the wine industry could not be addressed by expressing them in terms of intrinsic or extrinsic waste. These are the odor problem from wastewater in sumps, and the quality of the effluent. Clearly these problems can be viewed as indicators of effectiveness in the handling, elimination or reuse of intrinsic and

Table 4.9: Generic waste minimization strategies for intrinsic wastes.

Waste type generated	**Type of WM practice**	**Waste minimization strategies**
S1, S3, S4, L5 S5, L1, L2	*Operating practices*	• Avoid spillage of organic matter waste on floor surfaces and wastewater streams. • Optimize organic material recovery from all unit operations e.g. tanks, vacuum presses, crushers for compost and fertilizer manufacturing or for responsible disposal. • Institute operational procedures to reduce waste dispersion. • Segregate various solid waste for easy recycling or recovery of useful products (consider all possible reusable or recycling possibilities before landfill option) • Embark on progressive training of personnel on significance of integrated approach to waste and product handling, to mitigate against waste dispersion and product loss. • Improve storage and handling of solids, e.g. by use of impermeable base layer or keeping/isolating them away from the drainage system. • Improve system surveying and maintenance to reduce/avoid spills and leakages both incidental and accidental. • Installation of drip pans under equipments to collect leaked process materials. • Increase process controllability to reduce spillages, incidentals and accidents. • Ensure bulk packaging of material purchased for both auxiliary and utility processes to reduce the disposal of packaging and dusty bags. • Explore/test new markets for the byproducts and other wastes which may increase revenue.
	Technological modification	• Use of dry recovery techniques of solids from surfaces, floors, e.g. equipments etc using brooms, brushes and pneumatic devices. • Change of vessel bottoms design to increase access to residues, hence improving the removal and consequent segregation of the organic matter sources into liquid effluent streams. • Installation of containment systems in case of incidents and accidents to recover product and avoid its loss to the waste streams or for responsible waste disposal.
S3, S5, S6, S7	*Technological modification*	• Improve the internal surface smoothness of tanks to enhance the recovery of these vital byproducts.
	Waste/byproducts recovery	• Consider recovery of useful materials e.g. tartrates, grape seed oil, etc. using possible recycling and reuse options before considering land fill techniques for solids disposal.

Table 4.10: Specific waste minimization strategies for intrinsic wastes.

Operation/ process unit	**Waste type generated**	**Type of WM practice**	**Waste minimization strategies**
Destemming/ Crushing	S1	*Technology modification*	• Fit “crusher lips” to reduce spilling over of grapes during unloading from trucks or grape bins and loading on crushers and destemmers. • Conveyor belts and other solids handling equipments to be modified to reduce or avoid their spillage into liquid effluent.
		Input substitution substitution	• Use of high quality grapes to reduce quantity of solids and improve yield per unit throughput.
		Operating practices	• Dedication of crushers for a given grape type to reduce product contamination. • Improve site communication during unloading of grapes from trucks, grape bins and loading on the crushers to avoid spillovers of grapes. • Optimize scheduling of grape deliveries to minimize start-up and shut down waste and energy consumption.
Sulphiting	G1	*Input substitution*	• Replace SO_2 gas with liquefied or solid pellets of sulphur dioxide to avoid its dispersion and hence reduce its impact on personnel through air pollution.
		Operating practices	• Ensure that the gas storage is out door or in well ventilated rooms to ensure that it will not suffocate the personnel in cases of incidental or accidental leakages. • Sulphur dioxide to be handled by trained personnel only to avoid accidents. • Limit leaks and exposure to personnel (should occur in the shortest time possible). • Put emergency plans and simple procedures in cases of accidents in place.
		Technological modification	• Installation of sensors to detect SO_2 concentration or its presence before it exceeds the recommended lethal levels to staff’s health.
Fermentation	G2, G3, G4	*Technological modifications*	• Installation of efficient ventilation systems to ensure no accumulation of greenhouse gases in tanks and buildings. • Installation of sensors for CO_2 and VOCs for health and safety reasons for the personnel. • Use of carbon absorption technology to absorb & control the levels of ethanol & other VOCs concentration so that yeast cells are not killed which may lead to sluggish fermentation. • Use of centrifugal fans to blow clean air into tanks and hence pushing out heavy gases at the bottom to reduce health risks to staff.
		Operating practices	• Establish procedural measures to determine CO_2 and VOCs levels in tanks before personnel enters them for maintenance or cleaning purposes.

Table 4.10: Continued.....

Operation/ process unit	**Waste type generated**	**Type of WM practice**	**Waste minimization strategies**
	S6	*Input substitution*	• Use of tested commercial wine yeast strains to reduce chances of stuck fermentation process.
		Waste recovery product	• Reclaim the yeast cells and sell them to pharmaceutical and food companies or send them/it for recycling (also they are high source of protein and vitamin B).
	L6	*Operating practices*	•Tanks should be filled correctly to avoid spillages during the fermentation process.
		Technological modifications	• Installation of sensors to control filling of empty tanks to avoid overfilling them with wine
Piping and transfer systems	L2	*Operating practices*	• Ensuring adequate maintenance of pump seals and pipes to reduce spills and leakages.
		Technological modifications	• Modify fixed piping systems which are laid horizontally to inclined elevations to enhance product flow under gravity to minimize product and energy losses. • Reduce transfer lines length to reduce spillages, water, energy and chemical usage during cleaning and sanitization processes. • Install welded piping instead of screwed connections to facilitate pigging process-reduces product loss.
Filtration	S2, S4	*Technological modifications*	• Installation of effective separation technologies such as use of membranes. • Installation of hoppers to charge all filtration cakes (reduces waste dispersion from solid to liquid media).
		Waste/product recovery	• The filter aids can be used as compost/fertilizer in vineyards as well as suppression of weed growth. • Using the press, extract the filters of wine and materials for their re-use in the filtration process (reduces material purchases and disposal costs).
		Operating practices	• Reduce use of diatomaceous earth for filtration by replacing it with centrifuges and optimal capture techniques as alternatives.
Pressing	S1, L4	*Technological modifications*	• For old inefficient pressers should be replaced with modern vacuum pressers to reduce aqueous solution containing high wine content. • Ensure new acquired pressers have removable bottoms for easy discharge of pressed dry skins/pips.

Table 4.11: Generic waste minimization strategies for extrinsic wastes.

Operation/ process unit	**Waste type generated**	**Type of WM practice**	**Waste minimization strategies**
Cleaning and sanitization	Wastewater Used cleaning solvents	*Input substitution*	• Use of steam to reduce water and chemical usage. • Use of high quality water for cleaning equipments (reduces biofouling of equipments, amount of water and chemicals used). • Substitute chlorine hazardous based-cleaning agents with non-hazardous or toxic agents. • Replacement of sodium-based cleaning agents since they cause sodicity and salinity in soils such as hydrogen peroxide and ozone.
		Technological modifications	• Replace hose pipe cleaners with high-pressure-low-volume cleaning equipments to reduce water and chemical consumption. • Installation of high pressure rotary nozzles inside tanks to facilitate cleaning process. • Installation of water meters to monitor water consumption at various user points. • Improve the internal tank surfaces smoothness to reduce water and chemical demand. • Install CIP systems to reduce water and chemical use and improve byproduct recovery. • Use of modern dosing equipments and techniques to reduce quantities of chemicals used during cleaning and sanitization. • Fix-flow restrictors in taps and other water fixtures to avoid running taps after use.
		Operational practices	• Training of staff to view water as a highly valuable resource to achieve attitude change and thus to improve its handling and same for chemicals. • Develop strategies of reducing spillages and leakages of wine from pipes and equipments to minimize the number of cleaning cycles. • Optimize batch operations through scheduling of production processes to reduce cleaning sessions (conserves water and chemical usage) • Ensure closing of all taps when not in use to conserve water. • Segregate various streams to enhance water and cleaning chemical recovery. • Ensure correct chemical concentrations for cleaning by measuring of quantities before use. • Use mechanical means to remove their organic sources in equipments and surfaces to reduce water and chemical consumptions. • Practice effective pre-cleaning of equipments and floor surfaces to remove soiling to reduce water and chemical demands. • Emergency and cleanup procedures should be developed and communicated via training to contain cases of chemical spills or accidents. • Use of adsorbent to clean up wine and chemical spills, and immediately avoid its spreading before wet cleaning. • Separation of chemicals which are incompatible to avoid explosions and contamination in storage rooms. • Limit the quantities and inventories of chemicals purchased to control wastage via expiry (first in, first out).

Table 4.11: Continued.....

Operation/ process unit	**Waste type generated**	**Type of WM practice**	**Waste minimization strategies**
			• Apply counter cleaning technique during cleaning sessions to minimize quantities of water required per cleaning cycle. • Use de-ionized water for cleaning solutions preparations to minimize quantities of chemicals used due to water hardness. • Pump fixed amount of cleaning/sanitizing solutions to equipments and surfaces to reduce overall chemical required. • Adopt a policy of immediate cleaning of equipments and surfaces after operations to minimize quantities of water and chemical requirement.
		Recycling re-use	• Reuse of high quality wastewater as first rinse for the next cleaning session/cycle. • Recycle cleaning agents before they are sent for their recovery (on/off site). • Reuse of the cleaning solutions till they are saturated (avoid once through use). • Reuse of non-contact cooling water for the cleaning of floor surfaces. • Reuse of stormwater for cleaning of floor surfaces or as a first rinse for highly soiled equipment.
Energy transfer	G5, G6	*Operational practices*	• Prevent leaks through constant and periodical maintenance of the cooling systems to avoid emissions and high water consumption. • Reduce the levels of releases when performing maintenance in all cooling systems. • Emergency procedures should be instituted in case of accidents and accidentals to control the extent of damages and losses.
		Input substitution	• Substitute the environmentally harmful refrigerants with benign ones, e.g. ozone, to reduce the cost of replacement and damage to the atmosphere during refilling process.
		Recycle/reuse	• Recycle the refrigerants effectively in the cooling system.
Packaging	S10	*Recycle reuse*	• Send paper and cardboards and other recyclable solids back to the suppliers to minimize accumulation of solid wastes from outside sources. • Request suppliers that the deliverables be shipped in returnable containers and re-use boxes for shipping goods. • Paper from packaging and office can be shredded and be used as packing material thus saving both costs on disposal and purchase of packing materials.
	S11	*Operating practices*	• Avoid excessive use of glue. It makes recycling of bottles very difficult. • Prevent glue spillages which may result to wastewater stream leading to poor effluent quality.

extrinsic wastes. Effluent quality is influenced by the presence of organic matter, chemicals, and nutrients in the wastewater stream. In the event of organic waste remaining in the liquid effluent for some time, an offensive odor due to the development of anaerobic conditions is generated. In this sense, the two aspects are a cause-effect, where the poor quality of the effluent is manifested by the generation of odors from the wastewater.

Thus, the odor elimination and effluent quality improvement can be viewed as benefits derived from integrated production advocated in this work, premised on the principle of preventing cross media waste transfers. A number of strategies identified to meet these challenges are presented in Table 4.12. Note that most of these strategies mirror on those identified under intrinsic or extrinsic waste with only a few exceptions. This implies that the handling of the production and auxiliary processes has an inherent direct link to the impact of the vinification processes to the environment.

4.4 Results and Discussions

In this section, the focus is on the analysis of results conceptually derived for waste management in the wine industry and based on the concept of qualitative waste minimization. For each derived waste minimization strategy, it has been placed in either of the four categories as shown in Table 4.9 through to Table 4.11. Note that, while these categories represent a rough and broad division of the strategies, they have no definitive distinction. This is because some of strategies can be grouped in several ways, and certain specific strategies might arguably fall in more than one category. However, on the assumption that each strategy has been placed in a category that represent it best, the measures can be summarized as shown in Table 4.13 using results from Tables 4.9 to 4.11.

From the breakdown of 89 opportunities identified as possible waste management alternatives presented in Table 4.13, the results reveals that 47.19% corresponds to process execution and management, 29.10% are due to technological modifications, 14.61% are due to waste/product recovery and reuse/recycling, and 8.99% corresponds to input substitution-oriented alternatives. Nearly 50% of the total reported strategies for extrinsic and intrinsic wastes fall under process execution and management (operating practices) category.

Table 4.12: Waste minimization strategies for eliminating/reducing odor and improving of effluent quality.

Problem	**Cause**	**Waste minimization strategies**
Odor generation	Rotting organic wastes in wastewater	• Adopt effective solid separation from the liquid waste streams to ensure low BOD and COD values in wastewater stream. • Ensure spent diatomaceous earth is covered while in storage after use or in containers, for periods not beyond three weeks or spread it in vineyards. • Locate composting and storage sites for stalks and marc away from residences, cellar buildings and highways (should be at least 200m from such facilities). • Untreated wastewater should not be stored in open lagoons or ponds for periods exceeding 72 hours especially in areas where there are residences in the neighborhood. • Mechanically aerate the wastewater in lagoons and ponds to ensure BOD reduction, hence avoiding the generation of odor. • Improve operational practices where organic sources are mechanically removed from surfaces and equipments before wet cleaning process. • During irrigation using wastewater ensure irrigating rate should be equal to the infiltration rates to avoid residence of organic matter that can generate odors while pending on the soils.
Effluent quality	Presence of organic matter, chemicals and nutrients in wastewater.	• Avoidance/elimination of spillages and leakages of product and wine juice to water streams. • Pigging of pipes to avoid cleaning water being in contact with residue wine or while transporting it from different locations. • Effective mechanical removal of all organic solids from surfaces and equipments before cleaning wet processes starts. • Effective segregation of effluent streams from cooling and ion exchange operations to reduce impact of chemicals to the wastewater quality. • Recovery of organic solids from water streams as soon as possible using screens or through the sedimentation process. • Improve all process control to reduce incidents of interaction between organic sources and the wastewater stream. • Use of closed cooling systems to ensure that refrigerants and cooling water does not enter into wastewater (or segregate them during bleeding process). • Ensuring that extra storage containers are available during peak vintage season to ensure that excess wine or byproducts are not dumped into the wastewater stream. • Segregation of the chemical solutions from laboratory works and ion exchange operations from wastewater stream. • Recycling of used cleaning solutions till saturated to ensure that their pH is reasonably below 10.

Table 4.13: Quantitative summary of the derived waste minimization measures.

Waste Min. categories	**Intrinsic wastes**				**Extrinsic wastes**		**Totals**	**% of Totals**
	Generic	**%**[a]	**Specific**	**%**	**Generic**	**%**		
PEM[b]	10	*23.81*	11	*26.19*	21	*50*	42	*47.19*
TM[c]	4	*15.34*	15	*57.70*	7	*26.96*	26	*29.21*
WPR & RR[d]	1	*7.69*	3	*23.08*	9	*69.23*	13	*14.61*
IS[e]	0	*0*	3	*37.5*	5	*62.5*	8	*8.99*
Totals	15	**16.85**	32	**35.96**	42	**47.19**	**89**	

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[a] Percentage
[b] Process execution and management
[c] Technological modifications
[d] Waste/product recovery and reuse/recycling
[e] Input substitution

Of the strategies under the process execution and management, 50% are generic solutions focusing on extrinsic waste from auxiliary processes. The high number of strategies in this category reinforces the fact that active involvement and participation of the winery staff at all levels in waste minimization programs is crucial. In many wineries it was observed that, the level of involvement in waste prevention programs by the floor workforce personnel strongly impacted on quality and quantity of releases and discharges as well as resource conservation.

The profound implication of the above observation rests on the fact that since many of these strategies require no cost or require relatively low-cost investments and they can be rapidly implemented without requiring further detailed quantitative analysis. Such undertaking has the potential to produce impressive improvements in terms of reducing waste quantities, improving its composition, and lowering the consumption of resources (e.g. potable water and cleaning chemicals). In the course of this study, it became quite evident that the manner in which the operational practices were carried out had a strong influence on the quantities and quality of the resultant waste streams. The high number of alternatives in process execution and management category seemingly support this view, though indirectly.

Under the intrinsic waste, 47 strategies were identified and about 68% of these opportunities were specific in nature. Vinification is a batch process, which implies that most intrinsic wastes can be effectively handled at source through technological modifications and their possible dispersion to other waste streams can be effectively diminished. This is because, of the 68%, about 47% are under the technological modification category. Based on these observations, two things are clear: (i) most strategies are specialized for a specific process unit since vinification is a batch process, and (ii) as earlier discussed, technological modifications require high capital investment, and thus, a quantitative analysis becomes essential in determining the justification of implementing a particular strategy.

The process of justifying the strategy of choice for implementation should take into account economic returns as well as non monetary rated benefits such as environmental performance, ease of implementation, safety and hazard reduction, etc. rendering it essential to employ a multi-criterion decision analysis approach to rank the options. The ranking and consequent screening of the options is accomplished through a wide range of selection criteria considering different priorities that may include and not limited to the following factors: the quantity and frequency of waste stream, efficiency of material conversion into product resulting in waste reduction, cost of managing existing waste streams, possible regulatory impact in the future, and cost of implementing the chosen alternatives (Allen and Rosselot, 1997).

Of course, a deeper view of the actual waste reduction among other criteria used for the evaluation of strategies that qualifies for implementation, requires a detailed quantitative analysis. The large numbers of strategies identified emphasizes the desirability of applying an integrated approach to waste management in the wine industry (Musee et al., 2003a; Musee et al., 2003b).

Using the number of strategies falling in each waste minimization category as shown in Table 4.13, the results can be generalized as illustrated in Figure 4.4. While it is acknowledged that the generalization may be over stretched to a certain degree, it offers useful insights on the expected waste reduction possibilities after the implementation of strategies under each category. For instance; it is seen that under the process execution

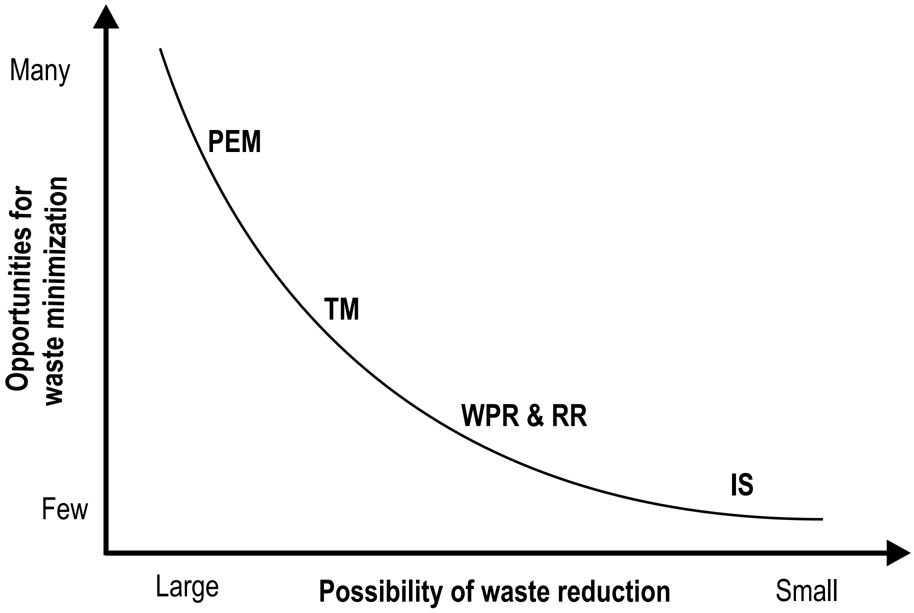


Figure 4.4: Generalization of opportunities to improve winery waste minimization based on strategies under different categories.

and management, not only is there a *large* possibility of waste reduction, there exists *many* opportunities to choose from in pursuance of this objective. On the other hand, very *few* opportunities exists under the input substitution category.

4.5 Concluding Remarks

Wineries are facing serious environmental challenges over waste disposal and utilization of process materials together with dynamic evolution of onerous regulatory regime concerning process waste handling and disposal. As a result, these challenges are calling for an integrated implementation of waste management during the vinification process to optimize the yield per unit throughput. Waste minimization as a concept that has gained significance as a preferred proactive approach of waste management was employed in this chapter for waste stream analysis and process analysis in the wine industry.

A systematic methodology has been presented for a qualitative waste minimization analysis applicable to any winery. From the systems approach, a conceptual framework was proposed and discussed aimed in optimizing the entire vinification process from a qualitative perspective where the primary goal was to reduce the quantities of waste generated and/ or improving its handling. Moreover, it facilitated the filling of data and knowledge gaps which was essential in order to develop an intelligent decision support system for waste minimization in the wine industry presented in chapter 5.

The systematic methodology for qualitative waste minimization through waste stream analysis and process analysis, culminated into the derivation of 89 alternative strategies. On the basis of pollution prevention techniques (Van Berkel, 1997a), the derived strategies were classified into four broad categories: process execution and management (PEM), technological modifications (TM), waste/product recovery and reuse/recycling (WPR & RR), and input substitution (IS).

The proposed methodology framework is based on three fundamentals: waste source identification, causality of wastes, and consequent derivation of waste minimization strategies. The waste source identification stage provided a suitable environment to identify and qualitatively quantify at the process and unit operation level, areas which are waste intensive and the nature of pollutants matrix . On the other hand, causality focused on establishing the true waste causes. This offered synergies that were exploited in deriving possible waste minimization strategies. Of the derived strategies, this study shows that majority of them are in process execution and management category, hence requiring minimal or no evaluation before they can be adopted in a given winery.

The results obtained can be utilized in two ways. First, they can be used for the allocation of environmental costs to the production unit(s) generating wastes or emissions based on their respective quantities and composition. This will act as a motivator to various production units in the winery to reduce their releases and emissions. Secondly, owing to the hierarchical feature adopted in analyzing and presenting the data, information, and knowledge in this domain, has led to their presentation in a format amenable for the development of an intelligent decision support system.

The intelligent decision support system will be of crucial value in the wine making community in two ways. Firstly, it provides expertise on diverse waste reduction alternatives to the wine industry. In this manner, it will assist nonexperts in various aspects of waste management, for instance by providing possible suggestions with potential to eliminate or reduce waste sources and causes via environmentally friendly and cost-effective means.

And secondly, owing to the laborious, time-consuming, costly, and knowledge-intensive process of carrying out a thorough waste minimization assessment, its automation will significantly reduce the barrier that prohibits extensive waste minimization analysis in the wine industry.

Chapter 5

Development of a Fuzzy-Based Expert System for Waste Minimization

5.1 Introduction

The primary objective of this chapter is to report the development and implementation of a decision support system for waste minimization in the wine industry. In the development phase, the concepts of system structure, knowledge base development, screening and ranking of the numerous strategies in an endeavor to build a consistent knowledge base are presented. Particularly, the aspect of screening and ranking which entailed a wide range of criteria was found crucial in evaluating the potential contribution of a given strategy towards overall waste reduction. This multi-perspective approach differs strikingly from the single (linear) dimensional criterion mostly used in screening options considered for implementation in many environmental oriented problems.

The implementation phase entails the transformation of the conceptual aspects presented at the knowledge acquisition phase into a decision tool that possesses intelligence. Intelligence here refers to the developed system's ability to reason on the basis of the heuristic knowledge acquired from various sources and achieved through the integration of AI technologies (ES and FL). This property is critical in successful diagnosis of waste minimization challenges in the wine industry. Further, the intelligent nature of the system allows to overcome the limitations of classical control in complex waste management industrial problems and particularly in the wine industry. This is because the data and knowledge available is mostly vague and imprecise owing to nonstatistical uncertainties.

5.2 Process Hierarchy for Waste Minimization Synthesis

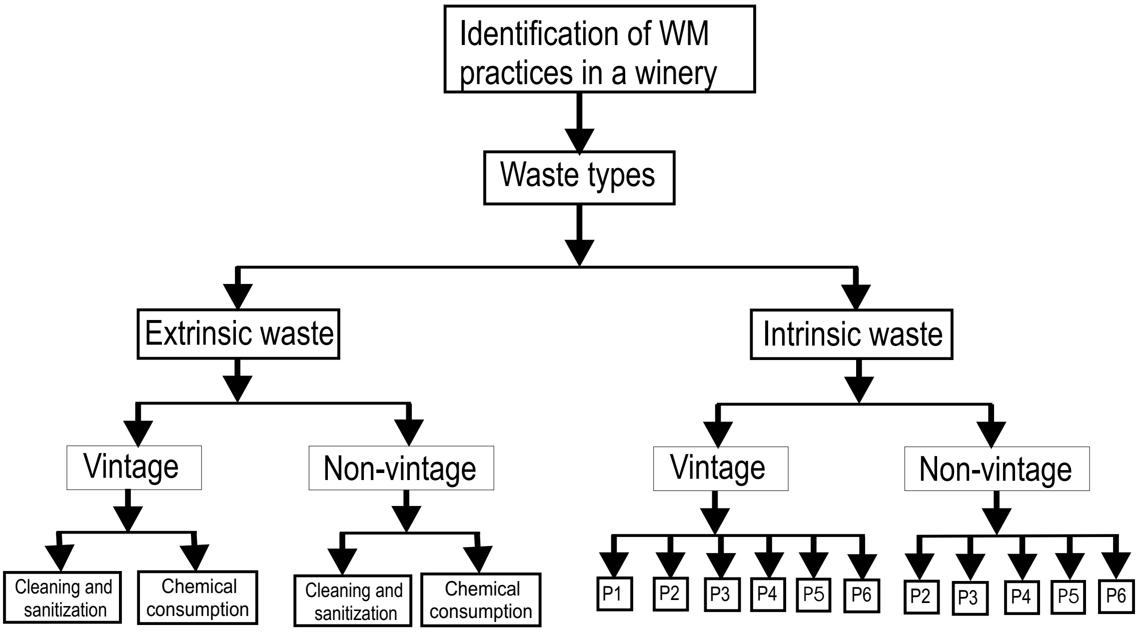
The hierarchical approach in industrial process problems has its origin in the hierarchical decision approach to process design developed by Douglas (1985). In this study, the approach was adopted for a retrofit application in the wine industry. In the present context, it provided a systematic framework for reviewing the performance of existing wineries with regard to waste management during the vinification process.

Thus, the focus in this section is to decompose the vinification process into subtasks in order to facilitate the identification of key variables that influences: (i) the loss of product and byproducts during production, (ii) the quantity and quality of effluent generated during cleaning and sanitization processes and, (iii) the consumption of chemicals during cleaning and sanitizing processes.

Waste minimization is essentially a process oriented task and effective when implemented as an integral part of the production process in the wine industry. A process hierarchy illustrating the decomposition of the vinification process is shown in Figure 5.1. In pursuance of finding the influencing variables for waste generation in the wine industry, it became apparent that numerous influencing factors were involved. In this case the hierarchical approach was employed to structure and classify the influencing factors methodically and transform them into a few input variables.

The hierarchy for vinification process decomposition was achieved through a series of four levels. At the first level of the hierarchy, types of waste generated from the wine making process were considered. Of particular concern in this study are the extrinsic and intrinsic wastes. This form of classification laid a broad basis to avoid a situation where certain waste or wastes were left out unconsidered, or overlooked during the solution synthesis stage. It also ensured consistency on the strategies recommended for a particular kind of waste though it may be generated at different unit operations and processes at various stages of production.

Vinification, being both a batch and a semi-batch process generates, wastes of different matrix (composition) exhibiting strong season dependance. To evaluate the effect of this factor, the next level of classification was to consider seasons at which different wastes were generated. The vinification process has two seasons; vintage season and non-vintage



P1= Crushing and desteming processes
P2=Transfer processes and operations
P3= Filtration
P4= Pressing
P5= Fermentation
P6= Bottling and packaging

Figure 5.1: Vinification process decomposition hierarchy for waste minimization.

season. The vintage season is regarded as the period in which harvesting, crushing of grapes, and fermentation of grape juice[1] takes place. The remarkable feature of vintage season is its short period close to 10 weeks. The remainder of the year is categorized as the non-vintage season. Other processes take place throughout the year in the winery except harvesting, crushing and destemming of grapes[2].

Therefore, the kind of wastes were examined in the light of the season they were generated. The classification of vinification process in terms of season of production led to the identification of predominant processes under each season. The challenge here was to identify how each process (e.g. crushing, fermentation, etc.) influences the final waste matrix in a particular season.

At the third level of the hierarchy focused on the processes that generates various wastes (see details on various wastes in chapter 4). The season and thus, in turn the

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[1] There is difference between fermentation of grape juice and fermentation of wine, see for instance the arguments advanced by Rankine (1989).

[2] A definitive distinction between vintage and non vintage is more or less on the processes that takes place at a particular time of the year during the vinification process calender.

predominant processes at a particular season, assert a significant influence on the product and byproduct losses, composition and quantities of the effluent generated, and chemical consumption during the vinification operations. The fourth level of the hierarchical decision approach was to examine the causes influencing waste generation at unit operations and processes. Examination of different causes for waste generation has been comprehensively presented in chapter 4.

By setting up the described hierarchical approach, an effective systematic waste minimization analysis at each process or unit operation emerged. It also revealed that, attempts of waste minimization on a particular waste type in level one had positive synergies on waste reduction on the other waste type. For instance, proper handling of product and byproducts at all processes that generate intrinsic waste had a positive impact on the quantities and composition of effluent generated under the extrinsic waste category. Such complex relationships among numerous aspects of vinification process reinforced the need of adopting a systematic integrated approach in deriving solutions in this domain. Moreover, the approach presented a germane insight in the nexus of environmental protection on one hand and process execution on the other.

5.3 Screening and Ranking of Waste Minimization Strategies

Faced with numerous waste minimization strategies derived and discussed in chapter 4, it is necessary to screen and rank them to ensure that superior options are given higher priority. This implies that during the decision making process, alternatives having high potential to yield huge benefits after being screened through a multifacet criteria are given priority for integration into the production process. To reiterate, waste minimization at industrial production is only effective when the strategies are implemented as an integral part of the normal production process. In this sense, ranking and screening of options with respect to waste management were used as a means of identifying options that offer real potential in minimizing waste at a lower cost, after being evaluated using a multifacet criteria.

The subject on ranking and screening of waste streams and pollution prevention options have been extensively discussed by Hanlon and Fromm (1990), Crittenden and

Kolaczkowski (1995), Allen and Rosselot (1997), Smith and Khan (1995), and Balik and Koraido (1991). For each case reported by the various authors, the criteria used for ranking and screening the derived options were strongly influenced by the industry (problem) under investigation and the nature of process databases accessible in the domain of study. In this study however, Smith and Khan's index (Smith and Khan, 1995) developed for the ranking and screening of pollution prevention options was adopted for the purpose of ranking of waste minimization strategies. However, the index was modified to suit the unique challenges that exists in the wine industry. It should be noted that the Smith and Khan index was designed for chemical based industries which have certain unique features that are not apparent in the wine industry.

To produce a broader and more acceptable prioritization of the derived waste minimization strategies, each strategy had to be evaluated based on a set of multi-criterion including the position of the strategy in the waste minimization hierarchy (where the source reduction is considered of higher priority than reuse and recycling), the possibility of reducing the targeted waste, ease of implementing the strategy, cost of implementation, technical feasibility, just to mention a few (Allen and Rosselot, 1997). The waste minimization index (WMI) is calculated for each strategy on the basis of these criteria. For each criterion different weights were assigned. This is because each criterion was viewed to assert impacts of different magnitudes in terms of reducing the overall quantity of waste generated and capital costs required for its successful implementation. The criteria perceived to be of more significance were assigned higher weights, and hence in turn asserting more influence to the final WMI calculated.

Smith and Khan proposed an index made up of eight weighted factors for ranking pollution-prevention solutions. In their index, it consisted of source reduction, recycling, and waste treatment according to the EPA pollution prevention hierarchy (US Environmental Protection Agency, 1988). In this hierarchy, source reduction is more superior to recycling and reuse, thus was assigned the highest weight.

The other five criteria used in describing the waste minimization solutions are; ease of implementing the alternative, degree of waste reduction expressed in percentage, capital cost of the solution, payback period and the depth of solution. The weights were in the descending order in accordance with the forgoing description, such that the depth of solution was assigned the least weight factor of 10^0 while source reduction had a weight of 10^{11}. Note that while the pollution prevention techniques were expressed in two crisp values (yes=1 or no=0), the last five factors were qualitatively expressed in four to five values, except the expected waste reduction and payback periods which were expressed in the scales of; 0-100% and 0-9 years, respectively. However, in the case presented in this dissertation, using qualitative modeling as discussed in chapter 3, waste minimization techniques were expanded from two crisp values to multivalues of between three to five qualitative values as depicted in Table 5.1. The original Smith and Khan index is presented in Appendix C.

First, waste treatment, payback period and depth of solution factors were excluded from the index considered here. Waste treatment factor is excluded because it is not seen as a waste minimization activity[3] in the wine industry. Payback period was excluded owing to insufficiency of data and information on vinification processes in terms of detailed costs. Nevertheless, the criterion on payback period can easily be incorporated in as a criterion when evaluating strategies in a specific winery where data on costs are accessible. The depth of solution factor was unattainable owing to the fact that for the problem under investigation, there was lack of sufficient company and EPA case studies to be used as a guide for the rating of the solutions under this criterion.

In this case, the percentage of reduction has been expressed in qualitative terms and regarded as waste reduction possibility (WRP). The waste minimization index (WMI) for a given strategy was calculated using the expression:

$$WMI = SR \times 10^5 + Re \times 10^4 + R \times 10^3 + WRP \times 10^2 + IP \times 10^1 + CC \times 10^0 \qquad (5.1)$$

where SR: Source reduction, Re: Reuse or recovery, R: Reclaim or recycle, WRP: Waste reduction possibility, IP: Implementation potential, CC: Capital cost.

As the weights and the criterion values are not fixed for the Smith and Khan index, and therefore in this study they were changed to suit the problem under investigation in the wine industry.

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[3] The definition, and breadth and scope of waste minimization has been shown to be depended on the industry of study. See detailed arguments advanced by Hilson (2003) in this respect.

Table 5.1: Waste minimization ranking index.

Criteria	**Weight**	**Activity**		**Index value**
Source reduction (SR)	10^5	Elimination		1.00
		Minimize	High	0.75
			Medium	0.50
			Low	0.25
Reuse/Recovery (Re)	10^4	Full		1.00
		Partial		0.67
		Low		0.33
Reclaim/Recycling (R)	10^3	Full		1.00
		Partial		0.67
		Low		0.33
Waste reduction possibility (WRP)	10^2	no reduction (nr)		0
		low reduction (lr)		1
		Moderate reduction (mr)		2
		high reduction (hr)		3
Implementation potential (IP)	10^1	procedure change (pc)		5
		material substitution (ms)		4
		preventive maintenance (pm)		3
		retrofit equipment (re)		2
		new equipment (ne)		1
Capital cost (CC)	10^0	no cost (nc)		5
		low cost (lc)		4
		Moderate cost (mc)		3
		high cost (hc)		2
		Very high cost (vhc)		1

There are several shortcomings associated with the use of index rating procedure as discussed by Halim and Srinivasan (2002b), and Allen and Rosselot (1997). Firstly, assigning of indexes or weights to each of the criteria on the perceived importance is subjective and arbitrary. Therefore, the final outputs heavily depend on the choice of the criterion values and their corresponding weights. Secondly, while there was no difficulty in assigning weight values to reflect the best and worst cases in a given criterion, for intermediate cases where the values lie in between, the assignment was not straightforward. Despite these short comings, the index is crucial in screening and ranking large number of waste minimization strategies developed in this study. It helped to develop a robust system that mimics the operations in the wine industry, particularly with regard to waste management.

The index also offered a systematic procedure that produced quantitative results that proved effective in screening and ranking of numerous alternatives under different criterion. Furthermore, it offered a creative way of comparing criteria which are expressed either qualitatively or quantitatively and in reality difficult to compare as they are expressed in different units. Therefore, to rank the numerous waste minimization strategies using a diverse criteria, the practical way adopted was the development of a systematic procedure that produces quantitative results. This was achieved by assigning dimensionless weights to each criterion. The semiquantitative system of ranking the strategies proved effective by generating results that were consistent.

5.4 Development of the Knowledge Base

The core of a knowledge-based expert system is the knowledge base, which comprises the crucial problem-knowledge for understanding, formulating, and solving problems argumented with a specialized expertise in a specific domain. The knowledge base is a collection of facts, documented definitions, methods, rules of thumb (heuristic information), judgmental data and casual models expressing relations among the variables in a specific domain under investigation.

The core tasks in the development of knowledge base are; knowledge acquisition and knowledge representation (Turban and Aronson, 1998; Kidd, 1997; Ignizio, 1991). The acquisition of knowledge coded into the knowledge base has been recognized as the most significant stage, but also the principal bottleneck in the design and development of knowledge-based systems. This critical phase involves gathering, eliciting, analyzing and interpreting the knowledge that experts use to solve specific problems in a particular domain.

5.4.1 Knowledge Acquisition

This section presents a brief review of knowledge acquisition for the development of a knowledge base which is the kernel of a rule-based fuzzy expert system. Knowledge acquisition entailed searching and compiling information contained in diverse sources of knowledge, and identifying reasoning mechanisms followed by managers and operators in the wine industry in decision making with respect to waste. The acquired knowledge from various sources was compiled and represented in a computer program inform of production rules to aid decision making.

As earlier mentioned, knowledge acquisition is a daunting task because the domain under investigation is ill-structured. This is attributed to the large set of influencing factors on waste management in the domain under study. The other reason is the existence of numerous complex interactions among the influencing factors. This can be attributed to the widely varying production practices from one winery to the other or even from one batch throughput to the next.

Furthermore, many factors that determine waste generation in the wine industry have no linear relationship among themselves. This is because the winemaking process is largely intuitive task and has no formalized techniques of undertaking it. The significance of these observations is supported by the fact that, wine making is itself an artisanal activity and many of its processes were not designed from an engineering perspective. To circumvent this challenge, a methodology of trading off some factors or parameters at the expense of others was adopted. Such an approach had the benefit of ensuring the tractability of the developed system and effective means of aggregating key factors governing waste management in the wine industry.

The knowledge coded into the knowledge base was obtained from two main sources namely the documented sources (based on reported literature on industrial wine production and waste management) and the undocumented (experiences or expertise from experts or operators in the wine industry) sources. The documented knowledge used in this study was found in wide ranging sources including: textbooks (both text and reference), plant manuals, journal articles, flowcharts, tables, reviews, abstracts, plant manuals for operators, magazines, multimedia documents, databases, information from world wide web, etc. The expertise knowledge from the above sources was collected without much intervention of experts, and resulted in considerable savings in terms of time-consuming interviews. This knowledge acquisition approach was extensively used to improve the efficiency of knowledge-engineering methodology.

The documented source of expertise knowledge was mostly relied on in this study to eliminate the problem of inaccessibility of experts, reduce chances of missing vital information, and avoid time-consuming knowledge elicitation methods such as interviews (Moore and Miles, 1991). In spite of the merits of this approach, several demerits were apparent. These demerits included: encountering conflicting information in certain cases, having certain questions being raised regarding the integrity of experts' opinion, and the possibility of covering the same ground twice were noted as well. However, the use of a sensible approach in addressing these handicaps offered benefits that outweighed the demerits.

On the other hand, knowledge from undocumented sources was obtained through interviews with a waste management consultants in the wine industry and several wine makers. Both unstructured and structured interviews (Turban and Aronson, 1998, McGraw and Harbison-Briggs, 1989) were conducted. The task here was primarily to identify key facts and concepts that governs waste management in the wine industry. It also served as a cross validating exercise of the knowledge obtained from secondary sources to ensure the final integrity of the developed system. And thirdly, experts facilitated the inter-linking of numerous complex factors that govern waste management in the wine industry. As a result, the number of production rules necessary for the decision making were reduced to a reasonable number which proved very crucial in enhancing the system performance.

Numerous classification of elicitation methods have been developed and reported in the literature (see for instance; Turban and Aronson, 1998; Awad,1996; Scott et al., 1991). However, during the knowledge base development in this case study, the manual method was employed as depicted in Figure 5.2. The conventional method entails conducting of interviews and extensive literature review, where the literature sources of knowledge were given more emphasis for reasons we have advanced earlier. The knowledge acquired was decomposed into two classes: namely the generic knowledge and specific knowledge.

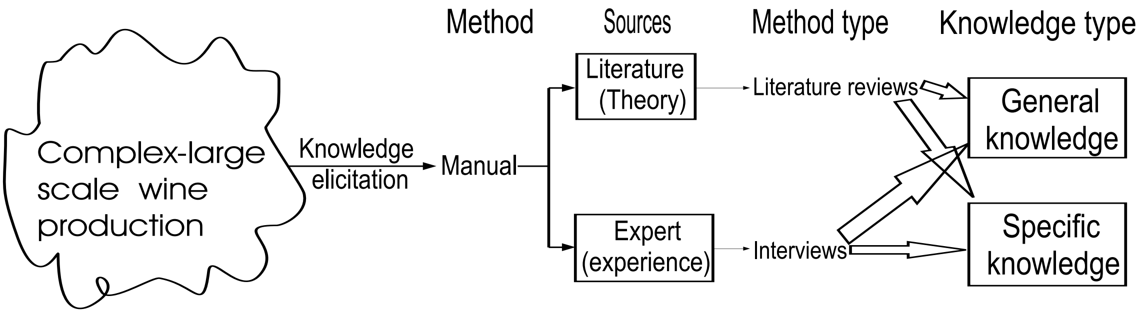

Figure 5.2: Classification of sources and methods adopted for knowledge elicitation from the wine industry.

The acquired knowledge was represented in the knowledge base using an object-oriented architecture.

The general knowledge entailed waste minimization techniques and practices applicable to a wide range of processes and unit operations (see Table 4.10). The remarkable feature of these strategies was their repetitive (routine) character stretching over different processes and unit operations. On the other hand, the specific knowledge focused on techniques and strategies that addresses waste minimization in specific processes and unit operations (see Table 4.11). The overriding factor in the latter case of strategies and techniques was the type of waste targeted for reduction or elimination. In particular the specific knowledge was focused in dealing with intrinsic waste. Interesting, these strategies and techniques were mostly found to be a function of equipment type (technology and design) employed in a specific operation or process.

Taking advantage of synergies existing between the two knowledge sources, a knowledge base that captures a good degree of the waste minimization strategies in the wine industry was developed. The knowledge captured was expressed in tables as discussed and presented in chapter 4. Before the rules could be developed through the use of decision trees, the relationships between the strategies, practices and operations were first established. It appeared that, depending on the waste problem targeted for reduction (e.g. product and byproduct loss, effluent quality, etc.), several strategies were applicable while others were not. At this stage then, the knowledge was expressed in blocks as shown in Figure 5.3.

The qualitative reasoning was used for assigning of values to the linguistic symbolic

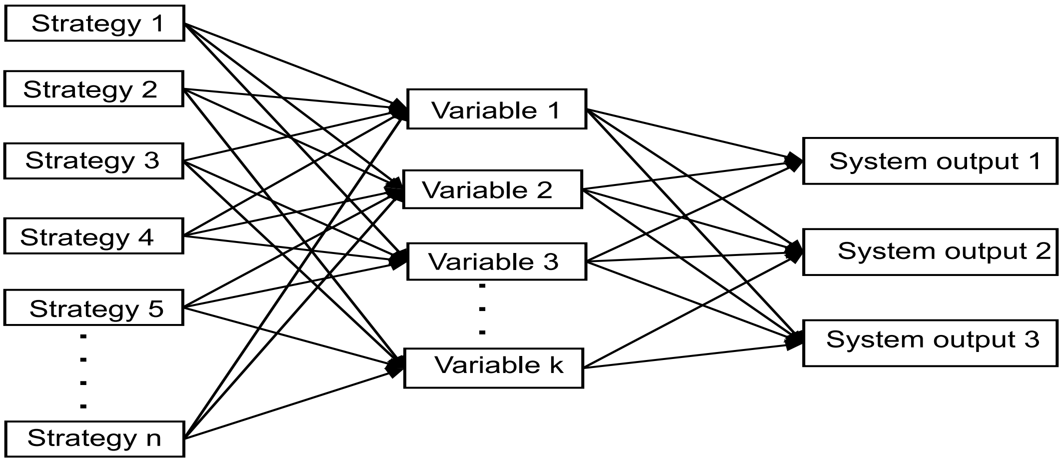

Figure 5.3: Systematic establishment of the relationship between a set of waste minimization strategies, a set of variables, and the system outputs.

parameters as pointed out in chapter 3 section 3.1.2. These linguistic variables were identified with the assistance of experts for a given waste reduction problem, and were between two and four for a given problem (e.g. product and byproduct losses (two variables), chemical usage (three variables), etc. Owing to the large number of strategies that constituted a given linguistic symbolic variable and their additive effect (strategies) observed during the production process, it was clear that no strategy could wholly represent a given linguistic variable.

Therefore, strategies in a particular process, operation or problem were clustered and ranked on the basis of their contribution to a particular variable (variable here refers to effluent quality and quantity, etc.). The ranking was done using WMI presented in section 5.3. The contribution of a strategy towards waste reduction was measured on the basis of its index size. This in turn determined the score the strategy is assigned during the aggregation of strategies to evaluate the final composite input variable to the fuzzy logic (see for example in Table 5.8).

5.4.2 Knowledge Representation

Flowing from the previous knowledge acquisition phase, facts, relationships and strategies suitable for waste mitigation were organized in several variables (see Figure 5.3). The a *priori* knowledge acquired in this domain was expressed in symbolic form. In deriving a decision-making rule based model, the variables were expressed in decision trees as schematically presented in Figure 5.4.

Decision trees are important tool in data mining. The most fundamental aspect is their hierarchical top-down descriptions of the linkages and interactions among pieces of knowledge used for ranking of system outputs considered in this study. Thus, decision trees enhanced both the presentation and decision-making process of determining the system outputs.

From each leaf of a decision tree, a rule was derived and expressed in a natural language containing two parts: an IF (antecedent) part and a THEN (consequent) part. The rules were represented such that they mapped the inputs (variables) into the outputs (system outputs) in the knowledge base.

The refining of the symbolic knowledge for enhanced system performance posed a challenge at this phase of rule-based fuzzy expert system development. However, it was found that reasoning with logic rules provided acceptable and comprehensive explanations that could easily be validated and verified through human inspection. It also increased the confidence in the system and in certain cases lead to identifying significant relationships among various components that govern waste management in the wine industry.

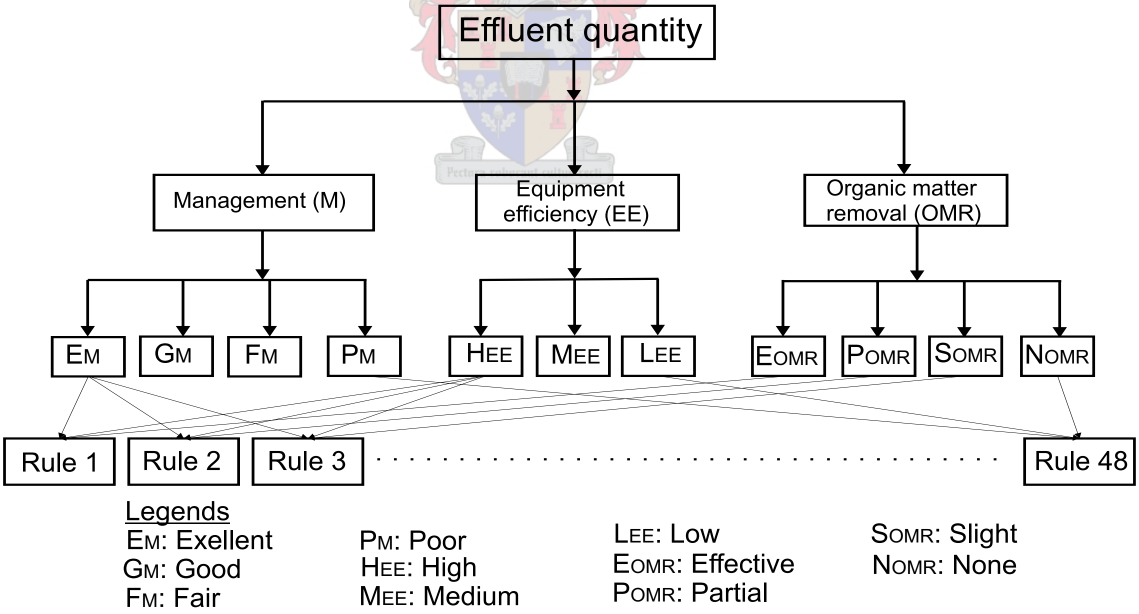

Figure 5.4: Effluent quantity output ranking using a decision tree.

Development of the Logic Rules

Several challenges were encountered in attempting to map the variable inputs into the system outputs using the decision trees. Firstly, there was the challenge of ensuring that the decision tree branches cover the entire solution problem domain. In this sense, decision trees had to be a true representation of experts step-by-step decision making algorithm expressed in the if-then rule format. From the knowledge acquisition phase, heuristics from operators and waste management experts were sought to act as a guide in the process of deriving logical fuzzy rules from the decision trees. Some of the heuristics used in this study in deriving consistent fuzzy rules for the evaluation of effluent quantity and quality were:

- When facility *management* is *excellent*, it is most unlikely to have *slightly or none* removal of *organic matter* from surfaces and equipment before the wet cleaning commences.
- When the *management* is *good*, it is highly unlikely to have *none* removal of *organic matter* from surfaces and equipment before wet cleaning begins.
- Under *poor management*, the question of having *high efficient cleaning equipment* and *effective removal of organic matter* sources is viewed as most unlikely scenario.

In deriving fuzzy rules using decision trees, if the number of variables are M and each variable has N fuzzy sets, then the total number of rules are M^N[4]. However note that some of the scenarios arising from the combinations of input linguistic variables predicted from the decision trees may not represent a norm under winery practices, but the possibility of such scenarios occuring cannot be ruled out.

For instance, to evaluate the effluent quantity and quality, a total of 48 rules were required in each case. The derived rules were expressed in if-then format. By applying the above heuristics, a total of 33 rules were derived in each case for effluent quality and

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[4] There are two types of linguistic variables in use (Duch *et al.*, 2004). In this study, universal context-independent variables were used (Combs and Andrews, 1998; Gu:ven and Passino, 1999).This means that the number of possible combinations grow exponentially with the number of attributes in order to cover the whole solution space. For example, from Table 5.2 the number of rules possible are $4^2 \times 3$. Clearly this indicates that it is difficult to determine all the possible states of the effluent quality and quantity easily and efficiently. This underscores why the dimensionless scores and extra heuristics were reguired to assist in deriving consistent rules.

effluent quantity. However, this meant that 15 rules to make a total of 48 rules were pruned from the decision tree after applying the above heuristics. The mechanism used to circumvent this challenge will be explained later. Thus, while the above heuristics provided a foundation for the derivation of some of the rules, they also had an underlying problem of developing conflicting decisions in certain instances and leaving other plausible cases unconsidered. In addition, they were unable to guarantee a 'right' answer in every case. A more comprehensive summary of limitations of using heuristics in knowledge-based approaches have been presented by Rossiter (1995).

The challenge of developing consistent rules void of contradicting system outputs was circumvented by assigning each variable linguistic quantifier a dimensionless score. The aim was to enhance the approximation of system outputs consistently and particularly when considering intermediate cases. From this approach, arbitrariness and subjectiveness of deriving the consequent part of the rule was significantly minimized. Examples of dimensionless scores assigned to the linguistic fuzzy set quantifiers considered in this study for deriving rule system outputs for effluent quantity and effluent quality are presented in Table 5.2. An example of how possible rules outputs were ranked using the additive sum of the scores is shown in Table 5.3 for effluent quantity.

The scores of variables in a given rule were added to rank the overall rule output. This was borne from the fact that each variable was dependent on several factors. In this sense, if the influencing factors had a positive impact on a given variable, then its impact should be reflected on the rule base. Likewise, there are scenarios where one or two variables may have high values but the overall rule output is reduced owing to the low value of the third variable. In this case by determining the possible rule output through simple addition of scores showed a good degree of mimicking consistently the rules formulated by the experts and operators. For instance, the predictions of Rule 9 and Rule 40 reflected correctly the rules that the experts had described as the best and worst cases in terms of effluent quantity resulting from various operations and processes in the wine industry.

For a complete derivation of 48 rules from the decision tree shown in Figure 5.4, two more heuristics were introduced to predict the possible system outputs for the 15 rules that could not be accounted for using the first set of heuristics. The two heuristics introduced were:

- Under certain cases, the top management level may ensure all or most of management related aspects are in place but at operations phase, the workforce can fail to deal with organic matter effectively. From this perspective, it is possible to have *fair* to *none organic matter removal* scenarios even though in overall, management can be said to be *good* or *excellent* .
- In circumstances where a facility is equiped with the state-of-art cleaning equipment, and the *organic matter removal* is *effective*, nevertheless it is feasible to have overall *management* being *poor.*

Table 5.2: Examples of dimensionless scores assigned to the linguistic quantifiers to enhance the evaluation of intermediate system outputs.

Input variable	**Linguistic quantifiers**	**Effluent Volume** **Assigned score value**	**Effluent quantity** **Assigned score value**
Management ($\mathrm{M}_{V^aQ^b}$)	Excellent	10	10
	Good	8	7
	Fair	5	5
	Poor	2	2
Equipment efficiency (E_E)	Low	2	10
	Medium	6	5
	High	10	2
Organic matter removal (O_MR)	Effective removal	6	8
	Partial removal	4	6
	Slight removal	2	3
	None removal	0	0

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[a] When considering management with respect to effluent volume.
[b] When considering management with respect to effluent quality.

A combination of the heuristics described above and the dimensionless scores, feasible system outputs for 15 rules that could not be covered under the generic heuristics from interviews of operators and experts were determined. This enhanced the system's ability to rank all possible quantity and quality of effluent on the basis of the user's responses.

Similarly, using decision trees the quantity of product and byproducts, and chemical usage were determined. However, the only significant difference from the former cases

Table 5.3: An example illustrating the application of assigned dimensionless scores in order to derive consistent if-then rules e.g. for effluent quantity under certain conditions.

Rule	**Effluent quantity input variables**				**Effluent**
No.	**M$_V$**[a]	**EE**[b]	**OMR**[c]	**Score totals**[d]	**volume (V)**
1	E[e] (10)	L[f] (2)	E[g] (6)	18	Low
2	E	L	P[h] (4)	16	Moderate
3	E	L	S[i] (2)	14	Moderate
4	E	L	N[j] (0)	12	High
5	E	M[k] (6)	E	22	Very Low
6	E	M	P	20	Low
7	E	M	S	18	Low
8	E	M	N	16	Moderate
9	E	H[l] (10)	E	26	Very low
10	E	H	P	24	Very low
11	E	H	S	22	Very low
12	E	H	N	20	Low
13	G[m] (8)	L	E	16	Moderate
14	G	L	P	14	Moderate
15	G	L	S	12	High
.	.	.	.	.	.
.	.	.	.	.	.
24	G	H	N	18	Low
25	F[n] (5)	L	E	13	High
26	F	L	P	11	High
27	F	L	S	9	Very high
.	.	.	.	.	.
.	.	.	.	.	.
36	F	H	N	15	Moderate
37	P[o] (2)	L	E	11	High
38	P	L	P	9	Very high
39	P	L	S	7	Very high
40	P	L	N	5	Very high
.	.	.	.	.	.
.	.	.	.	.	.
48	P	H	N	12	Moderate

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[a] Management of Volume

[b] Equipment Efficiency

[c] Organic Matter Removal

[d] Sum of the scores in a given rule e.g. in Rule 1: 10+6+2= 18.

[e] Excellent

[f] Low

[g] Effective

[h] Partial

[i] Slight

[j] None

[k] Medium

[l] High

[m] Good

[n] Fair

[o] Fair

discussed is that, no extra heuristics were required apart from those specified by the operators and experts.

5.5 Inference Mechanism

5.5.1 Introduction

In chapter 3, it was pointed out that knowledge-based systems consists of two basic components the knowledge base and the inference engine, and supported by several subsystems to enhance their functionality. In section 5.4, the knowledge base development was briefly presented. The focus in this section is to illustrate how the knowledge was hierarchically structured, coded into knowledge bases stretching over several sub-modules, and consequently manipulated using the inference engine to derive the solutions for a particular problem under investigation.

The inference engine is a knowledge processor incorporating reasoning methods and monitors the system using the knowledge base to modify and manipulate the context[5]. It achieves this by acting on the working memory and the knowledge in the knowledge base to solve the stated problem and generate an explanation for the solution. The inference mechanism also determines the problem solving-strategy on sequencing, as well as firing the production (IF-THEN) rules. The core issue in this phase was therefore, to model the reasoning process of an expert in an attempt to provide a solution based on the described conditions and practices by the user.

The inferencing mechanism was fully developed using built-in reasoning mechanisms of Matlab® (The Mathworks, 2002a) and the Fuzzy Logic Toolbox (The Mathworks, 2002b). It controlled the reasoning path, flow of data to various modules and finally integrated the modules' outputs so as to predict the overall system output. This was possible as outcomes of the modules were combined together and final conlusions derived. Such an approach is analogous to consulting several experts on a certain problem and then deriving a common conclusion by integrating all the individual expert opinions.

There are two methods of inference often used namely forward chaining and backward

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[5] The context in this case refers to the working memory which is a workspace by the inference from the information provided by the user and the knowledge base.

chaining. To derive the decisions in this study, the fuzzy inferencing system (FIS) used the forward chaining mechanism. Forward chaining was chosen because though data was available, there was no clear solution to the problem. Thus, to satisfy the problem goal, the role of the fuzzy expert system developed was to draw the possible inferences and find solutions based on the data provided by the user.

5.5.2 Modular Approach

To develop a robust system aimed in decision making for a non-linear, complex, multivariable and highly interactive industrial processes is itself a daunting task. In fact the complexity of the problem intensifies when the focus is to examine the possible impacts to the environment resulting from different but highly interrelated processes in the wine industry. In order to promote tractability of the developed system both at design and development stages, a modular approach was adopted. The modular approach employed in this study targeted the lower level sub-systems in order to aid in developing a robust system. The modular approach facilitated the development of independent knowledge modules where each performed a specific and specialized tasks.

In this study, robustness, tractability, and flexibility to accommodate future expansion of the developed fuzzy expert system for waste minimization in the vinification process was achieved by decomposing process knowledge and inferencing mechanisms into independent modules. The two main modules of this systems are: the knowledge module and the inference engine module. Each module consisted of several sub-modules. Morever, use of the modular approach offered several merits to the system. It enhanced the system flexibility, made it more adaptable for fast automation, easy to upgrade with new knowledge, and possible to build customized versions aimed in meeting a specific winery needs, constraints and requirements.

5.5.3 Knowledge Module

The knowledge module was aimed in handling a large amount of diverse, qualitative and incomplete knowledge for waste minimization in the wine industry. Therefore, the module basically represented the problem-solving knowledge. The knowledge module consists of the following four sub-modules namely; product and byproducts losses, chemical usage, effluent quality and effluent quantity. Each sub-module is discussed in detail in the following subsections.

I: Product and Byproducts Losses Submodule

Its primary concern was to examine factors that influence product and byproducts losses at specific processes and unit operations during the vinification process. The first task was to identify processes and unit operations that contribute significantly to these losses, and consequently derive possible reduction strategies. The knowledge in this module was classified into two categories.

The first category was concerned with strategies targeting specific processes (see a comprehensive discussion in chapter 4 section 4.3) and unit operations to reduce the losses. On the other hand, the second category was focused on the generic strategies that were influencing losses in all processes and unit operations.

Further, it was established that the losses were a function of the vinification season, and the process/or and unit operation under scrutiny. An example of experts' opinion on the maximum possible quantities of the losses in relative terms from each process or unit operation are presented in Table 5.4. The opinions were given taking into consideration two influencing factors. On the one hand, the vinification season and on the other, process or unit operation potential impact to the effluent quality and quantity. It is significant to note that, these values were estimated in relative terms between the processes and unit operations on the basis of heuristics. Further, it clearly shows that from specific and generic oriented factors, total product and byproducts losses can be approximated during the vinification process in a given season.

After gaining this knowledge and using the strategies derived in chapter 4, the level of product and byproducts recovery could be approximated under the user's defined operating conditions. This is possible by evaluating the degree to which both generic and specific strategies have been implemented in a given winery. For instance, if the implementation is satisfactorily, then the anticipated losses are considerably smaller. On the other hand, if the strategies were poorly or not implemented in a facility, the expected losses are high.

Table 5.4: Expertise opinion from two experts approximating the contributions of product and byproducts losses towards effluent quality and effluent quantity, under different processes and seasons.

Processes/ operations	**Effluent quantity**				**Effluent quality**			
	Vintage		**Non vintage**		**Vintage**		**Non vintage**	
	Ep1[a]	**Ep2**[b]	**Ep1**	**Ep2**	**Ep1**	**Ep2**	**Ep1**	**Ep2**
Crushing/destemming	0.10	0.25	0.00	0.00	0.15	0.30	0.00	0.00
Wine/juice/byproduct transfers[c]	0.25	0.15	0.35	0.25	0.30	0.10	0.40	0.35
Filtration	0.15	0.10	0.2	0.25	0.10	0.10	0.10	0.15
Pressing	0.20	0.20	0.15	0.15	0.15	0.30	0.10	0.20
Fermentation[d]	0.25	0.25	0.20	0.20	0.25	0.20	0.25	0.15
Bottling/packaging[e]	0.05	0.05	0.10	0.15	0.05	0.10	0.15	0.15
Sum of weights	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**

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[a] Expertise opinion of the first expert.
[b] Expertise opinion of the second expert.
[c] This also accounts for racking and associated fugitive emissions.
[d] This addresses tank cleaning and racking processes.
[e] It is strongly a function of wine type being packaged.

The intermediate losses possible on a facility were found to be dependent on the unique matrix of implementing both specific and generic strategies in a given winery.

To estimate the total recovery of products and byproducts during the vinification process in a given season, quantities recovered from each process or unit operation were first computed. This was executed as follows. Firstly by examining qualitatively the degree of implementation of both generic and specific strategies in a particular process. Then secondly, the values owing to the generic and specific oriented implementation of strategies/and or practices obtained from the process under consideration, were added. The additive value obtained was an indication to the degree at which products and byproducts were recovered from surfaces and equipment before wet cleaning (this was obtained using the numerator expression in Equation 5.5).

Thirdly, to ensure the value obtained from a given process is useful for the determination of the total product and byproducts recovered in the entire vinification process, the obtained value for a given process or unit operation had to be normalized. Normalization process had two-fold merits. One, it was possible to use the obtained value as an indicator of how successful the product and byproducts are handled in a given process or unit operation. A high index value indicated that the product and byproducts were satisfactorily handled in a particular process, while a low value signified they were not. Secondly, it adjusted the results of different processes and unit operations to a common dimension and therefore, aided in evaluating the total product and byproducts recovery from the entire vinification process in a specific season.

Assume for process i, the values obtained after examining the implementation of generic and specific strategies are A_i and B_i, respectively. Then the normalized value N_i for process i is given by the expression;

$$N_i = \frac{(A_i + B_i)}{A_{it} + B_{it}} \tag{5.2}$$

where A_{it} and B_{it} are the maximum values that can be realized when all generic and specific strategies were satisfactorily implemented in process i.

Again note that the normalization results were determined to provide an input to the weighting of the total product and byproducts recovery in the entire vinification process. From this point of view in a given season, the weighted value of recovered product and byproducts is approximated by a linear weighting expression;

$$PBR = \sum_{i=1}^{6} (N_{is}\beta_i) \tag{5.3}$$

where

PBR is the total recovered product and byproducts from all processes and unit operations in season s defined in the range 0 to 1. Zero (0) means no recovery hence maximum losses and one (1) maximum recovery or minimal losses.

β_i is the weight specified by the waste management expert in the wine industry for processes i (i=1, 2....6) during season s ($s = 1(vintage), 2(nonvintage)$) satisfying the condition;

$$\beta_1 + \beta_2 + \beta_3 + \beta_4 + \beta_5 + \beta_6 = 1 \tag{5.4}$$

Processes $i(i = 1, 2, 3, 4, 5, 6)$ represents; crushing and destemming, transfer systems, filtration, pressing, fermentation, and bottling and packing processes, respectively.

N$_{is}$ is an index in the range ($0 \leq N_{is} \leq 1$) of the recovered organic material in a specific process i before wet cleaning process commences and is computed using the relation;

$$N_{is} = \frac{\sum_{i=1}^{n}\{W_{nA} \times CF_k\} + \sum_{i=1}^{m}\{W_{mB} \times CF_k\}}{Max\{\sum_{i=1}^{n}\{W_{nA} \times CF_k\} + \sum_{i=1}^{m}\{W_{mB} \times CF_k\}\}} \tag{5.5}$$

where:

W is the dimensionless score assigned to the qualitative values of each strategy;

A symbolizes specific strategies;

n is the number of specific strategies considered in process i;

B symbolizes generic strategies and ;

m is the number of generic strategies considered to improve product and byproducts recovery in all processes and unit operations under consideration;

CF$_k$ is a measure of the degree of belief the user has on a given response regarding a particular practice or strategy;

$k = 1, 2, 3$ whose values were fixed at 1.00, 0.75, and 0.50, respectively.

A schematic representation on how computations for ranking the product and byproducts recovery in a given season are shown in Figure 5.5. Some of the illustrative examples of generic and specific knowledge contained in the product and byproduct losses submodule are presented in Tables 5.5 and 5.6, respectively.

The second variable that influences product and byproducts recovery is the generic management (GM$_{PBR}$). This variable was determined by evaluating qualitatively the last four strategies in Table 5.5. GM$_{PBR}$ was evaluated and normalized using the Equation;

$$GM_{PBR} = \frac{\sum_{i=1}^{q}\{W_{qC} \times CF_k\}}{Max\{\sum_{i=1}^{q}\{W_{qC} \times CF_k\}\}} \times 100 \tag{5.6}$$

where GM$_{PBR}$ was defined in the range from 0 to 100. The value zero (0) means the worst management scenario while hundred (100) implies the best management attainable in a facility with regard to product and byproducts recovery.

In real plant practices, effective product and byproducts recovery is not only a function of PBR but GM$_{PBR}$ as well. Since both variables contain uncertainty (vagueness) and are linguistically quantified, the effective product and byproducts recovery is evaluated using fuzzy mathematical formalism given by the expression;

$$PBR_{eff} = f(PBR, GM_{PBR}) \tag{5.7}$$

where f is a fuzzy logic function. PBR_{eff} is defined in the range 0 to 1, such that zero (0) represents a scenario where no recovery of product and byproducts before wet cleaning occurs. On the other hand, one (1) signifies the best case scenerio refering to optimal recovery of product and byproducts.

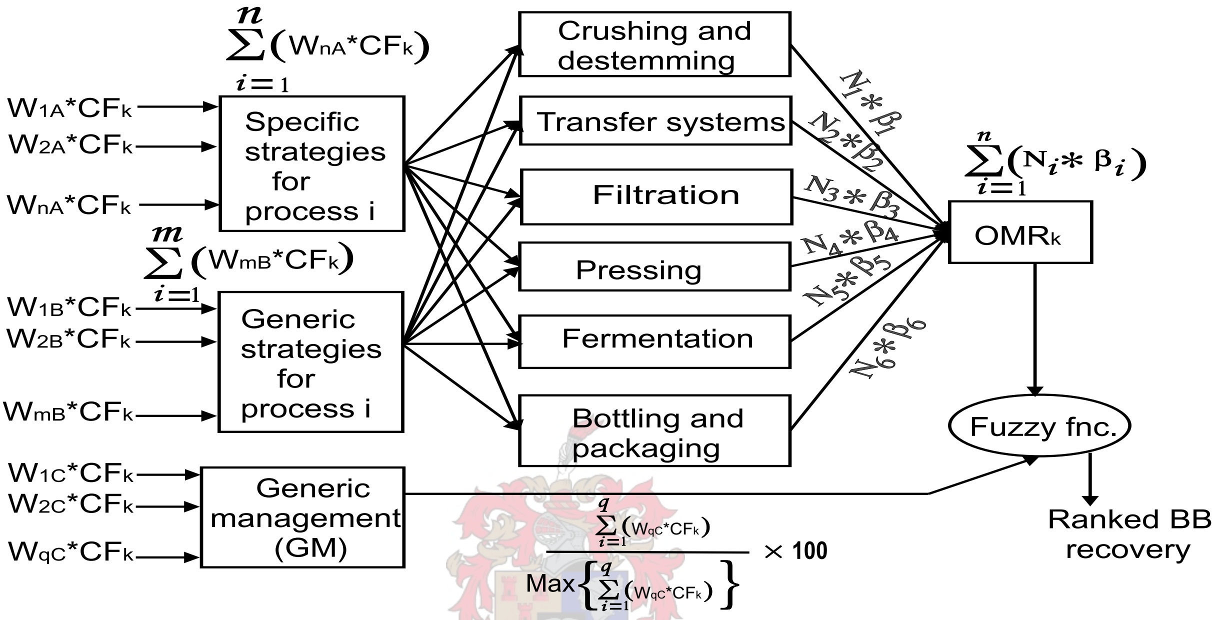

Figure 5.5: Hierarchical structure of evaluating the effective quantity of products and byproduct recovery/losses.

II: Chemical Usage

In the chemical usage submodule, the concern was to evaluate the quantity of chemicals consumed during the cleaning and sanitizing processes using fuzzy logic. This was borne from the understanding that uncertain and vague information was involved in decision making regarding quantities of chemicals used in a particular cleaning and sanitizing session. However, while this qualitative approach introduced some imprecision, bias, relatively unverifiable and inconsistent information, however, it also provided useful insights into how chemical usage can be optimized in a domain where quantitative information is scarce.

In this sense, the decision making process had to be done relying mostly on the rules of the thumb from the experts. Thus, to develop the rules and facilitate the decision making

Table 5.5: An example illustrating the rankings of generic strategies influencing the recovery and handling of product and byproducts (intrinsic wastes).

Influencing factors	**Qualitative levels of action**	**WMI**[a]	**Rank**[b]
Prevention/and or reduction of products and byproducts dispersion.	Effective Fair Low	100,451	**2**
Institutionalization of process procedures for waste dispersion elimination/ and dispersion.	High Moderate Low	100,355	**3**
Percentage of waste streams segregation.	High (65-100%) Moderate (40-65%) Low (below 40%)	75,292	**4**
Frequency of spillages, leakages, incidentals and accidents during the operations.	High (70-100%) Medium(30-70%) Low (under 30%)	50,313	**6**
Levels of progressive prioritization of education on waste management in a winery at the following personnel:			
Senior management.	High Medium Low		
Skilled workers.	High Medium Low		**1**[c]
Unskilled workers.	High Medium Low		
Levels maintenance of facilities and equipment.	Routinely done Often done irregulary/not done	75,241	**5**
Time laspe between end of a process or operation and commencement of products and byproducts recovery.	Immediately After sometime After long time	25,155	**7**

---

[a] WMI: waste minimization index discussed in section 5.3.

[b] The ranking was used to facilitate the process of assigning dimensionless scores to evaluate the extend at which product and byproducts were recovered on the basis of generic knowledge in relation to the possible impacts on effluent quantity and effluent quality.

[c] The extent in which the strategies are effectively implemented in a winery to minimize or eliminate waste depends significantly on the level of training and awareness of personnel at all levels in matters regarding waste management. For this reason, training and education factor was ranked as the most significant in this category using expertise knowledge.

process using an executable computer program, critical factors governing chemical usage in the wine industry were first identified. A total of 15 strategies (see Table 5.7) were identified that exhibited potential to optimize chemical usage.

Table 5.6: An example illustrating the rankings for specific strategies influencing the recovery and handling of product and byproducts (intrinsic wastes) under particular process or unit operation.

Influencing factors	**Qualitative levels of action**	**WMI**[a]	**Rank**[b]
1. Crushing and destemming			
Condition of grapes at the time of delivery.	Low quality		
	Moderate quality	100,334	**2**
	High quality		
Temperature of grapes at the time of delivery.	Low temp.($T \leq 20^{o}$C)		
	High temp.($20< T <30$)	50,253	**4**
	Very high temp.($T \geq 30$)		
Frequency of dedicating lines of destemming and crushing on the basis of different cultivars.	High		
	Moderate	100,355	**1**
	Low/low		
Gauge level of site communication during the unloading of grapes.	Highly effective		
	Moderately	100,355	**1**
	Poorly coordinated		
Effectiveness in terms of grapes delivery to reduce start-up and shut-up wastes.	Continous delivery		
	< 30 min. lag	50,255	**3**
	> 30 min. lag		
2. Piping and transfer systems			
Percentage approximation of pipes inclined horizontally to enhance products and byproducts flow.	Low/none		
	Medium	50,221	**3**
	High		
Estimate the overall piping line distances in your facility.	None/very short		
	Moderate to long	25,362	**4**
	Very long lines		
Extend use of pneumatic/mechanical systems for recovery of products and byproducts in piping and transfer systems.	Extensively used		
	Often used	67,212	**2**
	Routinely done		
Nature of pipe joints (nature of joints determines the possibility of using pigging techniques for recovery of products and byproducts).	Screwed connect.		
	Screwed and welded	67,282	**1**
	Welded connection.		
3. Filtration process			
Level of effectiveness of separation process of wine and constituent solids.	Very effective		

---

[a] WMI: waste minimization index discussed in section 5.3

[b] The ranking was used to facilitate the process of assigning dimensionless scores to evaluate the extend at which product and byproducts were recovered on the basis of generic knowledge in relation to the possible impacts on effluent quantity and effluent quality.

Table 5.6: Continued.....

Influencing factors	**Qualitative levels of action**	**WMI**	**Rank**
	Moderately effective Not effective	75,355	**2**
Estimated efficiency of handling fitration cakes/filtrates during and after the process.	High Moderate Released on floor	67,363	**4**
Reuse of filter cakes in the next cycle of filtration or use of virgin materials every cycle.	Often reuse Very limited reuse No reuse	67,354	**3**
Use of alternative filtration techniques such as centrifuges and optimal capture in place of diatomaceous earth.	Effectively used Often used Not used at all	100,255	**1**
4. Pressing process			
Level of efficiency for the pressing equipment in your facility.	Low efficiency Moderately Efficient High Efficiency	50,311	**1**
Levels of effectiveness in discharging solids from pressing equipment.	Effective Fairly effective Cumbersome	10,321	**2**
5. Fermentation process			
Appropriateness of filling wine to reduce spills and losses.	Correctly done Often done Unkown	100,255	**1**
To what degree of fermentation yeast recovered for reuse or resell to pharmaceutical companies.	Highly effective Moderately Poorly coordinated	67,255	**2**
Indicate the degree of tanks surface roughness used for wine fermentation.	Very rough Fairly rough Smooth	67,111	**3**
6. Bottling and packaging			
Indicate level of effectiveness in the use of labelling glue during labelling of bottles.	Effectively used Fair effectiveness None/unoften	25,155	**2**
How often are the spills and overfills during the bottling process.	Always Often None/unoften	100,255	**1**

Based on the assumption that, each strategy identified was independent, the acquired knowledge was narrowed into three variables to ensure the number of if-then rules developed for decision making in the knowledge base were manageable. This was accomplished

Table 5.7: The strategies influencing chemical consumption during cleaning and sanitizing processes.

Variable	Strategies/actions	WMI	Rank
AM[a]	Training and progressive education in chemical usage for the following level of winery personnel: personnel: • Senior management. • Skilled workers. • Unskilled workers.		**1**
	Level of chemicals effectiveness in cleaning and sanitizing equipment.	25,212	**10**
	Use of deionized water in preparing cleaning and sanitizing chemical solutions.	50,214	**9**
	Use of hot water or steam for cleaning and sanitization to reduce chemical.	75,211	**7**
	Isolation of different chemicals in store room to reduce explosions and contaminations.	50,355	**8**
	Keeping an updated inventory of new/old chemicals (first in/first out system to ensure no chemical wastage through expiry).	75,354	**4**
PM[b]	Application methods of chemicals on equipment/surfaces: • Flooding/filling of surfaces/equipment respectively. • Mechanical (use of brooms etc). • Spraying. • Use of foam.		**2**
	Immediate cleaning of equipment & surfaces after the preceeding processes and operations are completed.	50,355	**8**
	Use of fixed chemical quantities for cleaning and sanitization to reduce consumption.	75,255	**6**
	Dedication of specific lines of production to reduce cleaning (through adjustment of production schedule) cycles.	100,355	**3**
	Use of drip-pans and splash guards at chemical unlocking docks to reduce or prevent spillages.	75,354	**4**
RR[c]	Reuse of cleaning solutions till their saturated pH is below 10	10,255	**12**
	Sending used cleaning solvents for recovery to the central recovery facility.	13,547	**11**
	Use of cheaper agents for cleaning/sanitization (from recycled solutions).	75,344	**5**
	Segregation of chemical solutions to enhance their recovery.	914	**13**

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[a] Administrative management

[b] Procedural management

[c] Reuse & Recycling

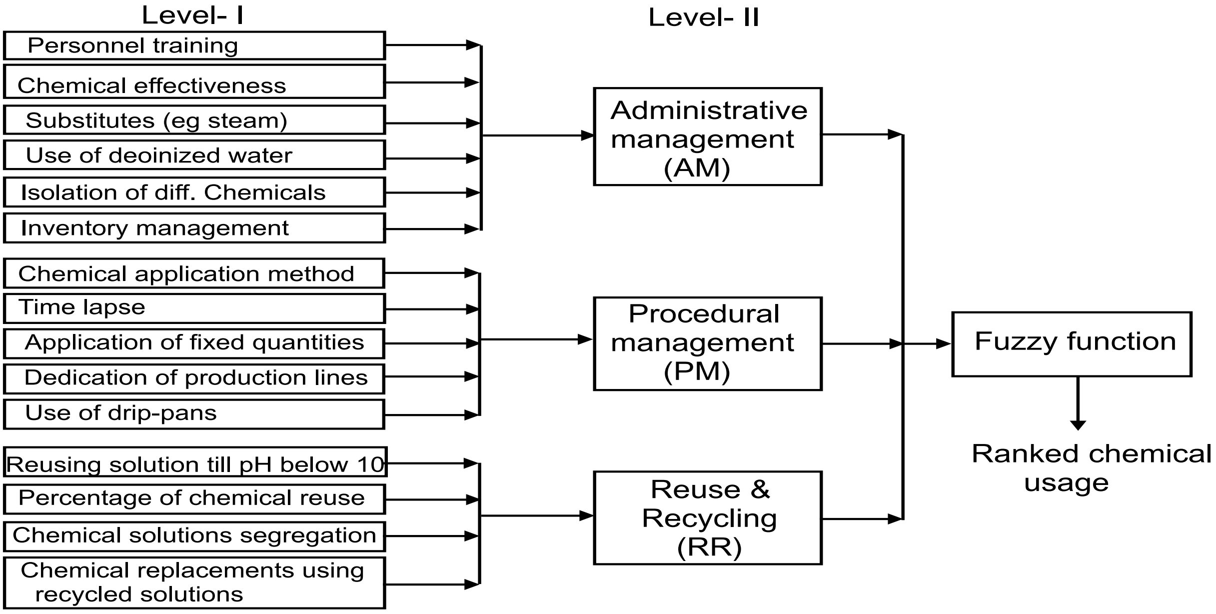


Figure 5.6: Hierarchical structure of evaluating critical factors governing chemical consumption during the cleaning and sanitizing processes.

using the hierarchical structure model shown in Figure 5.6 where the strategies were aggregated into three linguistic variables: administrative management (AM), procedural management (PM), and reuse and recycling of the chemicals (RR) at Level-II.

The AM variable focused on the strategies that refers to decisions and policies taken at the highest levels of management in the wine industry with regard to chemical usage. These included training and progressive education of personnel with regards to chemical usage, introduction of alternative materials as substitutes to minimize chemical usage among other. The effective crisp numerical value of AM variable is defined by the expression;

$$AM = \frac{\sum_{j=1}^{6}(AM_j \times CF_k)}{Max\{\sum_{j=1}^{6}(AM_j \times CF_k)\}} \times 100 \tag{5.8}$$

where;
AM is the dimensionless score for the jth strategy, j=1, 2, ...6. The AM variable was expressed in a 0 to 100 range, where zero (0) implies worst case scenario of decisions taken while hundred (100) represents the best case scenario.

The PM variable attribute was aimed in evaluating how well the strategies were implemented by the floor workforce during the cleaning and sanitization processes. At Level-I, five strategies constituted this linguistic variable. Some of the examples are different methods in applying cleaning and sanitizing chemicals on equipment and surfaces, the time lapse after the completion of a process or operation and the commencement of the cleaning process among other. The effective crisp numerical value of PM is expressed as;

$$PM = \frac{\sum_{j=1}^{5}(PM_j \times CF_k)}{Max\{\sum_{j=1}^{5}(PM_j \times CF_k)\}} \times 100 \tag{5.9}$$

where;
PM is the dimensionless score for the jth strategy, j=$1,2,3,4,5$. The PM variable was expressed in a range of 0 to 100, where zero (0) implies worst case scenario at procedural level involving workforce using chemicals while hundred (100) represents the best case scenario where the policies are implemented effectively.

Similarly, the last four strategies evaluated how effective reuse and recycling was carried out in a given winery. For the reuse and recycling (RR), the effective crisp numerical value of PM is expressed as follows;

$$RR = \frac{\sum_{j=1}^{4}(RR_j \times CF_k)}{Max\{\sum_{j=1}^{4}(RR_j \times CF_k)\}} \times 100 \tag{5.10}$$

where;
RR is the dimensionless score for the jth strategy, j=$1,2,3,4$. The RR variable was expressed in a range of 0 to 100, where zero (0) implies the worst case scenario where no recycling and reuse of chemicals is undertaken in a particular winery while hundred (100) represented the best case scenario where the most chemical used quantities were reused or recycled.

It should be noted that, each variable can only optimize chemical usage to a certain limit. Bearing this in mind, the numerous factors influencing chemical usage were integrated through hierarchical structuring and qualitative reasoning to obtain an optimal solution using fuzzy logic mathematical formalism. The system output can be mathematically defined as ;

$$C = f(AM, PM, RR) \tag{5.11}$$

where C is quantity of chemicals consumed and defined in the range 0 to 1, such that zero (0) represents the best possible minimum chemical usage while one (1) signifies the worst case scenerio of chemical usage and;

f is the fuzzy logic mathematical formalism function.

III: Effluent Quality Submodule

This submodule contained knowledge for evaluating the effluent quality depending on the vinification cleaning and sanitization processes during the vinification process. Figure 5.7 represents the hierarchical structure model of determing effluent quality involving three linguistic variables: effluent quality management (M_Q), organic matter removal (OMR_s), and cleaning equipment efficiency (EE) at Variable level-IV.

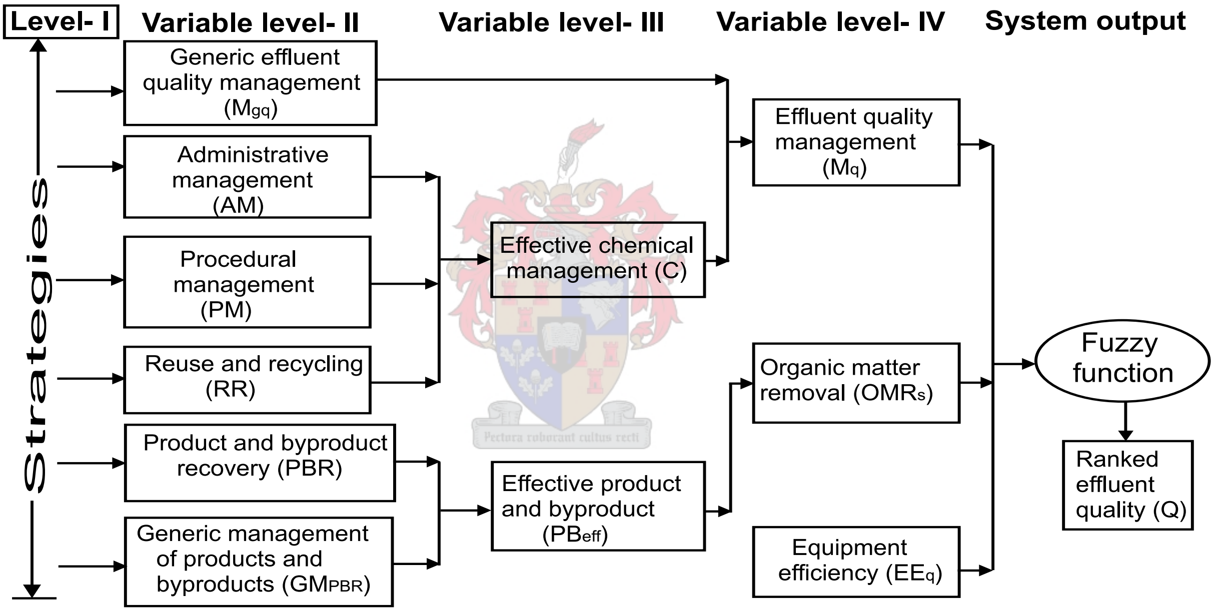


Figure 5.7: Hierarchical structure of evaluating the effluent quality during the cleaning and sanitizing processes.

As discussed in the product and byproduct losses and chemical usage submodules, strategies were the starting point of computing the input variables in Variable level-II. Examples of strategies for evaluating generic effluent quality management (M_{gq}) are presented in Table 5.8.

During the investigation of these strategies, they were found to exert influence on both effluent quantity and quality. Thus, the WMI values in Table 5.8 were computed on the basis of effluent quantity. This is because the effluent quantity to a large extent exerts a

Table 5.8: Rankings and assigned dimensionless scores to generic strategies influencing effluent quality & quantity during cleaning and sanitization processes.

				DS[a]	
Influencing strategies	**Qualitative states**	**WMI**	**Rank**	**EV[b]**	**EQ[c]**
Input substitution					
The degree of using steam and hot water for the cleaning and sanitization in your facility.	Highly used	75,343	**2**	11.00	2.75
	Moderately used			5.50	5.50
	None/un often			2.75	11.00
Indicate the quality of water for cleaning and sanitization processes.	High quality	50,244	**7**	6.00	6.00
	Moderate quality			3.00	3.00
	Low quality			1.50	1.50
Extent of using hazardous/toxic chemicals during cleaning/sanitization processes.	Not at all	25,143	**9**	4.00	4.00
	In small quantities			2.00	2.00
	In large quantities			1.00	1.00
Technological modifications					
The degree of roughness of the internal surfaces of tanks.	Very rough	73,321	**3**	2.50	2.50
	Fairly rough			5.00	5.00
	Smooth			10.00	10.00
Modification of equipment to ease cleaning processes in the facility.	Not done	25,114	**10**	0.75	0.75
	Few done			1.50	1.50
	Many undertaken			3.00	3.00
Indicate the efficiency of the chemical dosing equipment.	Inefficient	50, 111	**8**	1.25	1.25
	Moderately efficient			2.50	2.50
	Very efficient			5.00	5.00
Operating practices					
Define the degree of effluent streams segregation to optimize water and chemicals recovery.	Effectively	7,073	**12**	1.00	1.50
	Moderately			0.50	3.00
	None/ineffectively			0.25	6.00
Define the degree of scheduling improvements on the batch operations undertaken to optimize water and chemical usage.	Highly optimized	75,355	**1**	12.00	12.00
	Fairly optimized			6.00	6.00
	Not optimized			3.00	3.00
Indicate the level of emergency and clean-up preparedness in your facility in case of spills, leakages, incidentals and accidentals.	Inefficient	50,353	**6**	1.75	1.75
	Moderately efficient			3.50	3.50
	Very efficient			7.00	7.00
Indicate degree of counter current method application for cleaning equipment & surfaces in your facility.	Effectively	75,255	**4**	9.00	2.25
	Partially			4.50	4.50
	Not used			2.25	9.00
State time lapse between end of a process/ operation and the start of cleaning operations.	Immediately	50,355	**5**	8.00	8.00
	After sometime			4.00	4.00
	After a long time			2.00	2.00
Reuse and recycling of materials					
Indicate percentage of water reuse/recycling undertaken in your facility.	High (over 60%)	10,355	**11**	2.00	1.25
	Low/medium (30-60%)			1.00	2.50
	None/low (under 30%)			0.500	5.00

---

[a] DS: Dimensionless scores

[b] EV: Effluent quantity

[c] EQ: Effluent quality

considerable influence on the effluent quality. It should be noted however, that a strategy may affect effluent quality and effluent quantity positively, while another may have a positive impact on effluent quantity but negative on the effluent quality. A full rage of possible impacts on the resultant effluent is presented in Table 5.9 with regard to quality and quantity when focusing on a particular strategy.

Table 5.9: Possible impacts of extrinsic strategies on the effluent quality and quantity.

	Impact on effluent	
Strategy	**Quantity**	**Quality**
S1	+[a]	+
S2	+	-[b]
S3	-	+

---

[a] + the sign implies that the strategy impacts the parameter under scrutiny favourably.

[b] - the sign implies that the strategy impacts the parameter under scrutiny unfavourably.

The management variable was found to be a function of generic effluent quality management (M_{gq}) in Variable level-II and effective chemical management (C) in Variable level-III . To determine the crisp numerical value of M_{gq}, a similar approach to the computation of GM_{PBR} presented in Equation 5.6 was employed. As the quality of effluent is a function of the vinification season, thus, the number of strategies considered in a given season depended on the season selected by the user. The generic effluent quality management (M_{gq}) is generically defined as;

$$M_{gq} = \frac{\sum_{i=1}^{n}\{W_{ns} \times CF_k\}}{Max\{\sum_{i=1}^{ns}\{W_{ns} \times CF_k\}\}} \tag{5.12}$$

where;

M_{gq} is defined in the range 0 to 1. The value of zero (0) implies the worst management scenario while one (1) value means the best management attainable in a facility with regard to effluent quality;

W is the dimesionless score for the jth strategy, $j = 1, 2, 3, ...n$;

ns refers to the number of strategies considered in season s;

s can be s=1($vintage$) or s= 2($nonvintage$).

Effective chemical management (C) in Variable level-III was evaluated in accordance to the procedure described in chemical usage submodule. Thus, the effluent quality management variable (M_q) in Variable level-IV was evaluated employing the results obtained from Equations 5.11 and 5.12 using the algebraic relation;

$$M_q = \frac{(M_{gq} + (1 - C))}{2} \times 100 \tag{5.13}$$

where;

M_q is defined in the range 0 to 100, where zero (0) implies the poorest management of the effluent quality in a winery while hundred (100) represents excellent management of the effluent quality.

Note that as the best conservation of chemical usage is represented by value of zero (0) (see Equation 5.11), therefore optimal chemical management is inferred by subtracting the value computed in Equation 5.11 from one (1).

The effectiveness of product and byproducts handling in a given facility was found to significantly influence the effluent quality. For instance, under the circumstances that the product and byproducts were poorly or not removed from equipment and surfaces, the resultant effluent was found to be of very low quality. This is because water in such cases was used as a brush and the presence of organic matter in the wastewater stream degraded the effluent quality significantly. On the other hand, if the handling of product and byproducts was carried out satisfactorily, then effluent quality was found to be of high quality.

In this study, what is regarded as organic matter removal (OMR_S) in winery operations[6] that can be useful has been referred here as product and byproduct handling, and discussed in product and byproducts losses submodule. Thus, taking OMR_S in Variable level-IV to be equivalent to PBR_{eff} in Variable level-III, then the crisp input numerical value for this variable was computed by multiplying Equation 5.7 by 10 to get the values of OMR_S in the range of 0 to 10. The expression for evaluating OMR_S is;

$$OMR_S = PBR_{eff} \times 10 \tag{5.14}$$

where S denotes the vintage season.

---

[6] The term product and byproducts was used to broaden the scope of recovering materials from the vinification process. This is because, their presence in the wastewater stream will not only be a yield loss but causes the effluent quality to deteriorate significantly.

The equipment types used for cleaning and sanitizing the winery equipment and surfaces were also found to have a considerable influence on the resultant effluent quality. In this study, the variable of interest was the cleaning equipment efficiency. The efficiency was used as a measure of the quantity of water delivered from the equipment per unit of time. While the cleaning apparatus which has a high efficiency had the benefit of reducing the effluent quantity of effluent generated per unit time considerably, nevertheless if the organic matter were present on the surfaces being cleaned, then the high efficiency of the equipment had a negative impact on the resultant effluent quality. Thus, if the cleaning equipment efficiency was high, the effluent quality was most likely to be poor. This is because of the high concentration of organic matter and chemicals in the final low effluent quantity (volume). On the other hand, if the equipment efficiency was found to be low, the likelihood was that the effluent quality was also high due to the dilution effect. These heuristics were useful in modeling the equipment efficiency values in relation to effluent quantity and effluent quality.

The numerical crisp input of the cleaning efficiency (EE_q) variable in Variable level-IV was estimated using the heuristics aforementioned above and the fact that optimal efficiency of cleaning equipment falls in the region 60-70%. Thus, EE_q was calculated using the expression;

$$EE_q = K_q CF_R \tag{5.15}$$

where;

K_q is a constant and a function of the cleaning equipment used with regard to its influence on the effluent quality (see a full summary of the K_q values are presented in Table 5.10); CF_R gives the degree of belief the user has on the cleaning equipment efficiency used; $R = 1, 2, 3, 4, 5, 6$ with values fixed at $1.0, 0.9, 0.8, 0.7, 0.6$, and 0.5, respectively.

In view of the afore mentioned variables, the focus was to examine how the effluent quality varies under an integrated scenario where the effect of the three linguistic variables were considered simultaneously. The resultant outcome of the effluent quality was thus computed using the expression;

$$Q = f(M_q, OMR_s, EE_q) \tag{5.16}$$

Table 5.10: K values for modeling the cleaning equipment efficiency effect on final effluent quality and quantity.

Cleaning equipment	**Operating conditions**	$\mathbf{K}_q$ [a]	$\mathbf{K}_v$ [b]
Open pipe (with no nozzle)	High pressure	80	20
	Moderate pressure	70	30
	Low pressure	60	40
Open pipe with nozzle	All pressures	55	50
Pipe with auto shutoff throttle	”	50	60
High pressure cleaners	”	40	80

---

[a] The constant used to compute the efficiency of the cleaning equipment when considering the effluent quality.

[b] A constant used to compute the efficiency of the cleaning equipment when considering the effluent volume.

where;

Q is defined in the range 0 to 1, such that 0 represents the worst effluent quality while 1 signifies the best case scenario of effluent quality where all the influencing factors are well implemented in a given winery.

IV: Effluent Quantity (Volume) Submodule

Figure 5.8 illustrates an hierarchical model structure for evaluating effluent quantity depending on cleaning and sanitizing processes in a winery. The aggregated effluent quantity is a function of three linguistic input variables at Variable level-IV namely the organic matter removal (OMR$_s$), equipment efficiency (EE$_v$), and effluent quantity (volume) management (M$_v$). As discussed in the effluent quality submodule, the strategies influencing effluent quantity management are presented in Table 5.8.

The effluent quantity management variable (M$_v$) was found to be a function of generic effluent quantity management (M$_{gv}$) and the generic management of product and byproducts (GM$_{PBR}$) variable at Variable level-II as depicted in Figure 5.8. Thus, the crisp numerical value for the generic effluent quantity management, (M$_{gv}$) is defined as ;

$$M_{gv} = \frac{\sum_{i=1}^{n}\{W'_{ns} \times CF_k\}}{Max\{\sum_{i=1}^{ns}\{W'_{ns} \times CF_k\}\}} \tag{5.17}$$

where;

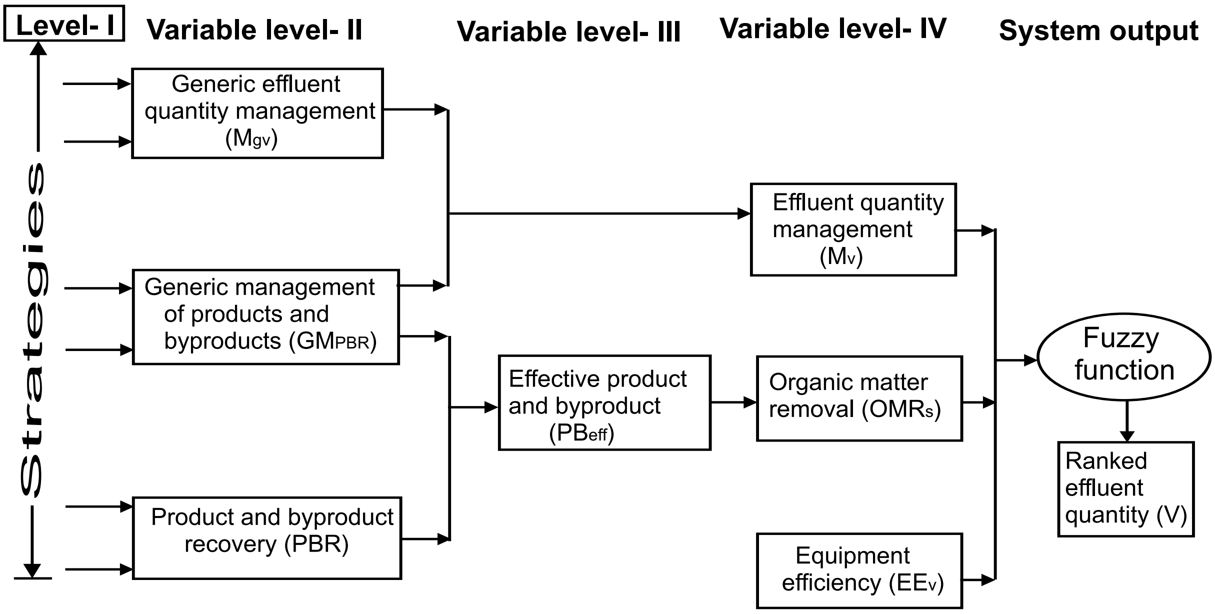


Figure 5.8: Hierarchical model structure of evaluating the effluent quantity during the cleaning and sanitizing processes.

M_{gv} is defined in the range 0 to 1. The value zero (0) implies the worst management scenario while one (1) signifies the best effluent volume management attainable in a given facility;

W' is a dimensionless score for the ith strategy, $i = 1, 2, 3, ...n$.

The generic management of product and byproducts (GM_{PBR}) is computed in accordance with Equation 5.6. For the effective effluent quantity management linguistic variable, M_v is defined by the relation;

$$M_v = \frac{(M_{gv} + GM_{PBR})}{2} \times 100 \tag{5.18}$$

where;

M_v is defined in the range 0 to 100, where zero (0) implies the poorest effluent quantity management in a winery while hundred (100) signifies an excellent effluent quantity management.

While discussing the evaluation of effluent quality, the equipment efficiency variable was discussed in great length. Thus, in this section we will only mention the salient features that relate to effluent quantity. It was noted that an increase in cleaning equipment efficiency reduced the resultant quantities of wastewater generated from the cleaning processes. The equipment efficiency linguistic variable EE_v with respect to effluent quantity was modeled by the relation;

$$EE_v = K_v CF_R \tag{5.19}$$

where;
K_v is a constant and a function of the cleaning equipment used with regard to its influence on the effluent quantity and a full summary of these values are presented in Table 5.10; EE_v is in range of 0 to 100, where zero (0) signifies the cleaning equipment having the lowest efficiency while hundred (100) represents the an equipment with high efficiency.

Note that if the equipment efficiency was low, large quantities of potable water were used while on the other hand, if the efficiency is high, minimal potable water was used.

The organic matter removal (OMR_s) variable was evaluated using the procedure described in effluent quality submodule using Equation 5.14. In view of the afore discussed variables, the focus was to examine how the effluent quantity varies under an integrated scenario where the effect of the three linguistic variables in Variable level-IV were considered simultaneously. The resultant outcome of the effluent quantity (V) was thus computed using the results obtained from Equations 5.14, 5.18, and 5.19 using the relation;

$$V = f(M_v, OMR_s, EE_v) \tag{5.20}$$

where;
V is defined in the range 0 to 1 such that, zero (0) represents the best case scenario signifying prudent management of potable water through an integrated management of the influencing factors, while one (1) denotes the worst case scenario representing large effluent quantities of water generated during the cleaning and sanitizing processes.

5.5.4 Inference Engine Module

The second phase of the inference mechanism development entailed the construction of the fuzzy inference. The inference engine is the core of the fuzzy logic expert system decision-making algorithm. This is because it controls the reasoning path of the system, flow of data in the modules, and finally integrates and aggregates results from various modules to derive the final decisions and conclusions for a particular targeted system output(s). Therefore, in the context of this study, inference facilitated the linking of antecedent (input data) to the consequent (possible scenario output) depending on: input and output variables, membership functions, the rule-base, and type of inference algorithm (Mamdani type was employed in this study) used.

Whereas the inference engine search mechanism is a software system inbuilt attribute, the focus in this subsection is to discuss the components that are in all knowledge bases to enhance decision-making processes. The four basic submodules in this module (Figure 5.9) are: membership functions, fuzzification, inference, and defuzzification.

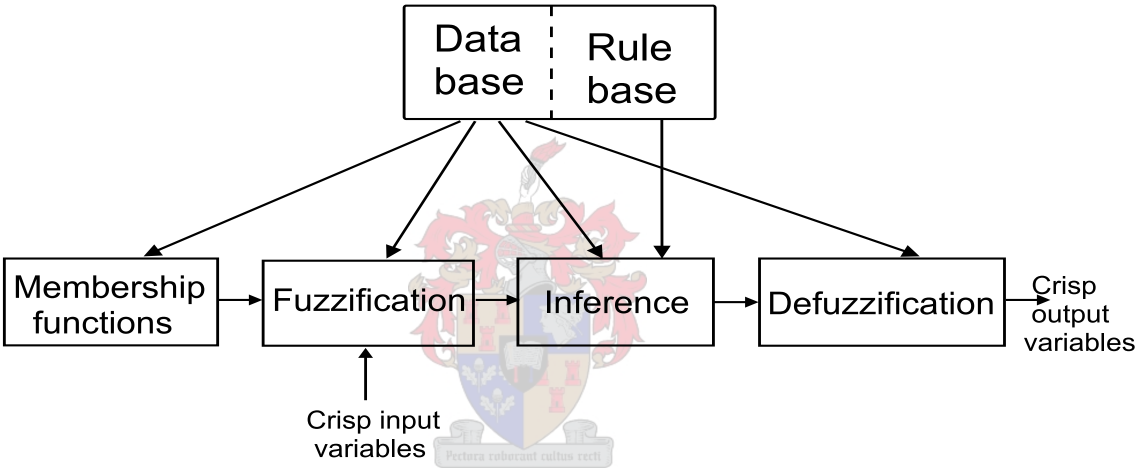


Figure 5.9: Configuration of fuzzy inference module.

Membership Functions

The design of membership functions is a significant step for the development of a fuzzy system. Sugeno and Yusukawa (1993) showed the critical role of MFs in formulating a qualitative fuzzy model through the definition of linguistic terms. This has the merit of taking any crisp input values and transforming them into degrees of membership in the interval [0,1]. Membership functions were designed such that they related directly to the individual rules encoded into the knowledge base.

To model the physical behavior of the vinification process system, MFs and if-then rules were employed to represent the manner in which, input variable(s) had a corresponding control on the output variable. Expertise understanding of how the system works was used to achieve this objective. Out of the several MFs described in the literature (viz: triangle-shaped, trapezoid-shaped, bell-shaped, exponential-shaped, etc.), triangular and trapezoidal MFs (as seen in Figure 5.10) were considered in this study. The assumption being, the fuzzy input and output numbers are triangular and trapezoidal forms and these forms approximate human thinking processes. A mathematical relationship between the input element x and its MF for a triangular fuzzy distribution is defined by the limits T_1, T_2, and T_3 as expressed by the Equation 5.21.

$$\mu(x_i) = \left\{ \begin{array}{rcl} \frac{x_i - T_1}{T_2 - T_1} & : & T_1 \leq x_i \leq T_2 \\ & : & \\ \frac{T_3 - x_i}{T_3 - T_2} & : & T_2 \leq x_i \leq T_3 \\ & : & \\ 0 & : & otherwise \end{array} \right. \tag{5.21}$$

Similarly, the relationship for trapezoidal fuzzy distribution defined by the limits T_1, T_2, T_3, and T_4 is expressed by the Equation 5.22.

$$\mu(x_i) = \left\{ \begin{array}{rcl} \frac{x_i - T_1}{T_2 - T_1} & : & T_1 \leq x_i \leq T_2 \\ & : & \\ 1 & : & T_2 \leq x_i \leq T_3 \\ & : & \\ \frac{T_4 - x_i}{T_4 - T_3} & : & T_3 \leq x_i \leq T_4 \\ & : & \\ 0 & : & otherwise \end{array} \right. \tag{5.22}$$

Various approaches using either expertise, data or both are used in constructing MF mappings. In the present work, heuristic knowledge and knowhow were introduced into the fuzzy set systems by a trial and error based approach to determine the MF ranges for a certain linguistic variable. This approach proved well suited to human inputs. Significantly, the approach optimized the fuzzy expert system functionality through a

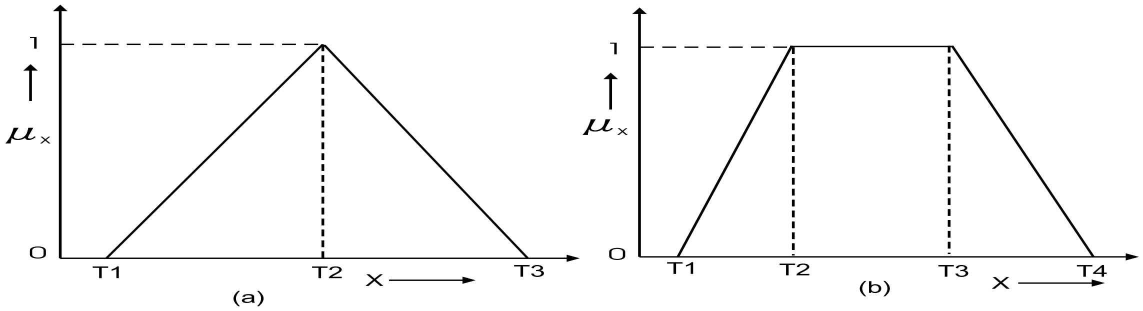


Figure 5.10: Triangular (a) and (b) Trapezoidal fuzzy membership distribution functions.

tuning process in an attempt to approximate non-linear mappings between the input variables and the output variables. Nevertheless, the approach had the disadvantage of being time consuming and laborious due to the numerous parameters affecting the results of the system. Other tuning methods used to improve the system performance were editing of the rule base, the number of MFs used per input variable, connectives in a rule, rule weights and introduction or reduction of new variables.

A summary of MFs for evaluation of product and byproducts losses system output are presented in Table 5.11. They constitute the linguistic fuzzy input variables and the output fuzzy variable as well as their ranges (break points). The MFs used in expressing linguistic input and output variables are illustrated schematically in Figure 5.11. Here, the degree of membership, μ, associated with the defined linguistic term is plotted against the linguistic variable universe of discourse.

It is therefore anticipated that the system tuning process can be tremendously improved in MFs design and development in the future using artificial neural networks and genetic algorithm. This optimism is premised on the new trends of increasing installations of actuators and data logging systems in the wine industry. As a result, the quantitative data will be more accessible and making it possible to employ integrated qualitative-quantitative based approaches in addressing waste minimization challenge in the wine industry.

The second merit of an automatic generation method is that, the MFs will be updated continously as the system responds to the dynamic changes of the production system. In this sense then, the system will adapt dynamically into new circumstances via membership functions tuning. Other payoffs include the increasing accuracy of the constructed fuzzy model and of course the alleviation of knowledge acquisition problem.

Fuzzification of Variables

The fuzzification module transforms a normalized point-wise (crisp) value of a state variable into a linguistic fuzzy set in order to make it compatible with the fuzzy set representation of the state variable in the rule-antecedent of the fuzzy rule in the inference phase. The fuzzy results are inferred from the memberships of fuzzy sets of input variables

Table 5.11: Fuzzy sets, membership functions, and their break points for input and output linguistic variables in the evaluation of effective product and byproducts recovery.

Input variables	**MFs[a], LVs[b], BPs[c]**	**Output variable**	**MFs,LVs,BPs**
Effective Product & byproduct (PB_{eff})	Very low ($T_{11}=T_{12}=0$, $T_{13}=0.3$, $T_{14}=0.45$) Low ($T_{21}=0.35$, $T_{22}=0.475$, $T_{23}=0.60$) Moderate ($T_{31}=0.45$, $T_{32}=0.55$, $T_{33}=0.65$) High ($T_{41}=0.55$, $T_{42}=0.65$, $T_{43}=0.75$) Very high ($T_{51}=0.7$, $T_{52}=0.8$, $T_{53}=T_{54}=1$)	Effective OMR[d]	Very low ($T_{11}=T_{12}=0$, $T_{13}=0.1$, $T_{14}=0.25$) Low ($T_{21}=0.1$, $T_{22}=0.3$, $T_{23}=0.5$) Moderate ($T_{31}=0.35$, $T_{32}=0.55$, $T_{33}=0.75$) High ($T_{41}=0.6$, $T_{42}=0.75$, $T_{43}=0.9$) Very high ($T_{51}=0.8$, $T_{52}=0.9$, $T_{53}=T_{54}=1$)
Generic management of PB_{eff}	Poor ($T_{11}=T_{12}=0$, $T_{13}=15$, $T_{14}=30$) Fair ($T_{21}=20$, $T_{22}=40$, $T_{23}=60$) Good ($T_{31}=45$, $T_{32}=62.5$, $T_{33}=80$) ($T_{41}=70$, $T_{42}=85$, $T_{43}=T_{44}=100$)		

---

[a] Membership functions.

[b] Linguistic variables.

[c] Break points.

[d] OMR: organic matter removal.

in the inference module with the aid of data and rule bases. An example of a linguistic value, LV, is represented by a fuzzy set using the membership function $\mu_{LV}(x)$.

The fuzzification process always produces a crisp value(s) in the interval 0 to 1 as they use the membership functions to quantify a given crisp numerical input. Take for example an input of *x=57* for the effluent management linguistic variable. The fuzzified values are calculated by intersecting the crisp input value to the fuzzy set associated with each linguistic label. In this case, two membership functions are computed owing to the overlapping of the fuzzy sets with values: $\mu_1 = 0.686$ in the fuzzy set labeled *Good* and $\mu_2 = 0.15$ in the set labelled *Fair* (see Figure 5.12) evaluated using triangular membership fuzzy function defined in Equation 5.21. Thus, the crisp input value *x=57* can be interpreted now as linguistic terms *Good* and *Fair* with the computed grade of membership.

Unlike in the membership function module which is crucial for tuning the system to

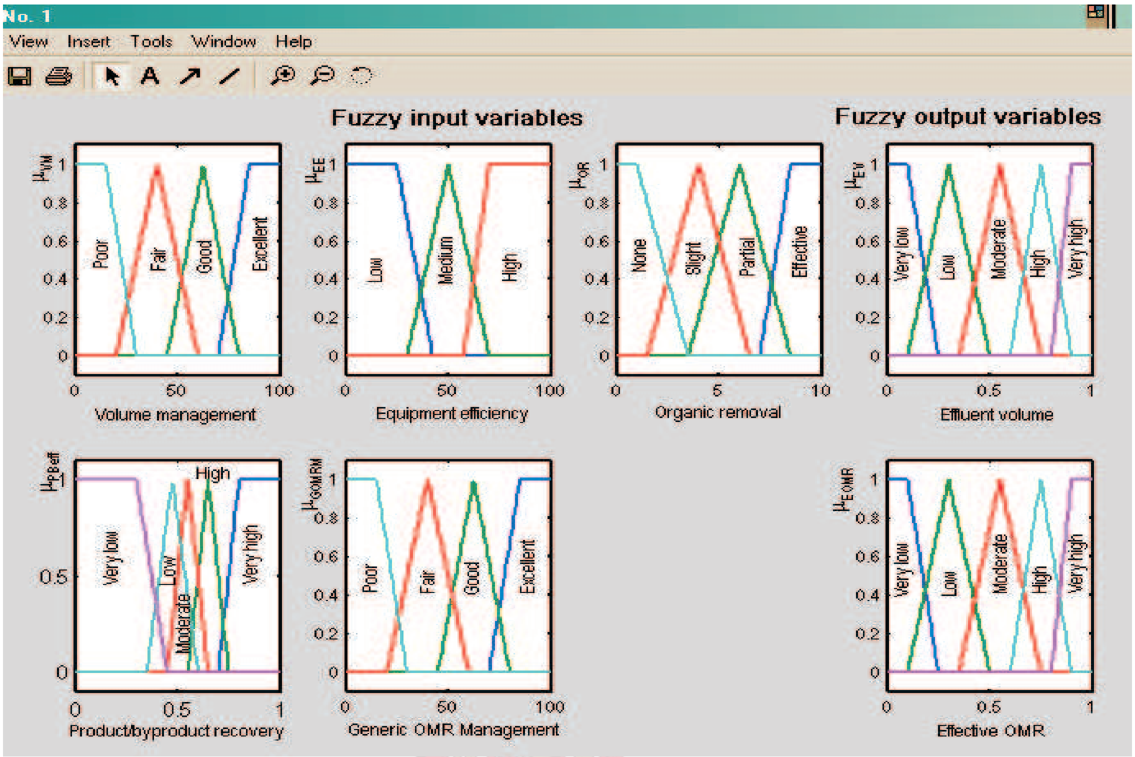


Figure 5.11: Membership functions defining the fuzzy linguistic input and output variables.

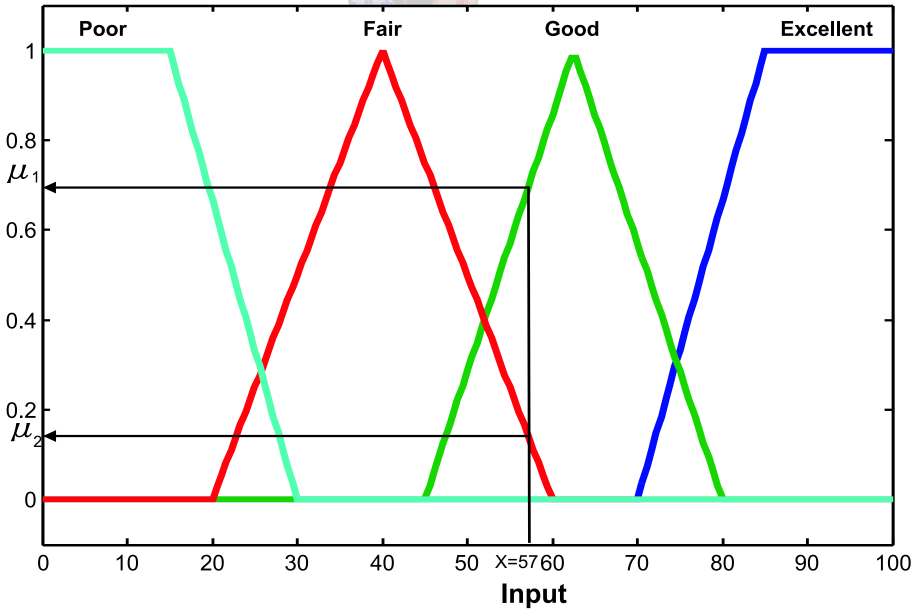


Figure 5.12: Graphical representation of linguistic values and fuzzification of crisp input.

improve its functionality, the fuzzification procedure itself is an inherent property of the software used and therefore, does not offer flexibility or degrees of freedom during the design of fuzzy models by the knowledge engineers.

Inference Submodule

Fuzzy inference submodule is the core decision-making algorithm where fuzzy results are inferred from the memberships of fuzzy sets with the aid of a knowledge base. The knowledge base contains a data base and a rule base. The data base has the information regarding the functioning of the normalization, fuzzification, rule base (if-then rules), and defuzzification phases. Its information includes: fuzzy membership functions, type of fuzzy relations, type of interaction and union operators, type of rule firing, and the number of hierarchical levels of reasoning.

The hierarchical reasoning structure of each knowledge submodule can be generically summarized in the following way (see Figures 5.5 to 5.8):

- **Step 1:** Linguistic strategies/actions were transformed through a ranking and screening process into dimensionless scores at the first hierarchical level of each knowledge submodule.

- **Step 2:** The qualitative/linguistic strategies/actions were broadly grouped into two or three fuzzy linguistic input variables for evaluating the targeted system output at different hierarchical levels of a given knowledge submodule.

- **Step 3:** The inference in computing crisp numerical input variable values was performed by solving a series of algebraic summation equations in a specific knowledge submodule (see details in section 5.5.3).

- **Step 4:** Reasoning results from step 3 were combined in accordance to the graphical illustrations in Figures 5.5 to 5.8.

- **Step 5:** Applying the fuzzy inference and using the results obtained in step 4 for each case under consideration, the targeted system output was finally aggregated and ranked reflecting the influence of user inputs on the output. The crisp system output was a measure of the winery's performance with respect to the targeted output such as chemical usage, effluent quality, etc.

The most significant merit of using a hierarchical model structure is that the number of rules increased linearly in the cases where several fuzzy inferences were required before the final system output is aggregated (e.g effluent quality). This is in total contrast to the exponential growth of rules in the knowledge base witnessed in conventional systems.

The size of data base for each knowledge submodule discussed in section 5.5.3 depends on two factors. First, the number of input fuzzy sets (MFs) used for the evaluation of a targeted output variable and secondly the number of qualitative domains (strategies) required in generating the normalized crisp inputs in a given submodule.

The MAX-MIN gravity reasoning algorithm was used in the fuzzy inferencing process (see discussions in section 3.2.3). To illustrate the fuzzy inferencing mechanism at step 5, discussions are centered on the product and byproducts losses knowledge submodule. First, lets assume that the results obtained from operations in step 1 to step 4 described above are: 0.48 for the recovery of product and byproducts (PBR) and 55% for generic management (see Figure 5.13). Therefore, using fuzzification submodule for the variable PBR, 0.48 produces 0.9600 degree of membership in the set *Low* and 0.3000 degree of membership in the set *Moderate*. Similarly, for the variable generic management, 55% produces degrees of membership: 0.2500 and 0.5714 in the fuzzy sets *Fair* and *Good* correspondingly.

To infer the final system output, each rule activated by the variable inputs is first individually evaluated. The evaluation of the rules proceeds as follows:

Rule 10: IF *PBR* is *Moderate* AND *Generic management* is *Good*
THEN *Effective PBR* is *Moderate*
EVALUATION: Min(0.3000, 0.5714)= 0.3000
Rule 11: IF *PBR* is *Moderate* AND *Generic management* is *Fair*
THEN *Effective PBR* is *Low*
EVALUATION: Min(0.3000, 0.2500)= 0.2500
Rule 14: IF *PBR* is *Low* AND *Generic management* is *Good*

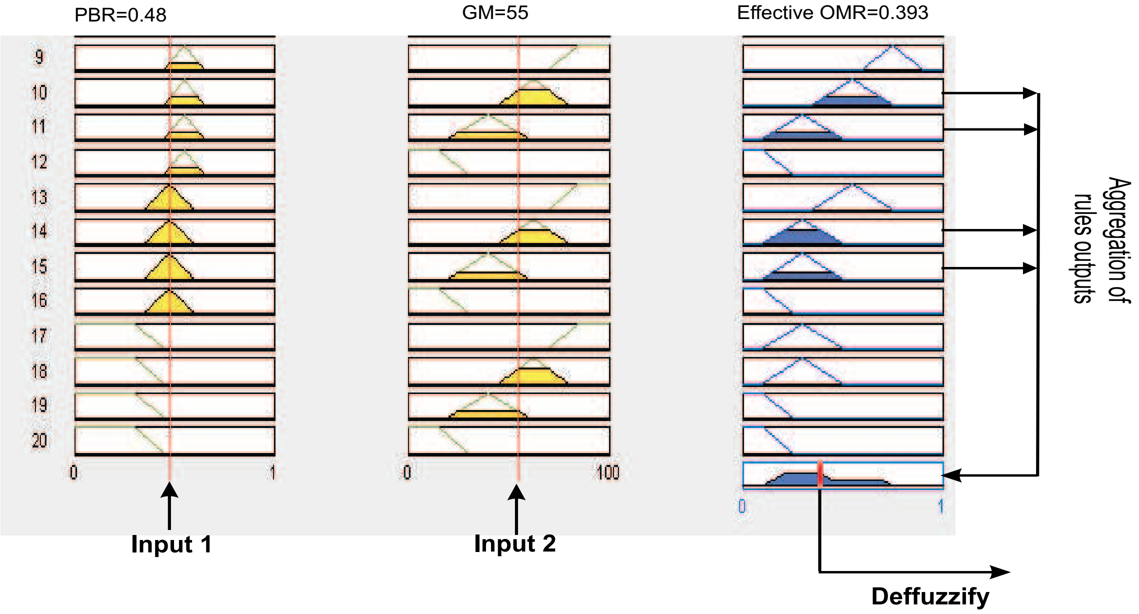


Figure 5.13: Fuzzy inferencing using Mamdani-Assilian model for the evaluation of product and byproduct losses.

THEN *Effective PBR* is *Low*

EVALUATION: Min(0.9600, 0.5714)= 0.5714

Rule 15: IF *PMR* is *Low* AND *Generic management* is *Fair*

THEN *Effective PBR* is *Low*

EVALUATION: Min(0.9600, 0.2500)= 0.2500

From the results of each rule, the output membership functions are used to clip the moderate and low membership functions of the output variable yielding the final figure seen in Figure 5.13. The clipped membership functions resulting from the application of four rules are then aggregated together to produce one fuzzy set using the disjuction (max) operator.

Defuzzification Submodule

Results derived from the inference submodule are a collection of fuzzy sets or a single aggregate fuzzy set represented again as a linguistic term and a membership value. Such an outcome has no significant meaning to the user, making it necessary to decompose and convert the fuzzy output variable into a crisp value that reflects an estimation of the system output.

The process of computing a single number that best represents the outcome of the fuzzy set evaluation is called defuzzification. Defuzzification of fuzzy inferences is performed in the fuzzification submodule. The defuzzification operator defines the defuzzification method used. In the fuzzy expert system reported in this dissertation, the centre of gravity (COG) method was used, and is mathematically expressed in accordance to Equation 3.19.

Considering the crisp input values (0.48, 55%) discussed in the inference submodule, the decision-making algorithm used these values to infer the linguistic output values, plotted on the right-hand of Figure 5.13 (see the blue color shaded regions). The four fired rules have the output plots representing the linguistic terms of the output variable (*Moderate, Low, Low, Low* respectively). Figure 5.14 illustrates the aggregation of four linguistic outputs, represented as shaded area under curve signifying the overall fuzzy conclusion. The area encompasses a range of fuzzy output values and must be defuzzified to resolve a single numerical value output, which is communicated and understood by the user. Defuzzification operation assigned the output numerical value in [0, 1] interval. Thus, for the example presented here, the crisp output was computed to be 0.393 and ranked as *Low*.

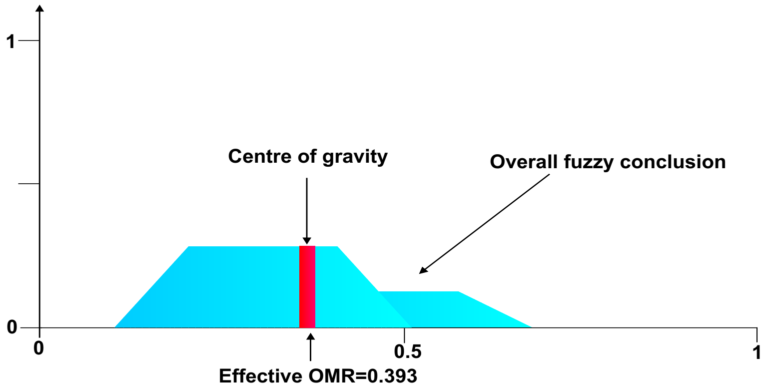


Figure 5.14: Graphical illustration of defuzzification of the overall fuzzy conclusion in a fuzzy model to estimate the degree of effective handling of product and byproducts. The COG method divides the area under the curve into two equal subareas and thus determines μ_{PBeff}.

5.6 Development of Fuzzy Logic Expert System Architecture

In this section the development of prototype software architecture for the simulation of waste minimization in the wine industry is discussed. Two principal factors were considered in designing the architecture of the fuzzy logic expert system. The first and most significant was on how to handle the large amount of diverse, qualitative and incomplete knowledge critical for minimizing waste generation in the wine industry. The second issue of concern was the need for system flexibility. System flexibility here refers to the ability to accommodate future expansions and incorporate additional features, new tasks, new knowledge and information as it becomes available without restructuring the entire system. The former challenge was addressed by using a hybrid of expert systems and fuzzy logic while the latter was achieved by designing the system using a modular approach.

In remaining consistent with these objectives, the system was structured into various components. The focus was to define the functionalities of each system component and show how they interacted with one another. The system structure comprised of four components, the knowledge base (rule base and database), graphical user interface (GUI), fuzzy inference engine, and knowledge acquisition and maintenance. Figure 5.15 illustrates the structure and information flow in the fuzzy logic expert system from a top-level, modular approach. Each of these system components are discussed in the following sections.

5.6.1 Graphical User Interface

Fuzzy logic expert system's GUI provides for seamless interactions of various components between the user and the knowledge and information contained in fuzzy logic expert system. The user interface provides a friendly environment for data entry, module evaluation, overall system evaluation and the presentation of the system results. During the system operation, the user is presented with snapshots of the form depicted in Figure 5.16. Each window was for a specific data entry to activate the system and evaluate a given system output. It also displays the choices the user can consisder.

Modules containing the knowledge were designed such that they can be evaluated in-

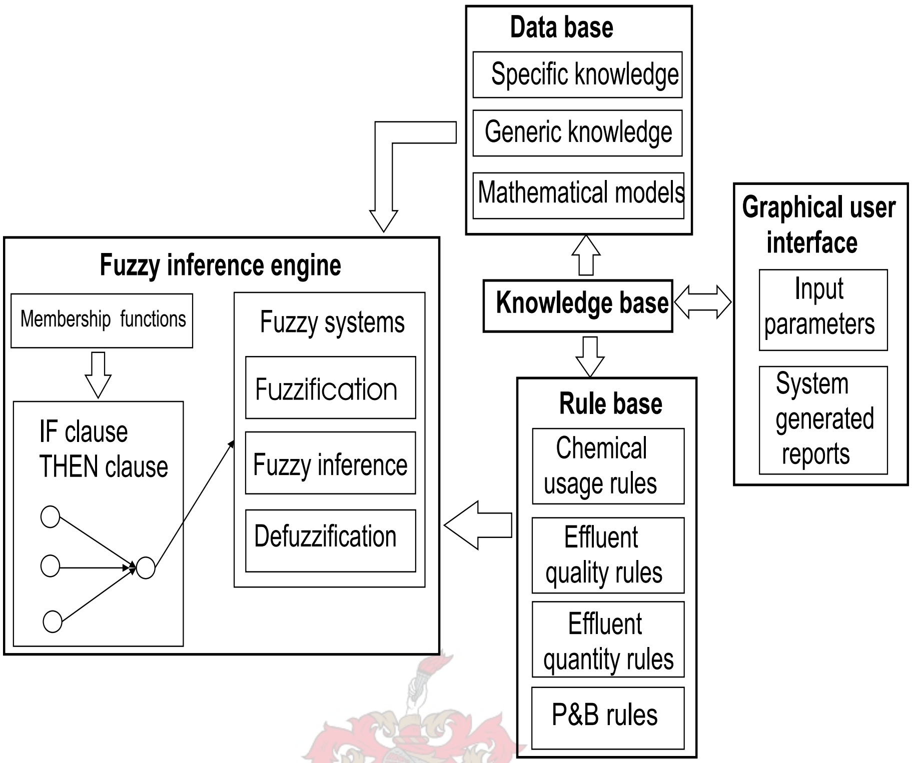
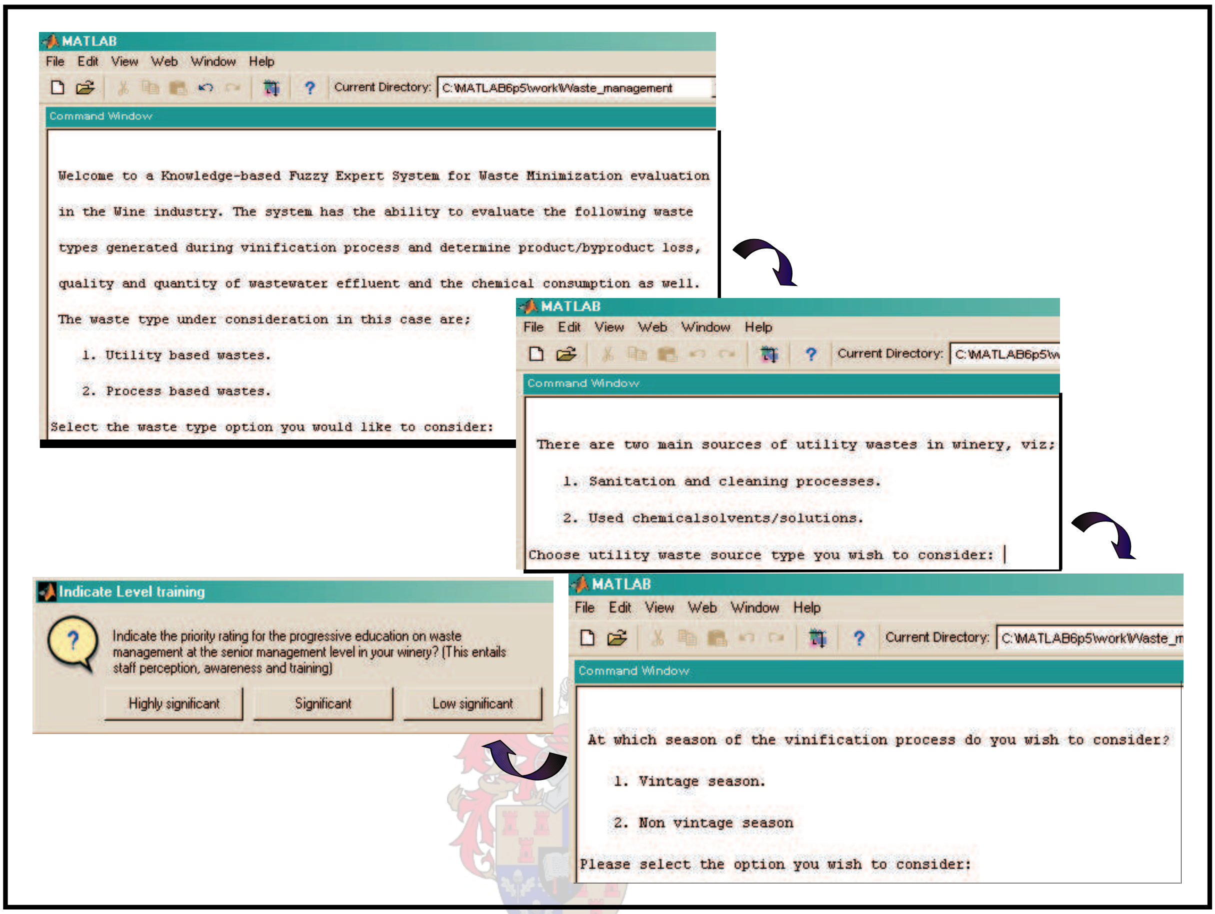


Figure 5.15: Fuzzy logic expert system functional architecture for evaluating waste minimization in the wine industry.

dependently (single system output) or simultaneously to give the overall system outputs for all four of the functional classes: effluent quality, effluent quantity, chemical usage, and effectiveness of handling intrinsic based wastes. An example of the GUI showing overall system generated results after analyzing the user inputs regarding chemical usage is schematically presented in Figure 5.17. GUI was also used to facilitate the integration of data sharing among various knowledge modules.

After getting the system overall conclusions as shown by the sample in Figure 5.17, the user is able to investigate why and how this conclusion was reached. In the current application the user is given the option to trace back the reasoning path. This is provided through the "Show FIS" button activated GUI showing the inputs for diagnosing chemical usage as depicted in Figure 5.18(a). To view the range of the membership function for the inputs and outputs, the "Edit Membership functions" button will activate the membership function of one of the input or out variable defined in Figure 5.18(a) as



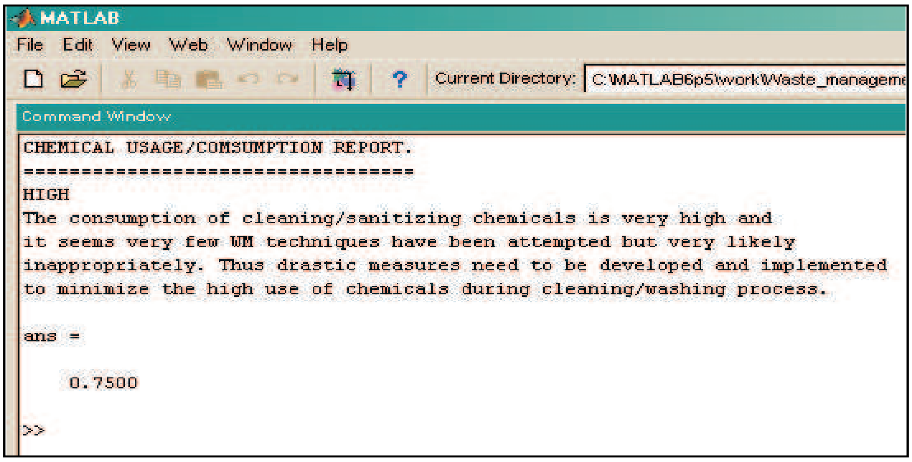
```
Welcome to a Knowledge-based Fuzzy Expert System for Waste Minimization evaluation

in the Wine industry. The system has the ability to evaluate the following waste

types generated during vinification process and determine product/byproduct loss,

quality and quantity of wastewater effluent and the chemical consumption as well.

The waste type under consideration in this case are;

   1. Utility based wastes.

   2. Process based wastes.

Select the waste type option you would like to consider:
```

```
 There are two main sources of utility wastes in winery, viz;

   1. Sanitation and cleaning processes.

   2. Used chemicalsolvents/solutions.

Choose utility waste source type you wish to consider: |
```

Indicate the priority rating for the progressive education on waste management at the senior management level in your winery? (This entails staff perception, awareness and training)

```
 At which season of the vinification process do you wish to consider?

   1. Vintage season.

   2. Non vintage season

Please select the option you wish to consider:
```

Figure 5.16: Graphical user interface for inputting process-specific information and data.

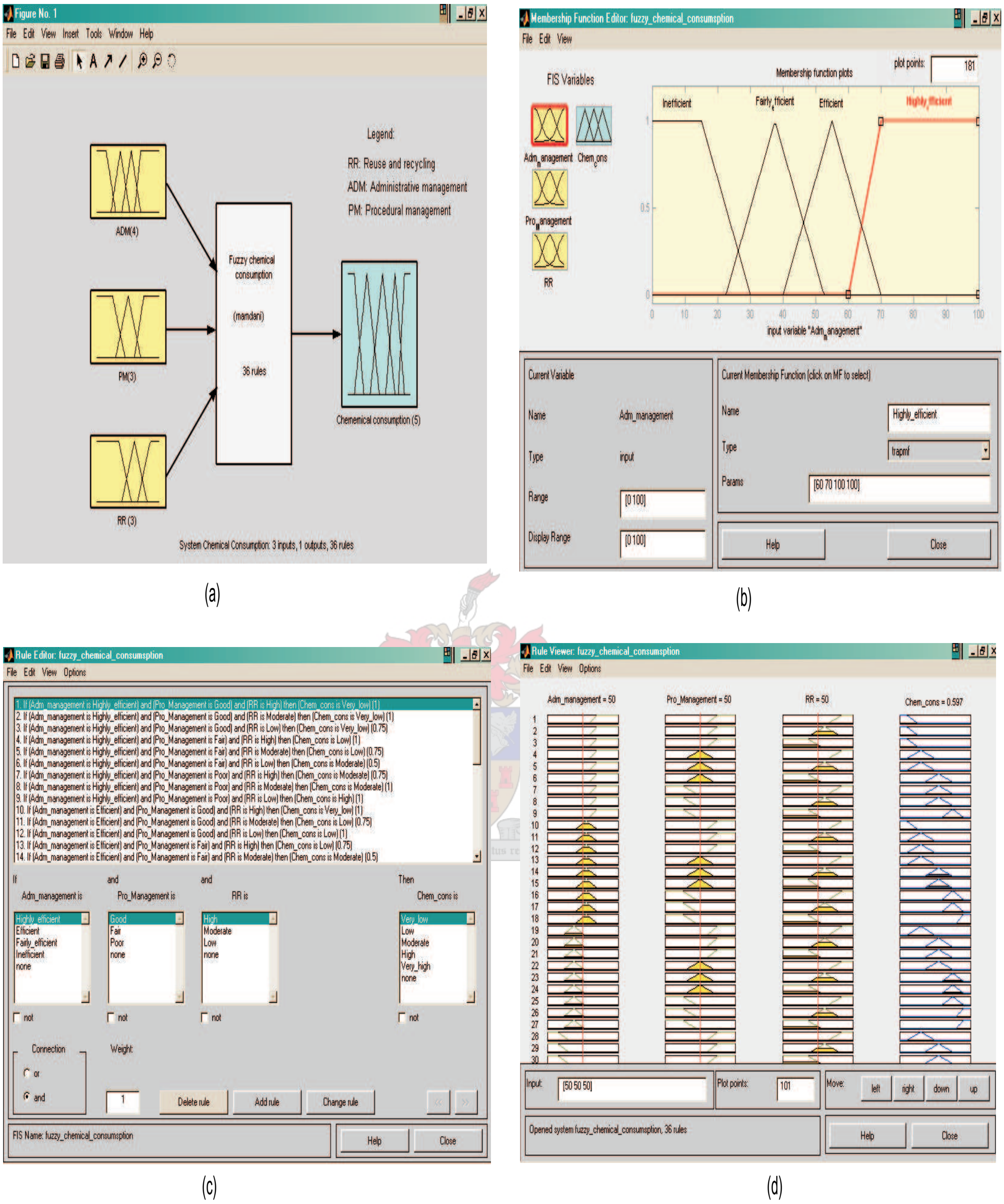


```
CHEMICAL USAGE/COMSUMPTION REPORT.
==================================
HIGH
The consumption of cleaning/sanitizing chemicals is very high and
it seems very few WM techniques have been attempted but very likely
inappropriately. Thus drastic measures need to be developed and implemented
to minimize the high use of chemicals during cleaning/washing process.

ans =

    0.7500

>>
```

Figure 5.17: System generated summary feedback response regarding chemical usage.

shown in Figure 5.18(b).

The rules were coded into the rule base using a "natural language" and Figure 5.18(c)



Legend:
RR: Reuse and recycling
ADM: Administrative management
PM: Procedural management

System Chemical Consumption: 3 inputs, 1 outputs, 36 rules

(a)

plot points: 181

Current Variable
Name: Adm_management
Type: input
Range: [0 100]
Display Range: [0 100]

Current Membership Function (click on MF to select)
Name: Highly_efficient
Type: trapmf
Params: [60 70 100 100]

(b)

1. If (Adm_management is Highly_efficient) and (Pro_Management is Good) and (RR is High) then (Chem_cons is Very_low) (1)
2. If (Adm_management is Highly_efficient) and (Pro_Management is Good) and (RR is Moderate) then (Chem_cons is Very_low) (1)
3. If (Adm_management is Highly_efficient) and (Pro_Management is Good) and (RR is Low) then (Chem_cons is Very_low) (0.75)
4. If (Adm_management is Highly_efficient) and (Pro_Management is Fair) and (RR is High) then (Chem_cons is Low) (1)
5. If (Adm_management is Highly_efficient) and (Pro_Management is Fair) and (RR is Moderate) then (Chem_cons is Low) (0.75)
6. If (Adm_management is Highly_efficient) and (Pro_Management is Fair) and (RR is Low) then (Chem_cons is Moderate) (0.5)
7. If (Adm_management is Highly_efficient) and (Pro_Management is Poor) and (RR is High) then (Chem_cons is Moderate) (0.75)
8. If (Adm_management is Highly_efficient) and (Pro_Management is Poor) and (RR is Moderate) then (Chem_cons is Moderate) (1)
9. If (Adm_management is Highly_efficient) and (Pro_Management is Poor) and (RR is Low) then (Chem_cons is High) (1)
10. If (Adm_management is Efficient) and (Pro_Management is Good) and (RR is High) then (Chem_cons is Very_low) (1)
11. If (Adm_management is Efficient) and (Pro_Management is Good) and (RR is Moderate) then (Chem_cons is Low) (0.75)
12. If (Adm_management is Efficient) and (Pro_Management is Good) and (RR is Low) then (Chem_cons is Low) (1)
13. If (Adm_management is Efficient) and (Pro_Management is Fair) and (RR is High) then (Chem_cons is Low) (0.75)
14. If (Adm_management is Efficient) and (Pro_Management is Fair) and (RR is Moderate) then (Chem_cons is Moderate) (0.5)

If Adm_management is	and Pro_Management is	and RR is	Then Chem_cons is
Highly_efficient Efficient Fairly_efficient Inefficient none	Good Fair Poor none	High Moderate Low none	Very_low Low Moderate High Very_high none
☐ not	☐ not	☐ not	☐ not

Connection: ○ or ● and
Weight: 1

FIS Name: fuzzy_chemical_consumption

(c)

Input: [50 50 50]
Plot points: 101

Opened system fuzzy_chemical_consumption, 36 rules

(d)

Figure 5.18: Several GUI windows: (a) Fuzzy inference window for inputs and output (b) Membership function plots for input and output variables (c) Rule editor window for viewing, editing and adding new knowledge (d) Fuzzy inference reasoning mechanism for system simulations.

is a GUI showing a set of rules for diagnosing chemical usage. To activate a plot showing the fuzzy inference reasoning mechanism using rules and MFs through rule simulation, the button “View rules” is used and the results are presented as a GUI in Figure 5.18(d). In addition, it shows the connection between the input and output MFs via the rules, and how the fuzzy inference mechanism computes the crisp output depending on the rules simulated by the inputs, provided by the user.

5.6.2 Knowledge Base

The knowledge base is comprised of the fuzzy rule-base and the database. The fuzzy rule-base was designed to evaluate different system outputs classified as functional groups for the determination of effluent quality, effluent quantity, chemical consumption and effectiveness of handling intrinsic oriented wastes. The number of rules in each module is obviously a function of input variables. The number of the rules in the current implementation for each module are: effluent quality (48), effluent quantity (48), chemical consumption (36), and product and byproducts handling (20). The knowledge was stored in the knowledge base using membership functions, which represented different linguistic qualitative terms.

The database consisted of qualitative knowledge on possible levels of waste minimization strategies embedded in question format. The qualitative *apriori* knowledge was classified as either generic or specific. The generic database was integrated in the system structure such that different modules have direct access, as it was applicable to all processes. On the other hand, the specific knowledge was only applicable to certain processes and operations. Furthermore, the database contained mathematical models for computing and normalizing the crisp numerical values as decision input variables in the fuzzy inference mechanism module.

5.6.3 Knowledge Acquisition and Maintenance

The core function of knowledge acqusition and maintenance component is to acquire and verify the consistency of knowledge or to modify and append the knowledge to the knowledge base. Thus, when new knowledge is added, replaced or deleted using this component, the consistency of the new knowledge base had to be ascertained. This was to ensure that the system does not give contrasting recommendations (advices) and erroneous diagnosis.

In this application, the rules and database were manually coded into the knowledge base. There were two ways of editing, browsing, and adding new knowledge in the fuzzy logic expert system rule-base and database. One was through the command line of the MATLAB® software technical computing environment. This approach enhanced the design, visualization, implementation of the fuzzy systems, and the development of a robust modular approach. In addition, the method was suitable in dealing with both the rule-base and database.

The other method was the use of GUI interactive tool, which proved only suitable for dealing with rule-base using the interfaces shown in Figure 5.18. The most profound merit of this method is its ability to walk the user through the entire system design, including rule definition, membership selection and inference system refinement. In this study, both approaches were integrated and their individual merits harnessed to develop robust knowledge bases and carry out an extensive diagnostic evaluation of system functionalities.

5.6.4 Fuzzy Inference Engine

As discussed in section 5.5.4 the inference engine is the kernel of the fuzzy logic expert system. Its main function is to use data and knowledge in the rulebase and database to infer the system outputs. To achieve this goal, the system acquires inputs via the question-answer interface supported by the GUI.

The next step focuses on the transformation of qualitative input values into numerical values, that are subsequently normalized in the defined ranges of the linguistic input variables membership functions. The normalized values are taken into the fuzzifier where they are fuzzified into degrees of membership. Using the fuzzified values, the inference engine evaluates the fuzzy if-then rules. As result of the evaluation process, through fuzzy conflict co-ordinating process, the firing rules are selected that satisfy the user inputs (in this case they can be viewed as constraints and conditions).

The second task is to aggregate the fuzzy outputs resulting from all the firing rules into a single aggregated fuzzy set. The inference system used in this work was forward chaining. This means that data and information flow in the system was unidirectional. In this sense the user inputs were transfered to the inference engine via GUI and processed along with other information inputs to the fuzzy inference engine. The final fuzzy output from the inference engine was synthesized back into a crisp output through the defuzzification process, which expressed the results of the modeling process.

5.7 Results and Discussions

In this section, two case studies are presented to illustrate the operation and many salient features of the developed decision support system tool for diagnosing waste minimization in the wine industry reported in this dissertation. Additionally, it demonstrates the integration of various modules in solving different waste minimization problems under different scenarios. As an illustration, waste minimization achieved through effective recovery of product and byproducts and the reduction of effluent quantity generated during the cleaning and sanitizing processes are exemplified below.

5.7.1 Product and Byproducts Recovery

To demonstrate how the system operates, inputs from four different runs are summarized in Table 5.12. For the user to enter the inputs, the GUI shown in Figure 5.16 provided the snapshots as seen on the screen and in the order indicated by the arrow. In practice, it is not clear how operational practices and the technology used explicitly affects the quantity of product and byproducts losses as wine is processed at different stages of the vinification process. This is because it is difficult if not impossible to mathematically express how these losses can be prevented. However, the fuzzy logic based expert system reported in this dissertation can provide a strong decision support based on various rules in the knowledge base.

The system interrogates the user and after all the user's qualitative inputs are entered, the system computes the recovery contributions from each process or unit operation. Secondly, the calculated values are normalized before they are transmitted into the fuzzy

Table 5.12: User's qualitative inputs for the evaluation of product and byproducts handling during the vintage season.

	User input factor choices:[a]			
Qualitative factors	**Run 1**	**Run 2**	**Run 3**	**Run 4**
Generic Equip. factors				
Dispersion reduction	M(1.00)	H(0.75)	L(1.00)	L(0.50)
Enforcement of procedures	H(0.75)	H(1.00)	M(0.75)	L(1.00)
Streams segregation	M(1.00)	L(0.50)	H(1.00)	M(0.75)
Spills, leaks, etc frequency	L(1.00)	M(1.00)	M(1.00)	M(1.00)
Specific factors				
Crushers and destemmers				
Grapes condition	M(0.75)	M(1.00)	L(1.00)	M(1.00)
Grapes temperature	H(1.00)	M(0.5)	M(1.00)	H(0.50)
Lines dedication	M(1.00)	H(1.00)	M(0.75)	M(0.75)
Site communications	M(0.75)	H(0.75)	H(1.00)	L(1.00)
Grapes deliveries	H(0.75)	M(1.00)	M(0.50)	L(1.00)
Pipe and transfer systems				
% of inclined pipes	H(1.00)	M(1.00)	L(0.50)	M(0.75)
Overall piping lengths	M(0.75)	M(0.75)	H(0.50)	M(0.50)
Mechanical recoveries	H(0.75)	H(1.00)	M(1.00)	L(1.00)
Type of pipe joints	L(1.00)	H(0.75)	M(0.75)	H(0.75)
Filtration process				
Effectiveness of separation	M(0.75)	M(1.00)	M(0.50)	L(0.50)
Handling eff. of filtration cakes	H(0.50)	H(0.75)	L(1.00)	L(1.00)
Reuse of filter cakes	L(1.00)	M(0.75)	H(1.00)	M(1.00)
Alt. filtration methods	H(1.00)	H(1.00)	H(0.50)	M(0.50)
Pressing Process				
Pressing equip. efficiency	H(0.75)	H(1.00)	M(0.75)	M(1.00)
Eff. of solids discharge	M(0.75)	H(0.75)	M(0.75)	L(1.00)
Fermentation process				
Wine filling in fermentors	M(0.50)	H(0.75)	M(1.00)	H(1.00)
Yeast recovery from fermentors	H(1.00)	M(0.50)	H(0.50)	M(0.75)
Roughness of tank surfaces	M(0.75)	H(0.75)	M(0.75)	L(1.00)
Bottling and packaging				
Effi. of using glue	H(0.50)	M(0.75)	M(0.50)	L(1.00)
Reduction of spills	H(1.00)	H(1.00)	L(1.00)	H(0.50)
Generic Man. factors				
Training & awareness				
• SM[b]	M(0.50)	H(1.00)	H(0.75)	H(0.50)
• SW[c]	H(0.75)	H(0.75)	H(1.00)	M(1.00)
• UW[d]	M(0.75)	M(1.00)	L(1.00)	M(0.75)
Equipment maintenance	H(0.50)	H(0.75)	M(1.00)	L(0.50)
Time lag period	M(1.00)	H(0.75)	M(0.75)	H(0.50)

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[a] All the user inputs are ranked as High (H), Medium (M), and Low (L). Detailed choices are presented in Tables 5.5 and 5.6.

[b] Senior management

[c] Skilled workers

[d] Unskilled workers

rule module to rank the possible product and byproducts recovery according to the user's inputs. The procedure to determine the fuzzy logic input crisp numerical value is as follows.

Each qualitative response choice has a corresponding dimensionless score assigned to it and the contribution of each considered strategy is computed using Equation 3.1. In summary the contribution of a given strategy towards the overall product and byproducts recovery was obtained from the product of the dimensionless score and the degree of belief the user has on the selected choice. Consequently, using this relationship the effective contributions of both specific and generic strategies were evaluated and normalized in accordance to Equation 5.5.

In each run, the contribution of each process and unit operation for the recovery of product and byproducts were calculated and normalized in the range 0 to 1 as shown in Table 5.13. To illustrate how these computations were carried out, lets examine the case of filtration process under Run 1. From the inputs specified in Table 5.12, the effective contribution from the filtration process is computed as;

$$N_{fv} = \frac{[2\times 1 + 3\times 0.75 + 1\times 1 + 0.25\times 1] + [2\times 0.75 + 2\times 0.5 + 0.5\times 1 + 6\times 1]}{24} = 0.6042 \qquad (5.23)$$

where 24 is the maximum additive sum in this process if all the strategies were sufficiently implemented towards product and byproducts recovery;
f denotes the filtration process and;
v denotes the vintage season.

Similarly the approach was used in evaluating the contributions from other processes and unit operations in product and byproducts recovery. The same procedure was extended in evaluating the generic management linguistic variable (GM) for handling the product and byproducts.

The next step was to combine the outputs from each process using Equation 5.3 to determine the "effective recovery of product and byproducts (PBR^v)". As the users' inputs considered were under vintage season, the expert (Exp1 under effluent quality) opinion on the relative contributions of different processes presented in Table 5.4 were employed

Table 5.13: Analysis results for product and byproducts recovery using qualitative inputs in Table 5.12 during the vintage season.

Process/ operation	**Tabulated values**	**Run 1**	**Run 2**	**Run 3**	**Run 4**
Crushing & destemming (CD)	$\mathrm{CD}_g{}^a$	4.1250	5.1875	3.7500	2.1875
	$\mathrm{CD}_s{}^b$	4.2500	5.2500	4.0000	3.0000
	$\mathrm{CD}_{ef}{}^c$	0.5234	0.6523	0.4844	0.3242
Piping & transfer systems (TL)	TL_g	10.750	13.250	9.5000	5.3750
	TL_s	12.125	14.125	7.3750	8.6250
	TL_{ef}	0.5719	0.6844	0.4219	0.3500
Filtration (F)	F_g	5.5000	6.7500	4.6250	2.5000
	F_s	9.0000	10.250	6.5000	3.5000
	F_{ef}	0.6042	0.7083	0.4635	0.2500
Pressing (P)	P_g	10.500	12.750	9.0000	4.8750
	P_s	7.1250	11.250	4.8750	4.7500
	P_{ef}	0.5508	0.7500	0.4436	0.3008
Fermentation (FE)	FE_g	9.5000	11.500	8.8750	5.0000
	FE_s	12.250	12.500	10.250	12.500
	FE_{ef}	0.5437	0.6000	0.4781	0.4375
Bottling & packaging (BP)	BP_g	2.5000	3.1250	2.3750	1.3750
	BP_s	2.5000	2.3750	0.7500	1.2500
	BP_{ef}	0.6250	0.6875	0.3906	0.3281
Generic management	GM (%)^d	45.349	80.233	65.698	44.186
Computed PBR^v	PBR^{ev}	0.5603	0.6709	0.4497	0.3495
Fuzzy inference output	PBR^{fv}_{eff}	0.3450	0.9185	0.5490	0.0994
Final system ranking:		**Low**	**Very high**	**Moderate**	**Very Low**

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[a] g: denotes the generic factors' contribution.

[b] s: denotes the specific factors' contribution.

[c] ef: denotes the total effective contribution of a given process.

[d] GM: generic management variable.

[e] PBR^v: organic matter handling during vintage season.

[f] PBR^v_{eff}: effective organic matter handling during the vintage season ranking computed using the fuzzy if-then rules.

to evaluate the effective PBR^v yielding:

$$PBR = 0.5234 \times 0.15 + 0.5719 \times 0.3 + 0.6042 \times 0.1 + 0.5508 \times 0.15 + 0.5437 \times 0.25 + 0.6250 \times 0.05 = 0.5603 \tag{5.24}$$

The last stage of this assessment was to compute the final effective recovery of product and byproducts using the fuzzy rules in the knowledge base. The system inputs are: PBR_v and GM computed and presented in the previous paragraphs. In Run 1 the input values were 0.5603 and 45.349 for the PBR^v and GM correspondingly. By simulating these input values using the fuzzy rules, the system effective PBR^v_{eff} crisp output value was found to be 0.3450. This value was consequently ranked as *Low.* The ranking of product and byproduct recovery as low means that there is a considerable loss of yield to the waste stream. It would also imply that the effluent quality as well as the effluent quantity are highly likely to be impacted negatively. The same methodology was repeatedly employed to compute the effective recovery of product and byproducts for Run 2, Run 3, and Run 4 based on the user's specified linguistic inputs. The results obtained are presented in Table 5.13.

By comparing the individual process contributions in Run 1 and Run 3 shown in Table 5.13, naturally one expects the final ranking of the product and byproducts to be higher in Run 1. To the contrary the system ranks the results in Run 3 more favorably in terms of recovering product and byproducts. On the basis of experience in winery operations in situations where management with regard to waste is classified as *Good*, then undoubtedly the possibility of reducing product and byproducts losses is much higher as opposed to a case where the ranking is *Poor.* It is in the light of this recognition that the fuzzy rules in the knowledge base were designed in a manner to reflect this reality.

The above observations further illustrate the necessity of adopting an integrated approach in managing vinification processes in an endeavor to enhance waste minimization. This is because the operations in the wine industry have been shown to depend largely on the managerial aspects. In that sense, to boost the performance of recovering product and byproducts, training of personnel and ensuring good operating practices are critical elements in a winery. These aspects have been modeled as generic management parameter in this study. Therefore, the GM value being much higher in Run 3 than in Run 1 explains why the resultant recovery is ranked favorably for the latter than for the former.

The results in Run 2 depict a scenario where an integrated approach has been adopted during the production process. This is exhibited by a high yield of product and byproducts recovery. This is confirmed by the high computed values of both PBR^v and GM parameters from the user's inputs. The final system ranking of the product and byproducts recovery is *Very high.* However, in Run 4 the evaluated values of PBR^v and GM are low and hence under such conditions the possible recovery of the product and byproducts is ranked as *Very low* by the system.

5.7.2 Evaluation of Effluent Quantity

To evaluate the system output (effluent quantity) from the qualitative inputs, a mechanism that was able to combine all the different strategies in a rational, reproducible and acceptable manner was developed. Thus in this study, the approach adopted was by using scoring and ranking techniques to circumvent this difficulty.

In chapter 4, numerous strategies with potential to reduce the effluent quantity consumed during the cleaning and sanitizing processes were discussed. Table 5.8 presents the ranking of the strategies using WMI on the basis of the defined criteria presented in section 5.3.

To evaluate the qualitative strategies and compute effluent quantity that can be possibly generated in a given scenario, the linguistic descriptive strategies were modeled into three states using qualitative reasoning. This is beacsue the linguistic terms were not mathematically operable. To cope with that difficulty, each linguistic state was assigned a dimensionless score. The state viewed as having a higher potential to reduce potable water consumption more effectively was assigned the highest value while the one with least effect was given the lowest value (see Table 5.8). The strategy ranked the best was assigned the highest dimensionless score while the least ranked was given the lowest score value. The strategies in between the best and the least were assigned intermediate values. In view of this nomenclature, the size of a score represented the significance of a given strategy in relation to its overall contribution to the reduction of effluent quantity during cleaning and sanitizing processes.

As discussed in section 5.5.3 under the effluent quantity submodule, three linguistic fuzzy variables were identified as exerting influence on the quantity of effluent generated during the vinification process namely the effluent quantity management (M_v), equipment efficiency (EE_v) and organic matter removal (OMR_s).

The M_v is computed from the generic effluent quantity management parameter (M_{gv}) and the generic management of product and byproducts (GM_{PBR}) according to Equation 5.18. The (GM_{PBR}) and OMR_s crisp numerical values were determined as described in section 5.7.1 and their values were used in evaluating the quantity of effluent generated.

The M_{gv} numerical value was determined using the strategies outputs in Table 5.8 while the EE_v values were computed using Equation 5.19. Table 5.14 shows the results of nine Runs for a vinification process during the vintage season.

The results indicate that in Runs 1, 4, and 8 various strategies were ineffectively implemented, effluent quantity generated was either ranked *High* or *Very high*. This can be explained by the fact that, in either case, M_v values were low (under 45%), the cleaning equipment used were open pipes (implying low efficiency) and the removal of organic matter from the equipment was poorly done. To show how low cost strategies significantly influence the conservation of potable water, the M_{gv} variable was fixed for each of the Runs 1, 3, 4 and 8. However, the GM input, viewed as easy to implement in a winery, was varied to improve the overall effluent quantity management variable M_v. In addition the OMR_{ve} and EE_v variables were varied as they were easy to implement as well.

By comparing the results of Runs 1 and 6, one finds that the M_{gv} is fixed at 0.4022 or 40% while the GM varied from 0.4535 in Run 1 to 0.6570 in Run 6. The GM variation produced an improvement of M_v value from 43% to 53%. Simultaneously, the input values of OMR_{ve} and EE_v were changed from 3.45 to 5.49, and 40% to 72% (i.e. replacing open hose pipe with a high pressure cleaner), respectively. Using the new computed values as fuzzy inputs, yielded an effluent quantity ranked *Low* as shown in Run 6. Similarly, the same procedure was repeated for cases Runs 3 & 5; Runs 4 & 7; and Runs 8 & 9.

Run 2 was presented as a base case depicting an ideal winery where all the strategies influencing the effluent quantity were implemented effectively. Of interest to note is that, if inputs of 100, 100 and 10 for M_v, EE_v, OMR_{ve} respectively were entered into the system, the predicted effluent quantity is 0.0902. This means the highest likely certainty of the system in predicting effluent quality is 90.98%. It is a conservative value that confirms the fact that heuristic rules do not accord a 100% certainty to their predictions. Similarly, for the worst case where the inputs are zeros, the likelihood prediction is 0.925 and not 1. Again the certainty is not 0% as expected but at 7.5%. This shows again that heuristics do not accord a 0% certainty in their predictions.

Table 5.14: Analysis results for effluent quantity generated from cleaning and sanitizing processes during vintage season.

	User input factor choices[a]								
Qualitative factors	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Run 6**	**Run 7**	**Run 8**	**Run 9**
Input substitution (IS)									
Hot water/steam usage	M(1.00)	H(0.75)	M(0.75)	M(0.50)	M(0.75)	M(1.00)	M(0.50)	L(0.50)	L(0.50)
Quality of water used	H(0.75)	H(1.00)	H(0.75)	L(0.50)	H(0.75)	H(0.75)	L(0.50)	M(0.75)	M(0.75)
Hazardous and toxic chems.	M(0.50)	H(0.75)	H(1.00)	L(1.00)	H(1.00)	M(0.50)	L(1.00)	H(1.00)	H(1.00)
Technological mod. (TM)									
Vessels surface roughness	M(0.50)	H(1.00)	H(0.75)	H(0.50)	H(0.75)	M(0.50)	H(0.50)	M(0.75)	M(0.75)
equipment modifications	L(1.00)	H(0.75)	M(0.75)	L(1.00)	M(0.75)	L(1.00)	L(1.00)	H(1.00)	H(1.00)
Eff. of chem. dosing equips.	M(1.00)	H(1.00)	M(0.75)	L(1.00)	M(0.75)	M(1.00)	L(1.00)	L(1.00)	L(1.00)
Operating practices (OP)									
Degree of effluent segregation	H(0.75)	H(1.00)	H(0.75)	M(0.50)	H(0.75)	H(0.75)	M(0.50)	M(0.75)	M(0.75)
Scheduling of batch processes	L(0.75)	H(0.75)	H(0.75)	H(0.75)	H(0.75)	L(0.75)	H(0.75)	M(1.00)	M(1.00)
Emergency preparedness	M(0.75)	H(0.75)	M(1.00)	L(1.00)	M(1.00)	M(0.75)	L(1.00)	M(0.75)	M(0.75)
Counter current method appl.	H(0.50)	H(1.00)	M(0.50)	M(0.50)	M(0.50)	H(0.50)	M(0.50)	L(1.00)	L(1.00)
Time lag period	M(1.00)	H(0.75)	M(0.75)	H(0.50)	M(0.75)	M(1.00)	H(0.50)	M(0.75)	M(0.75)
Reuse and recycling (RR)									
% of water reuse/recycling	M(0.50)	H(1.00)	H(1.00)	H(0.50)	H(1.00)	M(0.50)	H(0.50)	L(1.00)	L(1.00)
IS_{ef}	0.1410	0.2212	0.1619	0.0577	0.1619	0.1410	0.0577	0.0978	0.0978
TM_{ef}	0.0737	0.2212	0.1346	0.0897	0.1346	0.0737	0.0897	0.1026	0.1026
OP_{ef}	0.1811	0.3878	0.2372	0.2212	0.2372	0.1811	0.2212	0.1811	0.1181
RR_{ef}	0.0064	0.0256	0.0256	0.0128	0.0256	0.0064	0.0128	0.0064	0.0064
$M_{gv}(0-1range)$	0.4022	0.8558	0.5593	0.3814	0.5593	0.4022	0.3814	0.3894	0.3894
GM (0-1 range)	0.4535	0.8023	0.6570	0.4420	0.8023	0.6570	0.8023	0.4535	0.8023
M_v	42.787	82.905	60.815	41.164	68.080	52.963	59.185	42.145	59.587
OMR_{ve}	3.4500	9.1850	5.4900	0.9940	9.1850	5.4900	9.1850	3.4500	9.1850
EE_v	40.000	72.000	42.000	21.000	72.000	72.000	64.000	35.000	72.000
EV	0.7979	0.0937	0.4330	0.9170	0.0991	0.2370	0.2004	0.8161	0.1030
Effluent quantity ranking	**H[b] vol.**	**VL[c] vol.**	**M[d] vol.**	**VH[e] vol.**	**VL vol.**	**L[f] vol.**	**L vol.**	**H vol.**	**VL vol.**

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[a] All the user inputs are ranked as High(H), Medium(M) and Low(L) the detailed choices are presented in Table 5.8.

[b] H: High

[c] VL: Very low

[d] M: Moderate

[e] VH: Very high

[f] L: low

5.8 Concluding Remarks

The integration of fuzzy logic and expert systems approaches was successfully applied to incorporate the experts and/or operators reasoning into diagnosing the complex problem of waste minimization in the wine industry. In this study, complex, diverse, and mostly linguistic knowledge was represented by few fuzzy rules in each module (the entire system contains 152 rules) to facilitate the evaluation of production process outputs with regard to product and byproducts losses, effluent quantity and quality, and the amounts of chemicals used.

The application of fuzzy logic was crucial in dealing with sources of uncertainty contained in the domain data that are inherently vague and nonstatistical in nature. As such, it provided an adequate methodology for formalizing diverse input data such that the data can be used for diagnosing possible waste minimization outcomes under numerous wine production scenarios. This is because fuzzy logic allowed a more detailed description of the production variables, albeit arbitrarily, but through finite discretization of inputs and outputs using membership functions. The use of membership functions within a fuzzy linguistic variable space offered an opportunity for the subjective element of commonsense knowledge to also be incorporated in deriving the final solutions. In that way, the system derived solutions that were found to be more transparent in comparison to those obtained using deterministic mathematical models, and were more likely to be accepted by the targeted users.

In the development of this system, a modular approach was adopted, in this case implying that each targeted system output can be evaluated indepedently. This made the system flexible and easy to customize to suit the needs and specific operating procedures of a particular winery taking into account its production constraints and requirements. Moreover, it provided a simple and systematic form of upgrading easily a particular knowledge base without neccessitating the reconfiguration of the entire rule bases and databases.

The fuzzy expert system has the merit of providing a decision tool that offers the user the ability to model alternative operational scenarios. In this manner, the user is able to view and evaluate different outcomes and therefore assess trade-offs that need to be taken into account in order to improve the production per unit throughput and minimize effluent streams on the basis of available resources and other production constraints.

At the moment, the knowledge bases developed in this study are static and require regular upgrading as new knowledge becomes available. Thus, to enhance the system performance and ensure a dynamic rule base that responds to various production changes, the system should be integrated with other AI tools that have automatic knowledge acquisition capabilities such as artificial neural networks and genetic algorithms. As such, the integrated AI technologies approach will ensure that the decision tool evolves with time. This is because what is currently viewed as the best alternatives are highly unlikely to remain the same as new technologies evolve and more stringent waste management related legislations comes into effect.

The waste minimization index (WMI) that was developed, contained most of the significant criteria for ranking diverse waste minimization strategies. Owing to the strong qualitative orientation of the WMI, many strategies were ranked even in circumstances where their technical and economic data, and information were found to be inadequate.

As discussed, comprehensive and systematic waste minimization analysis in many wineries for identifying and examining feasible alternatives are rarely undertaken. The major drawbacks in this regard are 2-fold. First is the lack of specialized knowledge and technical expertise in many wineries, and secondly owing to the laborious and time-consuming nature of the waste minimization analysis process. As a contribution in addressing these drawbacks, in this study we proposed and developed an intelligent system employing the fuzzy logic and expert systems technologies to automate the waste minimization analysis in the wine industry. The automated waste minimization analysis has a merit of considerably reducing the time, effort, and resources required in undertaking this process. In addition, the system undertakes the analysis without requiring the user to posses prior in-depth environmental knowledge or to gather adequate precise data to model the winery in order to make feasible waste minimization decisions.

Chapter 6

Development of a Fuzzy-Based Expert System for Energy Minimization

6.1 Background

The ever increasing energy demand for cooling and heating applications in the wine making processes have recently become of great concern to the winemakers (UNEP, 1995; Rankine, 1989). This can be attributed to the exponential growth of the electrical energy costs and the large quantities of water generated that require extensive treatment before its release to the environment. This situation has been compounded by the use of inefficient traditional heat transfer mechanisms in the cooling systems and poor process control and management of operations, including particularly the cooling loads from various sources.

In this sense, the core objective of this chapter is to present a cohesive energy management system that integrates various factors that govern energy consumption at the first cooling process of must and grape juice at the maceration stage of the vinification process. The aim is to illustrate how energy resource consumption can be improved in a domain where accessible data contain uncertainty or are ill-structured, inherently vague and nonstatistical in nature.

In the wine industry, electrical energy is required for diverse purposes such as the pumping of grape juice, pressing of grape skins, receiving and crushing of grapes, mixing and filtering of wine, ion-exchanging, and cooling (refrigeration) of wine amongst others. It is significant to note that the energy uses highlighted here and many others are dependant on numerous, mostly unique factors. These factors are generally found to exhibit a strong link to the type of cooling equipment-, process-, site- and time-specificity as discussed in section 2.4. In view of this reality, it is seemingly impossible to generalize energy minimization strategies in the entire vinification process. Therefore, in this study the focus is on how to minimize the quantity of energy required for the cooling purposes during the maceration process. The maceration process was targeted because it has the largest refrigeration demand loads prior to the fermentation process, as the wine juice and must temperature ought to be stabilized immediately after the crushing process to enhance the resultant wine quality.

Secondly, the maceration process was targeted because of the qualitative nature of the common-sense knowledge which forms part of the solutions that yield a considerable energy reduction. Viewing the problem from this perspective, then its solution can be derived using fuzzy sets to develop a fuzzy qualitative simulation algorithm. The main merit here being, it allows a more detailed description of physical variables, through an arbitrary, but finite, discretization of the quantity space. As such, the approach avoids rigorous mathematical models and is consequently more robust than the classical approach in cases which are difficult to model (Yager and Filev, 1994; Driankov et al., 1993)

The energy demand for cooling purposes at several stages of the vinification process is used to control or retard unwanted enzyme, microbial, and chemical reactions (Boulton et al., 1998). These generally include must cooling in association with juice draining or skin contact prior to fermentation, juice cooling prior to fermentation and during fermentation, cooling of wines for control of temperature during storage, among other applications. A key aspect to good husbandry in all these processes in the use of energy resources is sound energy management and conservation. This ensures that all energy usage activities are undertaken from an economic point of view, resulting in reduced costs and enhanced profitability.

The energy management can be achieved via two routes. First, by paying less per unit of energy and secondly, through the reduction of energy consumption per unit of product. The focus in this work is to show how using fuzzy logic approach, the latter technique has the potential to achieve energy reduction in the wine industry. The former case is not a viable route of achieving energy reduction costs in the wine industry as wineries do not generate their own power, which is the case in other process industries (e.g. petrochemical and chemical).

As mentioned earlier, temperature control is critical at various stages in the vinification process in ensuring high quality wine production especially in hot climate countries such as South Africa (Vergunst, 1971) and Australia (Rankine, 1989). In an attempt to show the significance of temperature control at different stages of wine production from grape growing to the bottling process, findings from a number of studies have been reported by several authors. Some of these topics cover the temperature effect on grape composition and wine quality (Jackson and Lombard, 1993; Marais, 1998; Marais 2001a), the effect of cooling grapes in vineyards (Aljibury, 1993), wine refrigeration (Vergunst, 1971) and the climatic impact on grapes quality (Smart and Dry, 1989).

However, in the available literature, it shows that there has not been any reported practical attempt in applying integrated energy management to illustrate its impact on the refrigeration demand during the cooling process at the maceration stage. In this work, a case study is presented based on a rather typical vinification process practiced in South Africa. The study will attempt to show how integrated energy management influences the cooling demand through the application of artificial intelligence technologies and, specifically expert systems and fuzzy logic technologies.

6.2 Cooling at the Maceration Stage

The wine making industry constitutes a series of batch and semi-batch processes beginning with grape harvesting and ending with the bottling of wine. The fragmentation of the various processes within a time framework stretching over several hours to months or even years poses unique challenges to implementing techniques such as integrated energy management e.g. pinch technology (Korner, 1988; Linnhoff and Flower, 1978; Linnhoff and Hindmarsh, 1983).

Figure 6.1 shows the system boundary, providing information on the activities included or excluded from this study. Note that the maceration process follows immediately after the crushing of grapes, as discussed in section 2.1.3. The core function of this process is to control the temperature of grape juice and must to enhance the final wine quality.

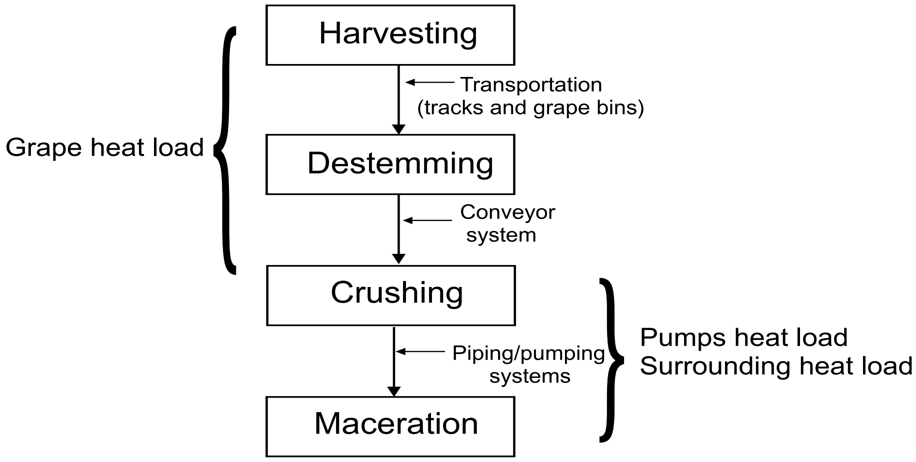

Figure 6.1: System boundary definition for this study. Processes highlighted are considered in terms of their contribution to overall energy demand for wine juice and must cooling at maceration stage.

This is achieved by cooling the crushed wine juice and must using heat exchangers. For instance, for the production of high quality white wine, temperature has to be maintained in the range 10°C to 18°C while in the case of red wine, higher temperatures of between 15°C to 28°C are required.

The temperature control at this stage is realized through the use of heat exchangers (Boulton et al. 1998). There are several types of heat exchangers that can be used for wine cooling at this stage. These include: shell and tube heat exchangers, plate heat exchangers, spiral heat exchangers, and tank cooling jackets. A review of heat exchangers[1] used in the wine industry has been recently presented by Boulton et al. (1998), and their heat transfer coefficient ranges are summarized in Table 6.1. Note the heat transfer coefficient values quoted here are only applicable when the exchangers are used for refrigeration of wine and must and, are different in applications involving other fluids like water, sugarcane, flour solutions, etc. Besides the influencing factors owing to the type of heat exchanger used on the quantity of cooling demand, operational-oriented approaches such as time of cooling, control of the cooling system, and managing of the cooling loads also play a fundamental role in achieving optimal energy resource consumption.

It is important to define the system boundaries in order to precisely determine the

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[1] A general treatment on the subject of heat exchangers has been presented by Nee, 2003.

Table 6.1: Summary of heat transfer coefficients for heat exchangers mostly used in the wine industry.

Name of heat exchanger	**Heat coefficients Units: $W/m^2/^oC$**	**Reference**
Tank jackets	12 - 60	Boulton et al., (1998)
Shell and tube	600 - 900	Boulton et al., (1998)
Spiral	760 - 1060	Ellis (1977)
Plate	2400 - 3600	Boulton et al., (1998)
Scraped-surface[a]	600 - 2000	Cuevas and Cheryan (1982)

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[a] Only suitable for cold stabilization of wine and therefore was not considered in this study.

breadth and scope of the influencing factors unambiguously in this problem. The factors considered in this work were evaluated using the qualitative systematic approach and within the time frame of grape harvesting up to the first cooling process at the maceration stage. Figure 6.1 illustrates the region this study concentrates on as it accounts for the highest refrigeration load in the entire vinification process. This is because all the compressors are at full load to ensure that wine does not spoil, which could lead to loss of production. In addition, effective must and grape juice cooling at this stage has a huge subsequent positive effects on the quantity of energy required for cooling in the successive processes such as fermentation, stabilization and maturation.

Two aspects characterize the extent to which energy is conserved at this stage. The first aspect concerns the system configuration and its properties, which are design dependant. In this respect, these factors will be modeled as a function of the heat exchanger used to cool the wine. The second aspect deals with the dominant factor, especially for the existing cooling installations which forms the core of this work. The dominant factor is the operational management of various activities and processes preceding and during the cooling process at maceration stage. Thus, reduction of cooling load demand via improvement of system operations geared towards achieving high system efficiency precedes technological measures in existing installations. The reason being, the technologically oriented factors are impeded by delimiting factors such as high capital investments and lack of space for expansion of the cooling system. In this study, the technologically oriented aspects will not be given further considerations.

6.3 Energy Minimization

6.3.1 Energy Minimization Overview

Though a lot of literature detailing different aspects of industrial vinification processes (Rankine, 1989; Chapman, 1996; Chapman et al., 2001; SRKCE, 1993; USEPA, 1995) has been published, there has been little attention given to integrated energy management with a clear objective of energy minimization at various points of wine production during the cooling processes. Using systematic qualitative methodology, various processes and operations were diagnosed beginning with the grape harvesting process up to the first cooling process at the maceration stage in this study. The aim was to identify possible alternatives having the potential to reduce the electrical energy demand per unit throughput achievable through integrated energy management. To realize this objective, it is my view that energy minimization is possible if the identified alternatives are integrated to be part of the vinification process operations.

The cooling load at maceration stage demanding refrigeration is dependant primarily on two heat load sources namely the grape heat load and the external heat load. The grape heat load is a function of ambient temperature, which is mostly influenced by the time of harvesting, the growing region and the distance between the vineyards and the processing wineries. For instance, in South Africa ambient temperatures vary between 10^{o}C to 40^{o}C during the vintage season as a function of the vintage region.

These temperatures exhibit both temporal and spatial variations. For clarity, Figure 2.2 illustrates several wine producing regions in South Africa distributed over diverse climatic zones. As a consequence of this diversity, wineries under different regions deal with varying grape heat loads. Other contributing factors to the quantity of grape heat load depend on operational management strategies that are put in place immediately after harvesting, and during the transportation process. A few examples are presented in Table 6.2.

On the other hand, the external heat load sources arise at the winery site owing to the heat from the pumps and the surroundings. These heat load sources are estimated to contribute a refrigeration load demand in the region of 5-10% and 5-20% (Rankine,1989) of the total grape heat load, respectively. Table 6.2 shows various heat load sources and a number of viable management alternatives.

6.3.2 Development of Decision Making Model

Owing to the complexity of interactions between factors that govern energy management during the cooling process (see Table 6.2), a model was designed to aid in developing a robust decision making algorithm. This was done with the understanding that adopting a linear technique of reducing energy consumption yields a nonoptimal solution. In that respect, a lot of effort was expended to identify data and knowledge through interviews and process site observations to identify all the influencing factors and the interrelationships amongst them.This investigation was carried out by the author through visitation of several wineries and conducting informal interviews with winery managers and operators. To cross validate the knowledge obtained, two experts knowledgeable in the wine industry operations were consulted and verified the data and offered useful suggestions as well. The results were obtained in the period running from late January 2003 to early April 2003.

A systems approach was used because it is well-suited to identifying and integrating the decisive data and knowledge that supports a transparent decision making process. Moreover, the approach calls for an explicit identification of linkages among diverse factors that influence the overall energy consumption during the cooling process. In that way, the causing factors were identified, investigated and remedial alternatives derived. It became quite clear that the problem solution of high energy consumption during the cooling process could be realized through the integration of identified alternatives that were classified broadly as follows:

- Good housekeeping measures: for example turning-off of machines when they are not in use.
- Preventative maintenance of operational processes and piping transfer system. This

is aimed at enhancing operational efficiency and minimization of energy losses.

- Knowledge on cooling equipment and resource material inherent characteristics. Some examples are the heat transfer coefficients of heat exchangers, systems insulations, material qualities, etc. and their relationship to the final energy consumption.

Using the modular approach, the knowledge acquired was structured into discrete components to facilitate efficient decision making. According to this methodology, the overall energy consumption was found to be a function of mainly two components: the technology (type of cooling heat exchanger) and the total heat load to be cooled from various heat sources. These will be referred to as the *primary components* that influence the overall energy consumption.

The technological dimension of energy consumption are represented by the heat transfer coefficient. The heat transfer coefficient property was viewed as the representative feature of any given heat exchanger used for refrigeration purposes. On the other hand, the total heat load refers to all the refrigeration loads that require cooling and are generated from several sources. These sources are comprised of two *secondary components*: grape heat load and effective external heat load. The grape heat load was established to be mainly influenced by the daily weather of the region (see Table 6.2). In that sense, in days when the solar energy is abundant the grape heat load was found to be high, otherwise it is low during the cooler days. The *basic* variables describing the grape heat load are temperature control, distance and ambient atmospheric temperature.

The external heat load refers to the heat absorbed by the grape juice and must during the crushing and pumping processes. In this model, two components were used to evaluate the external heat load. These quantities are the pump heat load and the surrounding heat load, and are referred here as the *tertiary components*.

The pump heat load is generated from the transfer pumps as they pump the wine juice and must through the heat exchangers and its associated piping. It is a function of two basic factors the pump operational management and pump efficiency. Each of these basic variables constitute several primitive factors (see section 6.4.1) that were used in

Table 6.2: Heat load sources for grapes, must, and wine juice and several alternatives to reduce high energy resource consumption.

Heat load type	**Process**	**Heat load sources**	**Causing factors**	**Possible energy minimization alternatives**
Grape heat	Harvesting	Solar energy	Time of harvest	• Harvesting of grapes at low temperatures (night or early morning hours.)
			Ambient air temperature	• Immediate cooling after harvesting using carbon dioxide pellets.
				• Covering the grape bins as soon they are harvested.
	Transportation	Solar energy	Distance	• Cooling of grapes during transportation using carbon dioxide pellets.
			Ambient air temperature	• Using covers over grape bins during transportation. • Use of natural overnight cooling.
External heat	Maceration	Solar energy	Ambient air temperature	• Insulation of heat exchangers. • Air conditioning/cooling of part or entire winery.
		Frictional energy	Frictional forces	• Lubrication/regular maintenence of pumps. • Switching off motors when not in use. • Use of variable speed drives to reduce load on motors.
		Water quality	Biofouling/ scaling/ corrosion	• Use of biocides to control or remove scaling and corrosion on the pumps. • Regular cleaning of pumps surfaces. • Use of high quality water for cleaning of pumps.

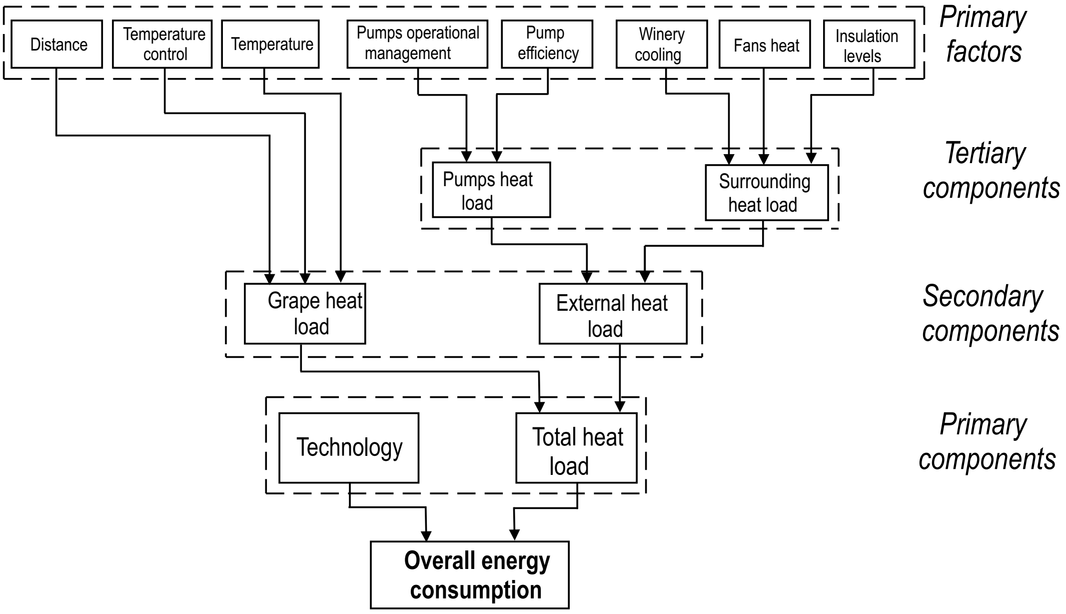

Figure 6.2: A tree-like network of components influencing overall cooling energy demand at the maceration stage.

computing the composite variables the pump efficiency and pump operational management. This heat energy is manifested as frictional heat and has to be removed by the heat exchanger.

Surrounding heat load is the heat transfered from the surrounding air to the must or wine juice through the piping. To effectively control the heat gains from the surrounding to minimal levels is realized through three basic variables: insulation, winery cooling and use of efficient cooling fans. Insulation of the coolers with effective insulators reduces the heat gain from the surrounding drastically, while in circumstances where the insulation is poor or nonexistent, the heat gains are high. Winery cooling which mainly is essential for fermentation of wine in barrels and storage of wine in bottles plays a role, since in cases where it is done over the entire winery, it significantly reduces the heat load from the surroundings. The efficiency of the cooling fans influences the surrounding heat load. In this study, the efficiency factor of the fans was used as an indicator of their contribution to the overall surrounding heat load.

The identified knowledge modules were integrated into a hierarchical structure that allowed all the influencing factors to be aggregated until the final-level, the overall energy consumption required for the cooling grape juice at the maceration stage is evaluated. The schematic representation of these dependencies among various modules is shown in Figure 6.2.

6.4 Fuzzy Logic Algorithm Approach

Bellman and Zadeh (1970) argued: "much of the decision making in the real world takes place in an environment in which the goals, the constraints, and the consequences of possible actions are not known precisely." Indeed the same scenario exists in the management of the overall quantities of electrical energy required for cooling during the vinification process. In this manner the decision-making is based on complex and ill-defined parameters including inevitable degree of uncertainties owing to incomplete understanding of the their underlying causing factors. As such, the dynamics of energy usage, their overall impact and interaction with environment system cannot be described using traditional mathematics because of its inherent complexity and ambiguity. Moreover, the concept of overall energy consumption can be described as polymorphous and fraught with subjectivity.

Therefore, it is appropriate to use fuzzy logic to predict the possible quantities of energy consumed using both qualitative and quantitative data as it does not require rigorous traditonal mathematical models, which are infact very difficult or impossible (as in this case) to build from the first principles. A fuzzy system is a nonlinear linguistic model mapping an input vector into a scalar output employing a set of rules formulated as IF-THEN statements using fuzzy logic (Mendel, 1973). The profound merit of employing fuzzy logic model in this problem domain rests on its ability to use several relevant knowledge bases to represent interactions and principles governing energy usage during the cooling process. The model has the ability to symbolically express inputs and outputs using linguistically specified terms such as: *High, Moderate, Very High, etc.* For any fuzzy-based model, it has two main components of the decision-making algorithm the knowledge base and the inference engine which have been discussed in some length in sections 3.2.3 and 5.5.4.

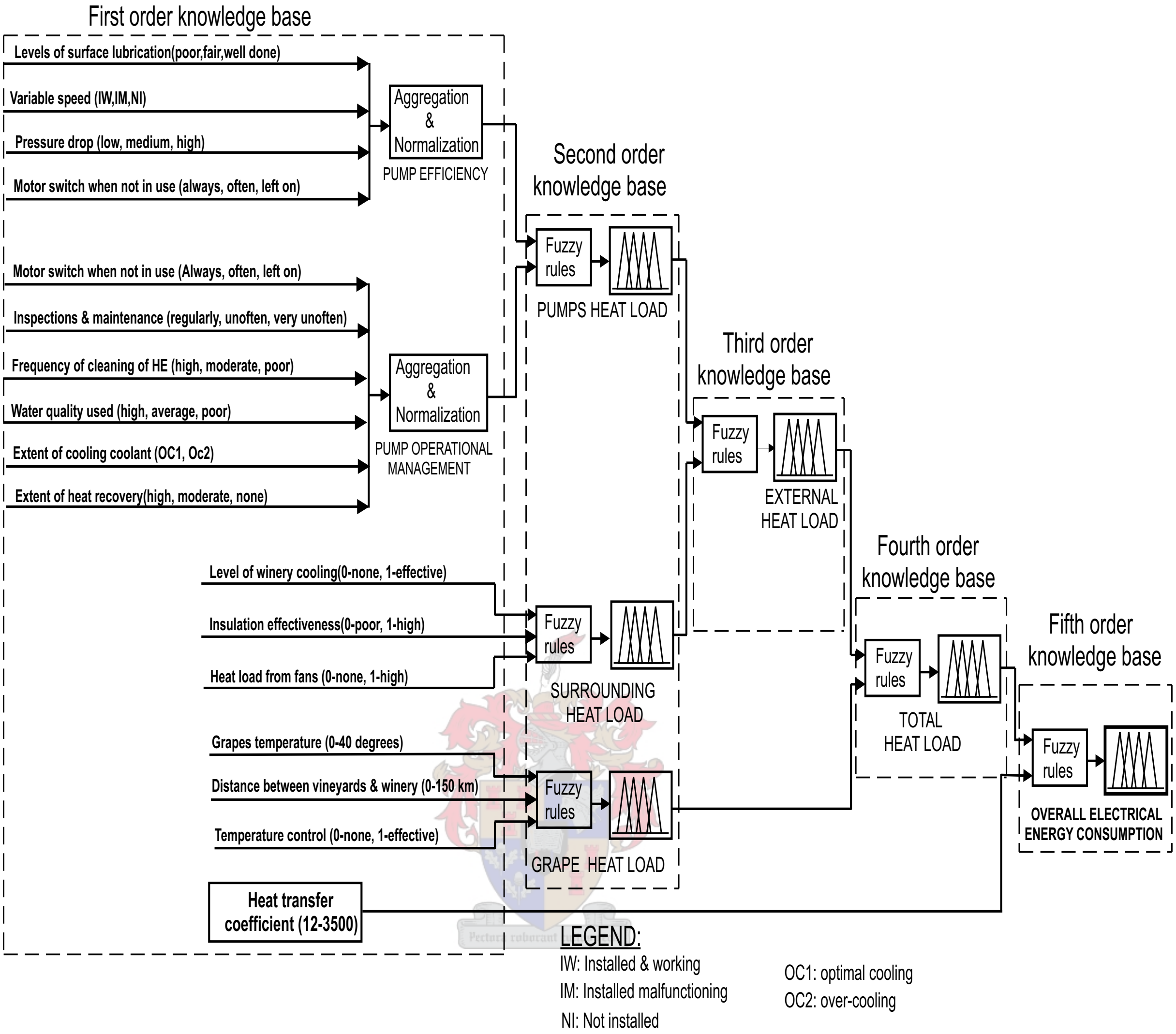

Figure 6.3: The hierarchial modular structure of the fuzzy logic expert system for the evaluation of energy minimization.

6.4.1 Knowledge Base

The knowledge base is the core of the system, and the breadth and quality of the knowledge determines the capacity of the system to render useful decision support. Hence the first stage in system construction was the knowledge acquisition in which the domain knowledge was extracted, refined and structured so that is amenable for the reasoning process. This was carried out progressively through a series of consultations with wine making experts as well as obtaining other information from reported literature. Figure 6.3

shows the hierarchically designed network of knowledge bases. In this case, the inputs were either provided by the user or were computed values from other knowledge bases. The knowledge expertise was modeled using IF-THEN rules. These fuzzy rules consist of two parts: an antecedent (hypothesis) part stating the conditions on the input variable (s); and a consequent (conclusion) part describing the corresponding values of the output variable(s).

The rules describe the heuristic knowledge about the behavior of the physical system, typically implying that, if a fact is known (the condition) then it is possible to infer or derive another fact regarded as a conclusion (consequent). The knowledge base contains the knowledge upon which a specific decision by the human expert is based on. In the knowledge base described here, it is delineated into energy minimization strategies in question format and the production rules.

6.4.2 Inference Mechanism

Basically, the fuzzy inference system (see discussions in section 5.5.4) consists of three conceptual parts: a rule base, a data base and a reasoning (inferencing) engine. The rule base contains the fuzzy rules while the data base defines the membership functions used in the fuzzy rules for transforming crisp input into a linguistic value. The linguistic value is the truth value that signifies the degree to which the numerical inputs belong to a fuzzy subset. This is done by matching each crisp input with associated membership functions. The reasoning mechanism performs the inference procedure upon the rules depending on specified input conditions and consequently derives the output(s).

In the process of reasoning, the input information or data may activate several rules simultaneously in the knowledge base where the antecedent parts of the fuzzy rules are evaluated to determine the final degree of fulfillment of that given rule. This clearly indicates the contribution of each rule to the fuzzy set of possible values to the overall output variable. The inference engine through conflict resolution mechanisms derives a single conclusion using the Mamdani-Assilian type reasoning model (Mamdani, 1977) using the facts and fuzzy rules in the knowledge base in deriving various conclusions on the basis of the user inputs.

6.5 Development of Fuzzy Expert System

The development of the fuzzy expert system comprise three major steps namely the knowledge acquisition, knowledge representation and design of the inference engine (Yager and Filev, 1994; Driankov et al., 1993). Fuzzy expert system uses fuzzy logic in expressing qualitative data in the knowledge base and as a reasoning mechanism to derive the system inferences (Dubois and Prade, 1980; Kandel, 1992). The design and the development of the fuzzy expert system as a decision tool for energy management at maceration stage was achieved through a number of phases. The fundamental phases that have been followed to build the prototype using the Fuzzy Logic Toolbox (The Mathworks, 2002b) integrated into MATLAB® (The Mathworks, 2002a) technical computing environment following the methodological outlines of Nunamaker et al., 1990 and Zadeh (1973).

The first five phases concentrate on the common procedure for developing the fuzzy inference which is designed such that a crisp solution is derived in any problem where the inputs are qualitative values and fuzzy numbers. This entail qualitative inputs of the user, aggregation of the fuzzy numbers derived from qualitative inputs, normalization of the input fuzzy numbers in their respective universes of discourse for each variable, a crisp-to fuzzy transformation (fuzzification), an inference mechanism that applies fuzzy rules, and a fuzzy-to-crisp transformation (defuzzification). The rest of the phases outline the final phases of system development and validation. Table 6.3 presents a list of all the system development phases.

Table 6.3: Summary of key fundamental phases of fuzzy expert system development.

Phase	Objective
1	Identification of key factors
2	Knowledge base development
3	Fuzzification of input and output variables
4	Generation of fuzzy inference
5	Defuzzification of fuzzy variables
6	Development of system conceptual framework
7	Develop a system architecture
8	System implementation and validation

6.5.1 Phase1: Identification of Key Factors

Knowledge acquisition is the first critical phase in constructing the fuzzy expert system as it determines the usefulness of the system based on the quality of data, information or knowledge acquired. Thus, at the initiation of this study, critical factors based on literature review and interviews with wine experts with regard to energy management were extracted, refined and structured into a format amenable for the reasoning process.

A common challenge in energy minimization studies is the large number of influencing factors, and especially where most of them are qualitatively quantified. However, by hierarchically structuring of the acquired knowledge in the first order knowledge base (see Figure 6.3), the first 9 of the 16 primitive identified factors were synthesized into two outputs through the aggregation and normalization processes. The aggregation process entailed the determination of the final user's responses by linearly adding the dimensionless scores assigned to each linguistic descriptive input. Next, the obtained values were normalized on a scale between zero (lowest level of output value) and one hundred (highest output value signifying the best system performance) for the input variables: pump efficiency and pump operational management.

Thus, the critical decision variables identified for the cooling process implemented in our fuzzy expert system to evaluate the second order knowledge base are grape temperature, temperature control, winery cooling, transportation distance between the vineyards and processing wineries, effectiveness of insulation of pipes and surfaces, pumps efficiency, heat from the cooling fans, pumps operational management and heat transfer coefficients. The pump efficiency and pump operational management variables were used in computing the heat load from the pumps in the second order knowledge base. Whereas, the grape heat load and the surrounding heat load were evaluated using the respective primary input factors as illustrated in the first order knowledge base in Figure 6.3.

6.5.2 Phase 2: Development of the Knowledge Base

The heart of computer-aided decision tool for the energy minimization during the vinification process is its knowledge base as it encapsulates the human expertise. It is important to note that knowledge base development is a crucial stage in developing decision tools. The objective was to formulate and refine the information and knowledge to be stored in the knowledge base. The most salient steps in developing the knowledge base are briefly described below.

(i) Development of the Membership Functions and Fuzzy Sets

The design of the membership functions is a significant step in developing a knowledge base for fuzzy expert systems. In formulating the qualitative fuzzy model (Sugeno and Yasukawa, 1993), the starting point was by defining the linguistic terms using membership functions. The membership function is used for mapping crisp input values into degrees of membership in the interval [0,1] (also referred as linguistic truth). Membership functions were designed such that they related directly to the individual rules encoded into the knowledge base.

Two membership distribution functions were used to represent the knowledge in this domain, the triangular and trapezoid shaped distribution functions. The inputs were trapezoidal shaped while the outputs had a mixture of both triangular and trapezoidal forms. Typical example of the input membership functions and fuzzy sets are schematically presented in Figure 6.4. Here, the confidence, μ, (where μ can be defined for any element in the interval 0 to 1 associated with a defined linguistic label) is plotted against the linguistic variable, ν^2. For instance, the grape temperature was decomposed into linguistic labels *Low, Medium, High* while the insulation variable was defined by the fuzzy sets *Poor, Fair, Good.* For both variables, their membership functions were represented using trapezoidal distributions as depicted in Figure 6.4.

A summary of the membership functions, their fuzzy variables and break points are provided in Table 6.4 which is based on the information and knowledge obtained in this problem domain from experts and reported literature. Note that the heat transfer coefficient values employed in developing this system were adopted from the reported literature in the wine industry after Boulten et al. (1998), Ellis (1977), and Cuevas and Chervan (1982).

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[2] Where ν can be temperature control, heat transfer coefficient, pumps efficiency, external heat load, etc.

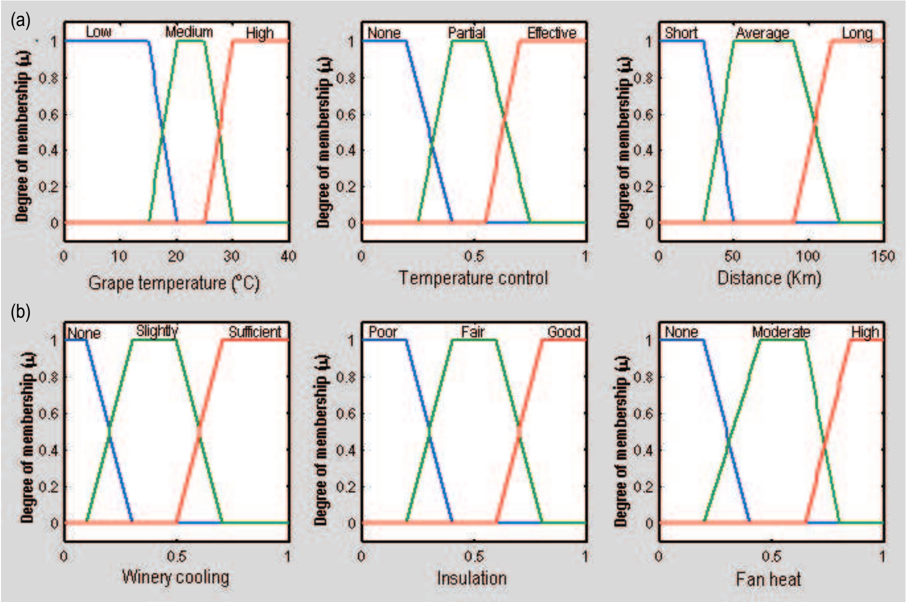

Figure 6.4: Typical examples of the membership functions defining the input fuzzy linguistic variables for the evaluation of: (a) Grape heat load and (b) Sorrounding heat load.

(ii) Construction of IF-THEN Rules

The IF-THEN rules define the relationship between the linguistic variables and their fuzzy sets, and are a critical step because they describe the heuristic knowledge about the behavior of the physical system. In that sense, the fuzzy rules serve to describe the quantitative relationship between variables in linguistic terms. The rule base specifies qualitatively how the output parameter "overall energy consumption" is determined after all the input parameters summarized in Table 6.4 are evaluated at different orders of the knowledge bases shown in Figure 6.3.

Several rule bases of varying complexity were developed at each level of the system hierarchy. The number of rules in any given rule base is a function of the linguistic input variables as well as the fuzzy set quantifiers in each variable. For instance, at the second order knowledge base, the three linguistic input variables: grape temperature, distance and temperature control each having three fuzzy set quantifiers yielded a knowledge base of 27 rules for the evaluation of grape heat load.

In each knowledge base, the continuous process of coding the IF-THEN rules, linking the input variables and output variable generated a three-dimensional surface plot in each

Table 6.4: Definition of the system input membership functions and fuzzy sets.

Input parameter	**Membership functions, their linguistic variables and break points.**
Grape temperature	V_{11}=V_{12}=0, V_{13}=15, V_{14}=20 (low), V_{21}=15, V_{22}=20, V_{23}=25, V_{24}=30 (medium), V_{31}=25, V_{32}=30, V_{33}=V_{34}=40 (high) (^{0}C)
Temperature control	V_{11}=V_{12}=0, V_{13}=0.30, V_{14}=0.40 (none), V_{21}=0.25, V_{22}=0.4, V_{23}=0.55, V_{24}=0.75 (partial), V_{31}=0.55, V_{32}=0.70, V_{33}=V_{34}=1.0 (effective)
Transportation distance	V_{11}=V_{12}=0, V_{13}=30, V_{14}=50 (short), V_{21}=15, V_{22}=30, V_{23}=60, V_{24}=80 (average), V_{31}=80, V_{32}=110, V_{33}=V_{34}=150 (long) (km)
Pump efficiency	V_{11}=V_{12}=0, V_{13}=20, V_{14}=40 (low), V_{21}=20, V_{22}=40, V_{23}=60, V_{24}=60 (medium), V_{31}=60, V_{32}=75, V_{33}=V_{34}=100 (high) (%)
Pump operational management	V_{11}=V_{12}=0, V_{13}=20, V_{14}=30 (poor), V_{21}=15, V_{22}=30, V_{23}=40, V_{24}=55 (fair), V_{31}=40, V_{32}=55, V_{33}=65, V_{34}=80 (good), V_{41}=65, V_{42}=75,V_{43}=V_{44}=100 (excellent) (%)
Fans heat	V_{11}=V_{12}=0, V_{13}=0.2, V_{14}=0.4 (none), V_{21}=0.20, V_{22}=0.45, = V_{23}0.65, V_{24}=0.8 (medium), V_{31}=0.65, V_{32}=0.85, V_{33}=V_{34}=1.0 (high)
Insulation levels	V_{11}=V_{12}=0, V_{13}=0.2, V_{14}=0.4 (poor), V_{21}=0.2, V_{22}=0.4, V_{23}= 0.6, V_{24}=0.8 (medium), V_{31}=0.6, V_{32}=0.8, V_{33}=V_{34}=1.0 (good)
Winery cooling	V_{11}=V_{12}=0, V_{13}=0.1, V_{14}=0.3 (none), V_{21}=0.1, V_{22}=0.3, V_{23}= 0.5, V_{24}=0.7 (slightly), V_{31}=0.5, V_{32}=0.7, V_{33}=V_{34}=1.0 (sufficient)
Heat transfer coefficients	V_{11}=V_{12}=0, V_{13}=300, V_{14}=500 (very low), V_{21}=400, V_{22}=600, V_{23}=800, V_{24}=1000 (low), V_{31}=800, V_{32}=1100, V_{33}=1500, V_{34} =1800 (moderate), V_{41}=1500, V_{42}=1800, V_{43}=2300, V_{44}=2500 (high), V_{51}=2300, V_{52}=2500, V_{53}=V_{54}=3500 (very high) (W/m^2/K)

module. The surface plot described the behavior of the input variables at any point of the fuzzy model. Therefore, each 3D plot visualized the transfer characteristics between two input variables and one output variable at a time. Examples of three-dimensional plots illustrating the response surface at any point in the evaluation of grapes heat load, surrounding heat load, total heat load, and the overall energy consumption are presented in Figure 6.5. The graphical result has the merit of working with only two linguistic variables at a time. An illustration on the influence of each input variable to a specific module output is discussed using a case study in appendix D.

Assuming that only one linguistic variable defines each input parameter shown in Table 6.4, the IF-THEN rules must describe the relation among the nine variables with their respective fuzzy sets. It became apparent that two different approaches were possible in designing the IF-THEN rules and subsequently representing them in the knowledge base. The first option was to involve the construction of an all en-compassing set of rules com-

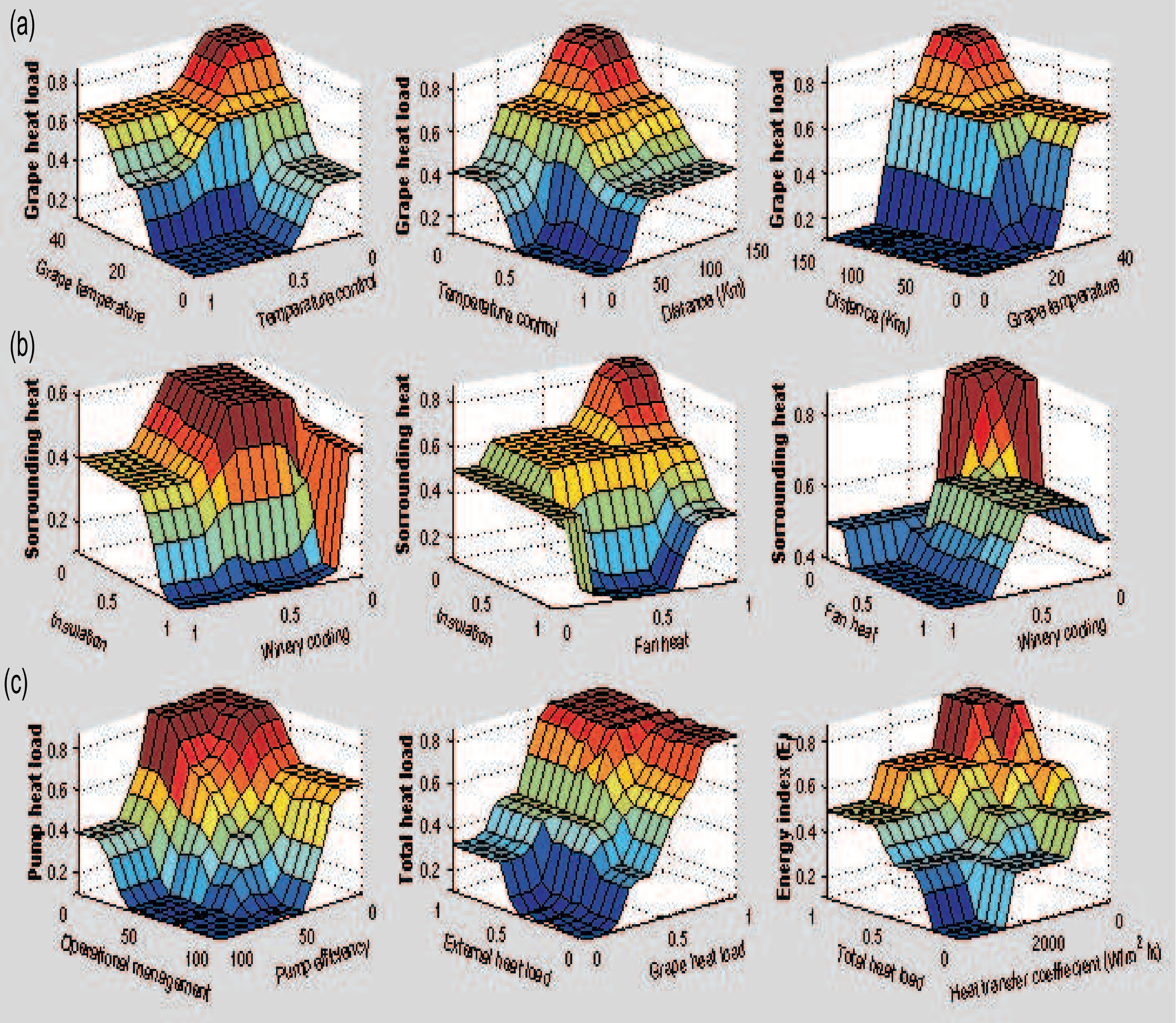

Figure 6.5: 3D graphical response surfaces describing the relationship between two linguistic input variables and the output variable as modeled by the fuzzy model for: (a) Grape heat (b) Surrounding heat (c) Pump heat, Total heat, Overall energy index.

bining all the nine linguistic variables at the same time to determine the possible overall energy requirement. Implementing this option required the development of an extremely large number of rules[3], which posed several problems. In all likelihood, the knowledge rule base was difficult to construct and modify, required an exhaustive testing procedure in ensuring the system accuracy, and owing to the large number of rules would make the system difficult to understand. Therefore, the first approach in effect was suspended as it was virtually impossible to manage such a large rule base effectively.

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[3] The possible maximum number of rules could be 43,740 ($3^7 \times 4 \times 5$).

An alternative approach was therefore, proposed and employed in this study, where the knowledge rule bases were constructed from a series of smaller and more compact modules. This approach entailed construction of independent knowledge rule bases that were smaller, resulting in more compact modules. The approach yielded simpler and fewer rules because only two or three variables were analyzed at the same time. It also enhanced the combination of two or more individual modules with ease as illustrated in Figure 6.3. Finally, it had the merit of having the potential to produce customized versions of the knowledge rule bases aimed in satisfying specific winery constraints such as the production schedules.

Each independent knowledge module has a specific and specialized task. In Figure 6.3, a simplified structure depicting how the knowledge bases were arranged in a cascade is provided. For instance, the heat load from the pumps was evaluated using the linguistic input variables pump efficiency and pump operational management modeled by the fuzzy model. The knowledge base module contained 12 rules that were used for computing the pump heat load from the two linguistic input variables.

Similarly, the approach was adopted in determining the heat loads from the surroundings and the grapes based on various primary fuzzy linguistic input variables. The external heat load demanding refrigeration was calculated using the second order knowledge base outputs: the pump heat load and surrounding heat load as the new input variables. By repeating this cascading modular approach, the total quantity of energy required for cooling the wine juice and must at the maceration stage was computed using a cumulative sum of 115 rules.

Note that the total number of rules used in this system only account for the rules embedded in various knowledge bases after insignificant and unrealistic ones were discarded. For instance, in deriving the fuzzy rules for the evaluation of the effective surrounding heat load, certain heuristics were considered. The reason was to ensure that only rules that represent realistic scenarios were coded into the knowledge base, and those found impermissible and contradictory be pruned off. As a result, the rules in the surrounding heat load module were pruned from 27 to 15. The heuristics used to ensure consistency in pruning the rules in the surrounding heat load knowledge base were as follows:

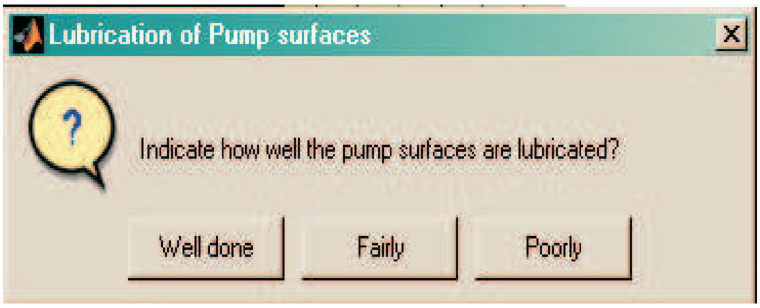
1. Winery cooling does not exist (*none*) in a given winery but then a rule asserts that the heat from the cooling fans can assume the fuzzy set values: *average* or *high*. This contradicts the fact that the fans cannot be working while there is no winery cooling being noted. In this sense, such rules were viewed as impermissible.
2. If there is winery cooling and the efficiency of the cooling fans in no way can be 100%, then the heat from the fans cannot be described as *none*. In such a scenario, if the winery cooling is said to be *effective* or *slightly*, then the heat from the fans cannot be in any way be regarded as *none*.

The second approach made our fuzzy expert system easy to construct, maintain, modify, and refine with ease, and having the ability to test each module independently before its incorporated into the final knowledge base structure. In addition, various modules were easily linked or one module could be able to access another module's calculated value that it required for its functioning. The first two merits lead to the third merit in that, the system developed can be rapidly customized to individual wineries to satisfy their specific operating conditions. This offered flexibility such that new knowledge can be added to the system without reconstructing the entire knowledge bases.

(iii) Construction of Question-Answer Interface Modules

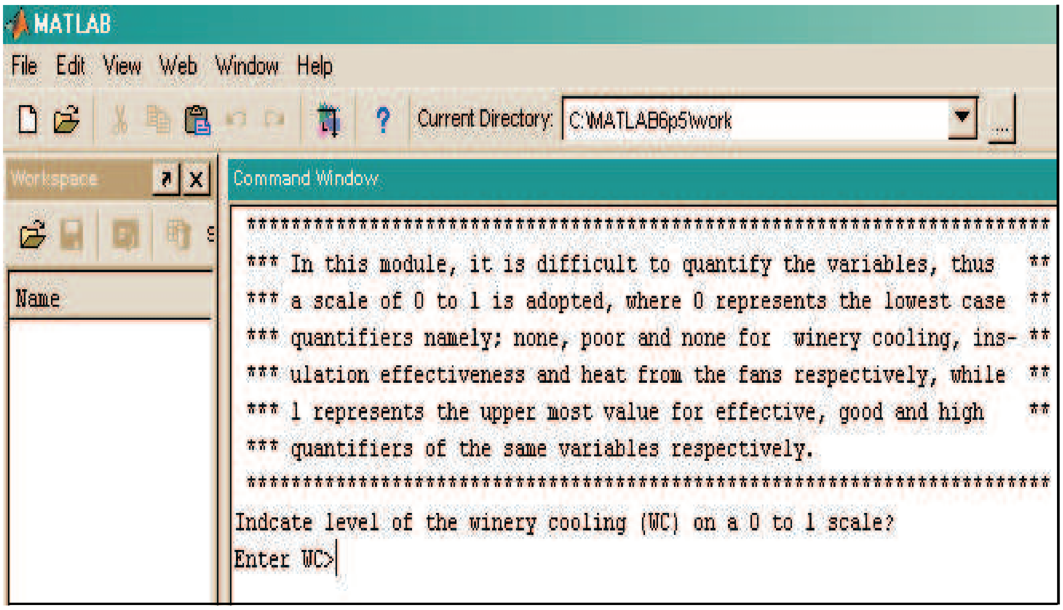
With question-answer design, the system interrogates the user by posing a series of questions. In this system, the question modules were linked to the second order knowledge bases having fuzzy rules. In each module, the user could express the response either in qualitative or quantitative terms. For the qualitative responses, the user had to indicate an answer from a set of three possibility choices posed by the system. A typical pop-up menus for the qualitative question-answer interface is shown in Figure 6.6. On the other hand, the quantitative values were within a specified range using as interface of the form shown in Figure 6.7. For example, the system could only accept user values that were within 0 and 1 for the qualitative linguistic inputs: winery cooling, fan heat and insulation while the heat transfer coefficient was defined within a universe of discourse of 0 W/m^2/K and 3500 W/m^2/K.

The question-answer modules were designed to obtain the input data for the determi-



Indicate how well the pump surfaces are lubricated?

Figure 6.6: An example of a man-machine communication interface for facilitating system acquisition of fuzzy qualitative information.



Current Directory: C:\MATLAB6p5\work

```
************************************************************************
*** In this module, it is difficult to quantify the variables, thus    **
*** a scale of 0 to 1 is adopted, where 0 represents the lowest case   **
*** quantifiers namely; none, poor and none for  winery cooling, ins-  **
*** ulation effectiveness and heat from the fans respectively, while   **
*** 1 represents the upper most value for effective, good and high     **
*** quantifiers of the same variables respectively.
************************************************************************
Indcate level of the winery cooling (WC) on a 0 to 1 scale?
Enter WC>
```

Figure 6.7: A window for facilitating quantitative data acquisition from the command line.

nation of the heat loads from the primary sources and also the heat transfer coefficient value for the heat exchanger under consideration. To obtain a crisp output to each user's qualitative response, each choice was assigned a dimensionless score. An illustrative example is provided in Table 6.5 for the evaluation of pump efficiency for various qualitative user inputs. In this submodule, all the best qualitative alternative choices were assigned equal scores (5). However, the alternative choices having lower scores signifies their relative impact to the overall pump efficiency. For instance, in considering a given pump, if the system scores constitutes the best scenarios, then the pump efficiency is rated as high.

Table 6.5: The experts' assigned dimensionless scores to the qualitative linguistic responses for evaluating the pumps efficiency.

Questions	**Qualitative description of user responses**	**Assigned dimensionless scores**
How well are the pump surfaces lubricated?	Well done	$PE_1=5$
	Fairly	$PE_1=2$
	Poorly	$PE_1=1$
Describe variable speed drives installations on pumps to reduce load on motor.	Installed & well functioning	$PE_2=5$
	Installed & malfunctioning	$PE_2=2$
	Not installed	$PE_2=0$
To what extent is the pressure drop due to biofouling?	Low	$PE_3=5$
	Moderate	$PE_3=3$
	High	$PE_3=1$
Are the motors switched off when they are not in use?	Always off after use	$PE_4=5$
	Often off after use	$PE_4=3$
	Often left on after use	$PE_4=0$

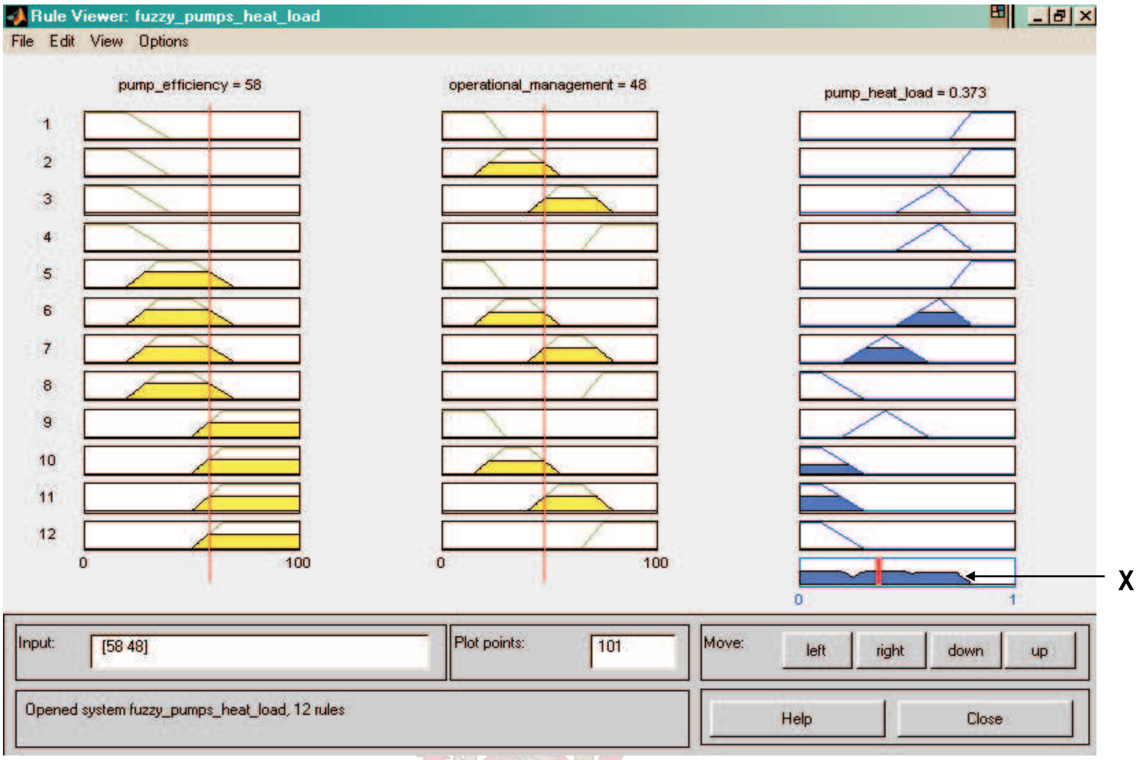
6.5.3 Phase 3: Fuzzification of Variables

Fuzzification refers to the mechanism where crisp numerical input values are converted into a degree of membership, μ, which is always in the interval 0 to 1 in the qualifying linguistic set(s). To quantify a given a crisp numerical input value into a given set(s), the degree of membership in each set is calculated. In cases where μ=0, implies that the crisp value does not belong to that set while where the calculated degree of membership falls in the range $0<\mu\leq1$, then the input value is described as partially or fully represented in that given fuzzy set.

The fuzzified values are calculated by intersecting the crisp input value to the fuzzy set associated with each linguistic label. For example, if the crisp input value for the pump efficiency is 58%, then it has a membership degree of 0.600 to the fuzzy set 'medium' and 0.533 to the fuzzy set 'high' (see Figure 6.8). These two values are as a result of the overlapping of the fuzzy sets for the pump efficiency linguistic variable.

6.5.4 Phase 4: Generation of Fuzzy Inference

Each knowledge base in the fuzzy model uses IF-THEN rules and approximate reasoning to compute a specific heat load or the overall energy consumption from its fuzzy linguistic input components. To generate fuzzy inference, first the crisp input values are



Rule Viewer: fuzzy_pumps_heat_load

pump_efficiency = 58

operational_management = 48

pump_heat_load = 0.373

Input: [58 48]

Plot points: 101

Opened system fuzzy_pumps_heat_load, 12 rules

Figure 6.8: Generation of fuzzy inferencing using Mamdani-Assilian model for assessing the quantity of heat load from the pumps with input values 58% and 48%, for the input variables pump efficiency (PE) and operational management efficiency (OME) respectively to obtain the output variable, pump heat load (PHL), through implication, aggregation and defuzzification processes using MAX-MIN method (Mamdani, 1975; Mamdani and Assilian, 1999).

fuzzified for each linguistic variable as their membership functions are piecewise linear and thus, can be numerically computed using Equation 5.22.

Fuzzy inference operates via the fuzzy rule(s) in the knowledge base whose conditions have been partially or wholly satisfied by the crisp input values. Several methods of inferencing are used in practice, but two of the most popular methods are the so called MAX-MIN and the MAX-DOT or MAX-PROD method. In this case, the standard MAX-MIN inference algorithm (Mamdani) was used in the fuzzy inference process, where the degrees of fulfillment of the fuzzy rules in question were computed as the minimum of the corresponding degrees of membership (see discussion presented in chapter 3).

The MIN operation was used for the AND conjunction (set intersection) to determine the minimum area under the clip line in the consequent part of each rule. The

CF values stated for each rule signifies the support under which the truth of the rule can be ascertained. The product of the CF values and the rule output obtained through MIN operation yields the final fuzzy output for the fulfillment of that given rule. As an illustration Rule 10 in Figure 6.8 is evaluated as follows:

Rule 10: IF *PE* is *High* (μ=0.533) AND
OME is *Fair* (μ=0.467)
THEN *PUMP HEAT LOAD* is *Small* (CF=0.75)
EVALUATION: MIN (0.533, 0.467)= 0.467
EFFECTIVE RULE SUPPORT: CF × MIN (0.533, 0.467) =0.75 × 0.467=0.35

Similarly, the rule evaluation was done for each rule whose conditions have been partially or fully satisfied by the two crisp input values; PE=58% and OME=48% for the linguistic variables pump efficiency (PE) and operational management efficiency (OME), respectively. The clipped membership functions resulting from application of AND operation on the IF part of each rule (R6, R7, R10, R11) calculates the truth value of individual rule.

To combine the results of all fired rules into a single truth value, the union of the individual rule meanings were aggregated together using the MAX (OR disjunction) operation (Driankov et al., 1996) in accordance with Equation 3.5 which selects the maximum output for each fuzzy set in the consequent part of each rule being evaluated. The resultant total area (marked as X) in Figure 6.8 represents the fuzzy outcome from the evaluation of the pump heat load based on the user crisp input values.

6.5.5 Phase 5: Defuzzification of System Outputs

After the fuzzy inference process is complete the resulting data for each output of the fuzzy classification system are a collection of fuzzy sets or a single aggregate fuzzy set. To obtain a single numerical crisp output value that best represents the outcome of the fuzzy set evaluation; the fuzzy output has to be defuzzified. Several methods for defuzzification have been discussed by various authors in the literature (Mamdani, 1974; Yager and Filev, 1993; Braae and Rutherford, 1978; Hellendoom and Thomas, 1993; Mazumoto, 1995). These include mean of maximum, bisectrix method, centroid method, and the average height methods, just to mention a few.

However, in this study the centroid method was used to defuzzify the fuzzy set obtained after the aggregation process. By employing this method, the entire fuzzy number obtained during the aggregation process is gathered in one value. This is achieved by computing the centroid value of the final aggregate shape area shown in Figure 6.8 marked X.

In this study the defuzzified numerical values serve two purposes. Firstly, the defuzzified values from the primary heat load sources were used as secondary system inputs to compute external heat load and the total heat load (see Figure 6.3 showing the hierarchical structuring of various heat loads under several orders of knowledge bases) requiring refrigeration. Secondly, the defuzzified value in the fifth order knowledge base is interpreted as an index representing the quantity of energy consumption during the maceration process. In that sense it helps to classify the quantity of electrical energy consumption using the fuzzy set theory in the universe of discourse 0 (zero) (minimal energy consumption) to 1 (one) (highest energy consumption). The significance of the latter function is that it represents the integrated overall performance of the entire processes prior and during the maceration stage cooling process in an attempt to minimize energy consumption.

6.5.6 Phase 6: Development of System Conceptual Framework

The conceptual framework described in this study was aimed at achieving two aspects. First, it envisaged a design model that facilitated the handling of large amount of diverse, qualitative, incomplete, imprecise and nonstatistical knowledge that is essential in minimizing energy consumption during the cooling process at the maceration stage. The second aspect relates to the need of having a system characterized by flexibility to accommodate changes such as: modification of linguistic variables, changing of fuzzy rules or redefining of the fuzzy sets. Moreover, the system should be able to allow future expansions which are transferable in the system architecture through the creation of new objects without re-doing the entire code.

To accomplish these two principal aspects, a modular approach in designing the system was employed. This led to the representation of knowledge in a number of compact and independent modules where each performed specific and specialized tasks. Two forms of modules were found sufficient for knowledge representation in a format amenable for automation namely; the fuzzy rule type module and the question-answer type module.

- The fuzzy rule type module using the fuzzy logic concept focused on evaluating the user inputs in determining various heat loads and ultimate energy consumption. On the basis of the user inputs, the system has the ability to advise on the possible energy consumption comprising of five scenarios namely: *Very Low, Low, Moderate, High, Very High*. An example of the functioning of the fuzzy model is depicted in Figure 6.9.

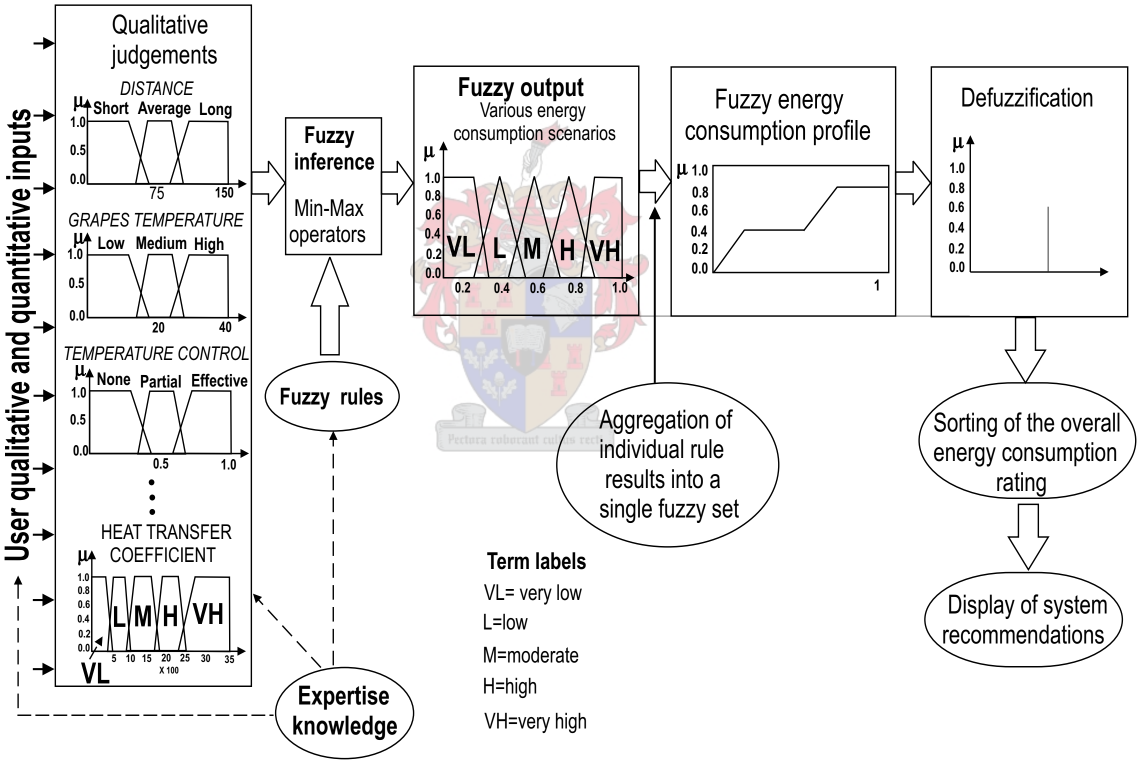


Figure 6.9: The schematic structure of the fuzzy logic reasoning inference process.

- The question-answer module contained the expertise knowledge regarding the practices and conditions that govern the energy consumption at the maceration stage. Owing to the design of the submodules in this module, the user is able to enter qualitative or quantitative data into the system facilitated by graphical interfaces in Figures 6.6 and 6.7, respectively. The input data is essential in triggering the operations at the fuzzy rule type module. This makes it possible to evaluate the energy consumption based on the described user operating scenario.

6.5.7 Phase 7: Construction of the System Architecture

A good system architecture provides a road map for the system building process, by putting the system components into perspective, defining the functionalities of the system components and the manner in which they interact with one another (Nunamaker, 1993). On the basis of the conceptual framework discussed in *Phase 6* (see section 6.5.6), the architecture of the developed fuzzy expert system for the evaluation of energy minimization comprised three components: (i) a knowledge base, (ii) a fuzzy inference engine, and (iii) a user interface.

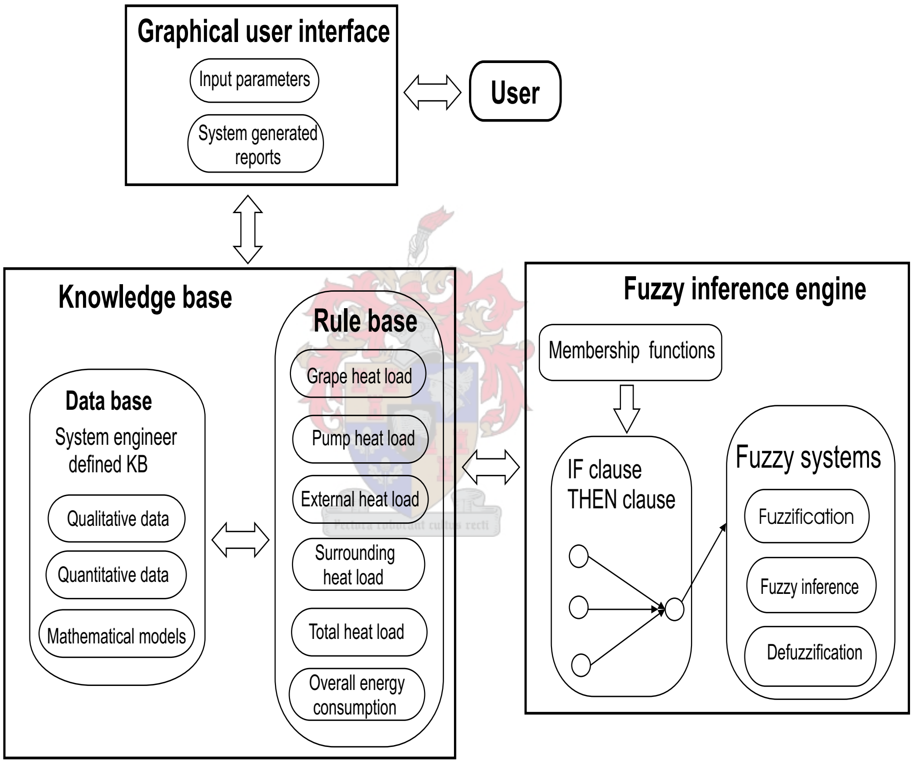


Figure 6.10: Fuzzy logic expert system functional architecture for energy minimization during the cooling process at the maceration stage.

Comprehensive discussions of each component are similar to those presented in section 5.6 and only key aspects that are of relevance to case study on energy minimization are presented in this section. Figure 6.10 illustrates the core components of the fuzzy logic expert system. A brief description of individual components is as follows:

(a) Knowledge Base

The knowledge base contains the database and the fuzzy rule base. The fuzzy rule base is a mechanism of storing fuzzy rules as expert knowledge using membership functions. The membership functions are important as they represent different linguistic qualitative terms. Different set of rules were used to compute certain specific outputs at various stages of diagnosing the energy minimization problem.

The treelike network of knowledge bases used in this study to compute the quantity of electrical energy is shown in Figure 6.3. The number of fuzzy rules in each set (as indicated on the parentheses) are: pumps heat load (12), surroundings heat load (15), external heat load (16) after combing the pump heat load and the surroundings heat load, grape heat load (27), total heat load (20) and the index of electrical energy consumption (25).

The database on the other hand, comprised qualitative and quantitative data crucial for evaluating processes and procedures that govern the cooling energy demand. It also contained mathematical linear models for the averaging and ultimate normalization of the qualitative inputs into their respective universes of discourse before being fed into the fuzzy model. It should be noted that the obtained scores in the defined universes of discourse represented the level of energy conservation impact associated with the input variable under question.

(b) User Interface

The graphical user interface (GUI) provides an effective interactive tool between the user and the system. To perform any analysis for the energy minimization, the user provides the system initialization values through the GUI. This was accomplished via the command line of the MATLAB® software technical computing environment as shown in Figure 6.7 or through a dialog-interface carried though a pop-up menus presented in Figure 6.6. In that way, the system was able to interrogate the user via a set of questions.

The GUI was also used as a base to enter and edit the knowledge into the system, and guide the user through various stages of synthesizing processes and operations that governs energy minimization prior and during the cooling process at the maceration stage. To achieve this, the GUI displays various possible operating conditions so that the user can indicate the choice(s) that defines the facility under consideration.

Upon the system acquisition of all the required inputs, the inference engine and the database in the knowledge base facilitated the system evaluation of the final state of energy consumption on the basis of conditions and operations specified by the user. The user inputs are evaluated by the system at the inference engine using the fuzzy rules, membership functions and other data in the knowledge base, and then recommendations are communicated as system outputs to the user through the graphical interface. Examples of system recommendation outputs will be presented in section 6.6.

(c) The Inference Engine

This is a core part of the fuzzy expert system that executes the inferencing of the fuzzy rules and resolving the order in which the rules are fired depending on specified user inputs via rule conflict-resolution mechanism. The functionalities and operations during the inference process are similar to those presented in section 5.6.4.

6.5.8 Phase 8: System Implementation and Validation

The prototype fuzzy expert system resides in the intelligent system development tool, MATLAB® fuzzy logic tool box integrated with MATLAB technical computing environment on a Microsoft Windows™ 2000 environment based Pentium PC. This tool box was selected because it can run on a PC under Microsoft Windows™. Secondly, the tool is a high level, object-oriented multi-paradigm programming language and hence proved effective in representing diverse domain knowledge in hierarchical format in the knowledge base. The system has a user-friendly Graphical User Interface (GUI) through which it displays via pop-up menus questions to the user and other information on the command environment to facilitate easy interaction the system.

Various modules were easily interlinked to enhance communication between them and improve the process of evaluating user inputs. The system provided the outputs via the graphical user interface.

The prototype fuzzy expert system is currently undergoing a validation process by developers and domain experts. Through this process, the knowledge in various modules is being tested for accuracy and completeness. The cyclic process of testing the system software and implementing the changes recommended by the users are envisaged to make the decision tool robust so as to meet the needs of the targeted users. Therefore, the system is intended to assist the users to comprehend how multi-decisions, operations, and processes prior and during the wine cooling process at maceration stage influences the overall quantity of energy required per given throughput.

6.6 Results and Discussions

Four examples are presented to illustrate the results generated from the prototype fuzzy expert system discussed in this chapter. The purpose of performing energy conservation under four scenarios was to observe differences in the final fuzzy results owing to differing contributions of variant operating conditions. This in a way also demonstrated the system capabilities under various user inputs underlying different operational conditions and other parameters. In addition, it is important to note that the core theme of these examples shows how an integrated approach on energy management provides a more robust solution under the constraint of limited or nonexistence of quantitative data. A key element in achieving this theme was through the utilisation of knowledge based on human reasoning, concept formulation, and decision making using words for an imprecisely defined problem (Zadeh, 1996b).

Table 6.6 provides a summary of the user inputs which are both qualitative and quantitative. In column 1, the user inputs in numbers 1 to 4 entail the evaluation of the pump efficiency from qualitative inputs, while numbers 4 to 9 establish the operational management of the pumps efficiency leading to and during the actual cooling process. The qualitative computed fuzzy numbers are used to evaluate the quantity of heat load owing to pumps that requires refrigeration as well.

On the other hand, numbers 10 to 12 provide quantitative input values for the determination of surrounding heat load, while 13 to 15 are the inputs facilitate the computation

Table 6.6: User data inputs for the worked examples.

	User required information inputs	**Example 1**	**Example 2**	**Example 3**	**Example 4**
1.	Levels of surface lubrication (poor, fair, well done)?	Fair	Poor	Well done	Well done
2.	Variable speed installation pumps (installed & working well (IWW), Installed & malfunctioning(IM), not installed (NI))?	IWW	NI	IM	IM
3.	What is the pump pressure drop due to biofouling (low, moderate, high)?	Moderate	Moderate	High	High
4.	Indicate frequency of pump switch-off of motors after use (always off, often off, left on)?	Left on after use	Often off after use	Always off	Always off
5.	Frequency of inspections and maintenance of pumps (regularly, unoften, Very Unoften (VU))?	VU	VU	Regular	Regular
6.	Frequency of cleaning heat exchangers (high, moderate, low)?	High	Low	High	High
7.	Quality of water used for cleaning heat exchangers (high, average, poor)?	Average	High	Average	Average
8.	Extent of cooling the coolant (very low temperature, optimal temperature)?	Optimal temp.	Very low temp.	Optimal temp.	Optimal temp.
9.	Extent of heat recovery implementation in facility (high, moderate, none)?	High	None	Moderate	Moderate
10.	Levels of winery cooling (0-none, 1-effective).	0.2	0.5	0.8	0.8
11.	Effectiveness of insulation of pipes and surfaces (0-poor, 1-good).	0.6	0.35	0.2	0.2
12.	Quantity of heat load from cooling fans (0-none, 1-high).	0.4	0.75	0.3	0.3
13.	Temperature of the grapes at the time of harvesting (Range 0-40 ^{0}C).	27	30	15	15
14.	Distance between winery and the vineyards (Range 0-150 km).	18	67	10	10
15.	What is the extent of temperature control immediately after harvesting and during the transportation process? (0-none, 1-effective).	0.4	0.4	0.5	0.5
16.	Heat transfer coefficient of the heat exchanger (Range 0-3500 W/m^2/K).	850	60	2750	60

of grape heat load. The input number 16 together with the system total heat load determined from inputs 1 to 15 are used as fuzzy input variables in evaluating the overall energy requirement index for a given throughput since the time of harvesting to the end of the first cooling process at the maceration stage. In the following paragraphs, each example is discussed to illustrate the application of the fuzzy model developed in this study as a support decision-making tool with respect to energy minimization.

I: Example 1

Once the user inputs are coded into the system, a number of computations are carried out by the system to ensure the acquired knowledge is amenable for the reasoning process. From the input values in example 1, given in Table 6.6, together with system computed output results presented in Table 6.7, it can be argued that, to mitigate the high energy consumption the pump efficiency needs to be improved. This can be achieved through several ways. For instance, by lubricating the pump surfaces well, switching off the pumping machines immediately after use, using either one or both physical and chemical means to check the biofouling growth in pumps and pipes surfaces, amongst others.

The high heat load from the surroundings can be reduced substantially by managing the winery cooling effectively since the user input indicates that it is inadequately done. One way can be through the installation of high efficient cooling fans. Note that though the heat load from the pumps can be regarded as moderate, the net external heat load was computed as high because of high surrounding heat load.

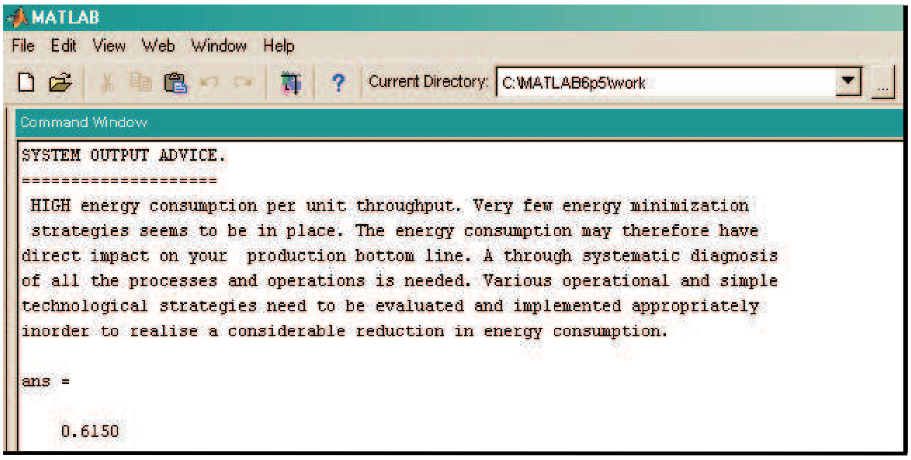
Table 6.7: Analysis results evaluated based on the inputs of example 1 in Table 6.6.

PE[a] **(%)**	**OME**[b] **(%)**	**PHL**[c] **Index**	**SHL**[d] **Index**	**EHL**[e] **Index**	**GHL**[f] **Index**	**THL**[g] **Index**	**TEC**[h] **index**	**System recommendation on energy usage**
50	66.1	0.376	0.608	0.650	0.422	0.475	0.61497	HIGH

---

[a] Pumps efficiency
[b] Operational management efficiency
[c] Pumps heat load
[d] Surrounding heat load
[e] External heat load
[f] Grape heat load
[g] Total heat load
[h] Total energy consumption

Furthermore, on the basis of the user input heat transfer coefficient value, it appears that the shell and tube or spiral heat exchanger was used in cooling the wine juice and must. As such, the heat transfer coefficient value is relatively low and forced the system to result in high energy consumption in order to cool the throughput to the desired product temperature. However, owing to the high capital investment requirement for replacing the heat exchangers, the most cost effective approach in mitigating the high energy consumption is via the improvement of operational-oriented strategies. Such strategies will in no doubt reduce the cooling load per unit throughput at minimal costs. The system recommendations after evaluating the user inputs of example 1 are presented in Figure 6.11.



```
SYSTEM OUTPUT ADVICE.
====================
 HIGH energy consumption per unit throughput. Very few energy minimization
 strategies seems to be in place. The energy consumption may therefore have
direct impact on your  production bottom line. A through systematic diagnosis
of all the processes and operations is needed. Various operational and simple
technological strategies need to be evaluated and implemented appropriately
inorder to realise a considerable reduction in energy consumption.

ans =

    0.6150
```

Figure 6.11: The system feedback recommendation based on the user inputs provided in example 1 with overall energy consumption evaluated as HIGH.

II: Example 2

The second worked example mirrors a scenario where little attention is given in mitigating against high energy consumption during harvesting, transporting, and cooling processes. Evidence of this observation lies in the low values of the pump and operational efficiencies determined from the user data inputs shown in Table 6.6. As such, the computed indices for the pumps and surrounding heat loads are moderate to large and medium to high as depicted in Table 6.8, respectively. The net effect is a very high energy demand for the refrigeration tonnage owing to the external heat load sources.

The grape heat load is high as the grape harvesting appears to have occurred at high ambient environmental temperature. Moreover, the grapes seemingly have been transported over a reasonable distance but with little attention to manage the grape heat load during the transportation process. On the account of these described conditions and operational realities, the fuzzy logic expert system computed the grape heat load as high.

Table 6.8: Analysis results evaluated based on the inputs of example 2 in Table 6.6.

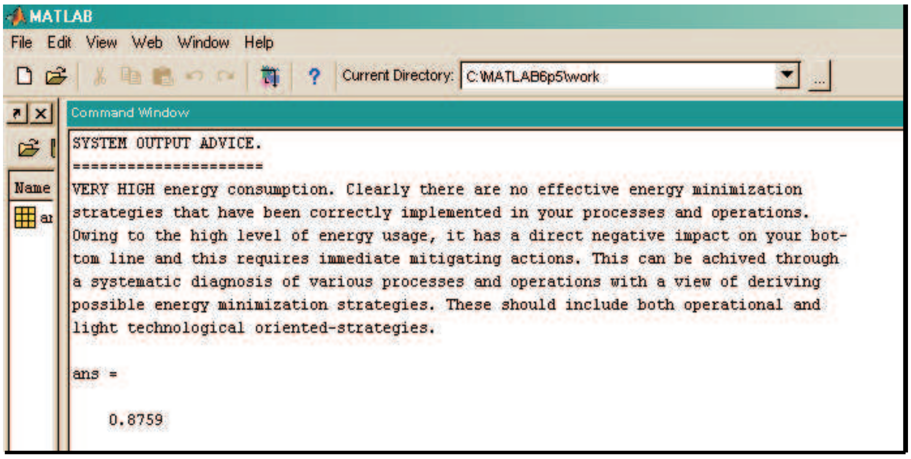
PE[a] (%)	**OME[b] (%)**	**PHL[c] Index**	**SHL[d] Index**	**EHL[e] Index**	**GHL[f] Index**	**THL[g] Index**	**TEC[h] index**	**System recommendation on energy usage**
33.3	50	0.574	0.682	0.831	0.633	0.849	0.87588	VERY HIGH

---

[a] Pumps efficiency
[b] Operational management efficiency
[c] Pumps heat load
[d] Surrounding heat load
[e] External heat load
[f] Grape heat load
[g] Total heat load
[h] Total energy consumption

As a result of the high cooling loads originating from the grapes and external heat sources, the resultant total heat refrigeration load was evaluated as very high. On the other hand, the heat exchanger used for cooling the wine juice and must has a very low heat transfer coefficient. From these data, the most likely heat exchangers employed in this run are tank jackets which are characterized by poor heat transfer. Thus, to compensate their ineffectiveness and maintain the required wine temperature, very low refrigerator temperatures were employed to provide adequate cooling.

Therefore, in view of the cumulative effect of high cooling demand from various heat load sources coupled with inefficient heat exchangers accounted for the overall very high energy demand during the refrigeration process. The system recommendations after evaluating the conditions and operations specified by the user in example 2 are shown in Figure 6.12. It is significant to note that through integrated improvement of operational procedures coupled with low cost technological modifications without replacing the heat exchangers, the energy demand can be reduced from very high to moderate (see for instance example 4).



```
SYSTEM OUTPUT ADVICE.
=====================
VERY HIGH energy consumption. Clearly there are no effective energy minimization
strategies that have been correctly implemented in your processes and operations.
Owing to the high level of energy usage, it has a direct negative impact on your bot-
tom line and this requires immediate mitigating actions. This can be achived through
a systematic diagnosis of various processes and operations with a view of deriving
possible energy minimization strategies. These should include both operational and
light technological oriented-strategies.

ans =

    0.8759
```

Figure 6.12: The system feedback recommendation based on the user inputs provided in example 2 with overall energy consumption evaluated as VERY HIGH.

III: Examples 3 and 4

These two examples are intended to illustrate how well managed operational processes and use of efficient heat exchangers impacts the energy consumption positively per unit throughput during the cooling process. In view of the user responses in Table 6.6 the following observations can be drawn:

- Both pump and operational efficiencies are high owing to effective integrated operations and processes management coupled with low technological modifications on the equipments.
- Winery cooling is effective (high) and the heat from the fans is low though the insulation of the transfer pipes and equipments can be described as poor.
- The grapes were harvested at low ambient temperatures, i.e. under 20°C and transported over a short distance under adequate temperature control.

Under the above described operating conditions, the heat loads from pumps and surroundings were evaluated as very low and medium, respectively. Using the pumps and surrounding heat loads as new fuzzy model inputs, the external heat load was evaluated as low. In the case of grape heat load, it was found to be low in accordance with the user inputs provided in Table 6.6. In the fourth order knowledge base, the total cooling load demanding refrigeration turned out to be very low as well. The system computed results are presented in tabular format in Tables 6.9 and 6.10 for examples 3 and 4, correspondingly.

Table 6.9: Analysis results evaluated based on the inputs of example 3 in Table 6.6.

PE[a] **(%)**	**OME**[b] **(%)**	**PHL**[c] **Index**	**SHL**[d] **Index**	**EHL**[e] **Index**	**GHL**[f] **Index**	**THL**[g] **Index**	**TEC**[h] **index**	**System recommendation on energy usage**
66.7	85.7	0.1056	0.400	0.350	0.11597	0.1163	0.1141	VERY LOW

---

[a] Pumps efficiency
[b] Operational management efficiency
[c] Pumps heat load
[d] Surrounding heat load
[e] External heat load
[f] Grape heat load
[g] Total heat load
[h] Total energy consumption

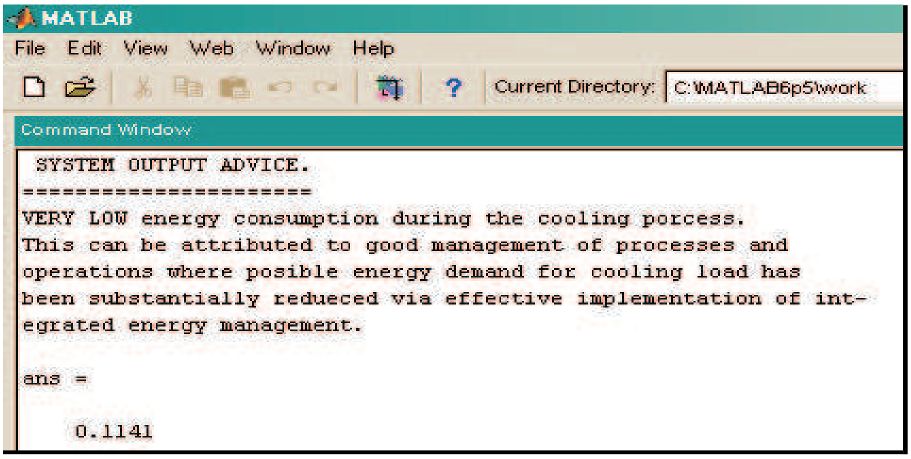
Table 6.10: Analysis results evaluated based on the inputs of example 4 in Table 6.6.

PE[a] **(%)**	**OME**[b] **(%)**	**PHL**[c] **Index**	**SHL**[d] **Index**	**EHL**[e] **Index**	**GHL**[f] **Index**	**THL**[g] **Index**	**TEC**[h] **index**	**System recommendation on energy usage**
66.7	85.7	0.1056	0.400	0.350	0.11597	0.1163	0.5000	MODERATE

---

[a] Pumps efficiency
[b] Operational management efficiency
[c] Pumps heat load
[d] Surrounding heat load
[e] External heat load
[f] Grape heat load
[g] Total heat load
[h] Total energy consumption

Note that in example 3, a heat exchanger of very high heat transfer coefficient is used (suggesting that the facility has the plate heat exchanger). In this case then the coolers do not require low refrigeration temperatures to achieve and maintain the desired wine processing temperature range. As a consequence of very high heat transfer coefficient and low total heat load, lead to the evaluated energy consumption by the system as very low. In contrast, with the same parameter inputs in example 4, the energy demand increased by an order of magnitude when a heat exchanger of poor heat transfer was used. From these two examples, its clear that the type of heat exchanger used during the cooling process has a significant impact on the overal energy consumption. The system suggestions after the evaluation of user responses in examples 3 and 4 are depicted in Figures 6.13 and 6.14.

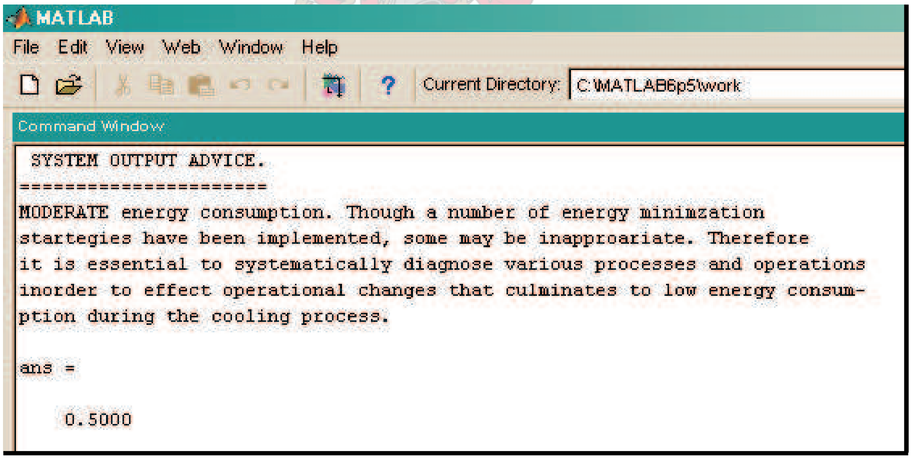


```
 SYSTEM OUTPUT ADVICE.
======================
VERY LOW energy consumption during the cooling porcess.
This can be attributed to good management of processes and
operations where posible energy demand for cooling load has
been substantially reduced via effective implementation of int-
egrated energy management.

ans =

    0.1141
```

Figure 6.13: The system feedback based on the user inputs provided in example 3 with overall energy consumption evaluated as VERY LOW.



```
 SYSTEM OUTPUT ADVICE.
======================
MODERATE energy consumption. Though a number of energy minimzation
startegies have been implemented, some may be inapproariate. Therefore
it is essential to systematically diagnose various processes and operations
inorder to effect operational changes that culminates to low energy consum-
ption during the cooling process.

ans =

    0.5000
```

Figure 6.14: The system feedback recommendation based on the user inputs provided in example 4 with overall energy consumption evaluated as MODERATE.

To sum-up, the four examples illustrated that the qualitative (subjective) and quantitative factors are critical in influencing the decision making on the overall energy requirements during a cooling process. Unlike the quantitative approaches, the fuzzy logic offered a means of incorporating quantitative and qualitative factors to examine and understand the dynamics of energy requirements under the constraint of nonrandom uncertainties or fuzziness.

In essence, the fuzzy logic expert system proposed and developed in this study represents scientific reasoning and therefore, provides a complete knowledge that is useful for decision-makers on energy conservation in the wine industry, particularly at the maceration stage. Secondly, the results presented here do not involve complex mathematical formalisms but are calculated using fuzzy rules embedded in the knowledge base using simple natural language. In this sense, it appears that the targeted users are likely to accept the system decisions as they are transparently computed. Thirdly, the user has the opportunity to trace the reasoning path and verify why the system has offered a particular suggestion or values.

6.7 Concluding Remarks

In this chapter, a computer-aided decision support system for energy minimization diagnosis during the cooling process at maceration stage of the vinification process has been proposed and developed. As such, the developed system provides an efficient alternative in performing systematic energy analysis because it diminishes significantly the time and cost required by such studies.

The use of expert systems and fuzzy logic approaches made it possible to take into account nonquantifiable factors such as winery cooling, frequency of pump inspections, etc. The inclusion of the qualitative factors was found crucial in developing an effective decision making tool as the expertise from experts and operators was easily embedded in the decision making algorithm using natural language (fuzzy if-then rules). This is an important practical advantage, in that, imprecise and nonstatistical data with respect to various functional relationships on many causing factors regarding energy conservation are often known, although not in enough detail to develop a well-posed numerical model. Clearly, this is in total contrast to the current quantitative techniques which fail to use such important knowledge or do so in an *ad hoc* manner.

Additionally, the system allows the decision maker to become fully aware of the potential energy consumption consequences caused by variations of the process operations, thereby enhancing better understanding of subsequent operational and technical considerations. This has been illustrated by presenting four worked examples. Each example yielded results which were found consistent with industrial practices.

The rule-based modular approach was used in knowledge representation, making the developed intelligent system flexible, compact, and easily amenable to adaptation. By developing and implementing the fuzzy expert system, we have shown the feasibility of using fuzzy logic and expert systems technologies in complex decision-making domain where only heuristic knowledge exists. In such domains, and in particular, energy requirement demand in a cooling process, the application of traditional mathematical formalisms are impossible or inadequate as the data accessible is difficult to quantify numerically in many cases.

Though a limited validation of the system was done, it is envisaged that with the current trends of better instrumentation and improved data logging systems in many wineries, it will be possible in the future to perform comprehensive verification of the functionality and authenticity of the knowledge bases. In addition, as a consequence of the accessibility of the quantitative data, the design and configuration of the rules could be automated using the Adaptive Network Fuzzy Inference System (ANFIS) (The Mathworks, 2002b). This would make the system easy to adopt to any winery setup regardless of its size and product ranges.

More research is currently focused in other vinification processes: fermentation, stabilization, storage and bottling where cooling is essential. The inclusion of energy usage knowledge profiles of these processes into the system will allow it to provide a concise and more comprehensive integrated energy management strategy in the entire vinification process.

Chapter 7

Conclusions and Future Work

In the following paragraphs, the main conclusions derived from this study are summarized, while preliminary conclusions have already been presented at the end of each chapter. The main contributions will be emphasized and commented in section 7.1. In section 7.2, the limitations of this work will be pointed out, laying the ground to make suggestions on the way forward through further work and open other lines of research.

7.1 Contributions of this Work

The main contributions of the present thesis are as follows:

Exhaustive literature reviews, scheduled interviews with experts and operators in the wine industry, and site observations of winery operations were used to identify gaps in the data and formalized knowledge in the wine industry, particularly with regard to waste and energy management. The acquired knowledge was crucial for the diagnosis of waste and energy management problems common in the wine industry. In this respect, a set of waste minimization strategies for the entire vinification process, that could be adopted by companies, have been reported. The study indicates that a high percentage of the identified waste minimization strategies falls under the process execution and management category. The importance of this observation underscores the fact that most strategies can be implemented without requiring rigorous evaluation and costly screening techniques.

Similarly, through a systems approach and focusing on energy consumption at the maceration stage of vinification processes, feasible energy minimization options were identified and organized in a format amenable for automation.

The main contribution of this thesis deals with the development of knowledge-based decision tools for waste minimization for the entire vinification process and energy minimization during the cooling process specifically at the maceration stage. Each fuzzy expert system developed was comprised of an object-oriented and hierarchical knowledge representation (allowing reasoning at different levels of abstraction). The application of the knowledge-based techniques was found most suitable for the problem solving in this domain as it proved difficult to obtain accurate mathematical models of waste and energy management owing to the predominantly qualitative data features in the wine industry.

In addition, the ability of these techniques to accommodate ill-defined knowledge was exploited in this work to circumvent the difficulty of representing, processing, and managing different forms of information and data which was either in numerical, qualitative, symbolic or logic format. In illustrating the applicability of the off-line decision tools developed, several case studies mirroring actual industrial practices were considered. The robustness and flexibility of these systems allowed the derivation of consistent results, provided intelligent suggestions in scenarios where there was minimal information and appeared to offer feasible suggestions in scenarios where an inexperienced operator would find it difficult to cope with large input data sets having both numeric and qualitative data features.

In a nutshell, the present thesis introduces the development of decision tools on waste and energy minimization using knowledge-based technologies on the basis of data and information sources related to current practices in wineries. The integration of these technologies has yielded decision tools that have the ability to carry out waste and energy analysis within their respective defined system boundaries with less effort, at low cost, and without a demand on users to possess in-depth expertise in either domain.

Industrial waste management differs from one process industry to another, though certain strategies may bear universal applicability across the board. However, in this study owing to the uniqueness of the food and beverage industry and particularly the wine industry, a waste minimization index (WMI) for ranking and screening waste minimization alternatives was developed. The index was designed taking into account current waste minimization practices and other possible alternatives that may emerge in future as important to the wine industry.

Specifically, because of the predominantly qualitative nature of the available data for waste minimization in the wine industry, the index offers a systematic methodology for screening and ranking of diverse alternatives under consideration for implementation though they may be measurable under different SI units or some are infact dimensionless. As there is lack of such indexes to screen and rank various waste minimization alternatives in the wine industry, it is envisaged that the proposed indices will offer promising results. This can be attributed to the fact that, the proposed index took into account the unique data features accessible in the wine industry.

Experience during the development of the knowledge-based decision tools revealed that the prototypes can be used as training tools on waste and energy management in the wine industry. The training potential of the prototypes finds application in two levels. In level one, the tools can be used for the training of personnel currently working in the wine industry. Using the prototypes in this manner will significantly improve the employees' understanding on the possibly wide range of consequences of their practices on both waste and energy management. The expected fruits of such improvement will be evident via improvement of personnel practices and perceptions in waste and energy management.

At level two, the tools can be used for the training of trainees in colleges and universities anticipating to pursue careers in the wine industry, like oenologists, consultants, private wine entrepreneurs, etc. This is because in the current curriculum on viticulture and oenology, waste and energy components, especially with regard to their potential impact on the environment, winery performance, and ultimate profitability have not been covered.

However, incorporating knowledge-based tools in presenting the subject serves as the single most influential teaching aid in equipping and shaping the perspectives of future wine makers and other key players in the wine industry. Essentially, it will offer them skills and expertise distilled from many years of experience from the current practitioners on aspects of waste and energy management. The benefit will be a future wine industry having more control over resources (e.g. water, chemicals, human capital), energy, and waste. And secondly, it will considerably change the current operational dispensation of company practices as most of them are struggling to comply with environmentally onerous legislations and are shouldering the burden of high energy costs. This would also minimize the resources required in investments on waste disposal technologies and help the companies to transform into a regime where they will experience a profile of sustainable productivity driven by optimal use of resources.

7.2 Study's Limitations and Recommendations for Future Work

Experience in using the MATLAB computing technical environment revealed that its knowledge abstraction tools were inadequate in representing, screening, and ranking alternatives expressed as qualitative variables. This is in total contrast to other dedicated expert system development shells like G2 (Gensym Corporation, 1997) and LEVEL5 OBJECT (Information Builders Inc., 1993). Owing to this limitation, the prototypes developed have limited flexibility, although it is a fundamental requirement for the knowledge-base systems. To construct knowledge based tools with comprehensive features that adequately satisfy the needs of the targeted users, it is recommended that the choice of the knowledge shell for the system development should have a versatile GUI. In that sense, the development shell should be able to provide comprehensive interactive windows based interface with hypertext capabilities so that the user can access different parts of the system easily and efficiently.

Due to the time constraints, the energy studies have not been extended to all processes and unit operations in the entire vinification process, where electrical energy is required for cooling purposes. Further research focusing on processes such as fermentation, stabilization, storage and bottling is recommended in order to develop a complete data base for energy uses in the wine industry. These findings will provide a basis for the design and development of an integrated energy management framework using AI technologies for cooling energy requirements in the vinification process.

The thrust of this study focused on developing knowledge-based decision tools for synthesizing minimization of waste generation and energy consumption for cooling in existing winery installations. During the knowledge acquisition phase, it became self evident that the structural design of the winery facilities including unit layouts, technologies employed, etc. played a significant role on how waste and energy management can be enhanced. In fact in most installations it was found that waste and energy management and control aspects were not factored in at the stage where the structural design alternatives were evaluated. More specifically, failing to articulate these aspects at process and basic (conceptual and preliminary) design stages, has significantly contributed to the current handicaps in managing waste and energy in the wine industry.

Furthermore, this has also contributed to certain winery designs, where technical modifications are not feasible to implement or may require intensive capital investments. As a result, this impedes incorporation of innovative options that bear long term solutions to waste and energy challenges in the wine industry. However, as the knowledge on environmental law, vinification process, product ranges, costs of materials among other is now well known and several winery designers exist, it is recommended that the challenge of waste and energy management in the wine industry be approached using a knowledge-based approach at the design stage. The merit of the approach over conventional algorithmic approaches is that it can manipulate both the first-principles knowledge and heuristic knowledge and can deal with both precise and imprecise information pertaining to the design problem. It is therefore envisaged that such research focus will open a new paradigm in the operations and usage of resources in the wine industry.

At the inception of this study, it was anticipated that sufficient quantitative data would be available to verify and validate the proposed decision support system prototypes. However, currently the data that have been acquired are inadequate to facilitate the achievement of this objective. As research in this area is ongoing, the findings will be presented in future publications.

Chapter 8

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APPENDICES

Appendix A

Possible Environmental Impacts from Winery Effluent

As a result of vinification operations and processes, different waste streams are generated namely wastewater, solids and gases. Each stream has a potential to cause single or multiple impacts on the environmental media. The level of impact depends on various factors and in many ways they are closely interlinked and difficult to draw distinctive boundaries. Some of these factors are the levels of stream concentrations, quantities of the waste, effectiveness of stream management and the location of the winery with respect to water courses and aquatic life. The waste stream with extensive impact on the environment is wastewater due to the large quantities generated in wineries and its application on soils for irrigation. This would imply that it has the potential to impact on large areas. A list of the variables and where they can cause environmental impacts are presented in Table A.1.

The adverse environmental impacts resulting from various contaminant discharges are shown in Table A.2. This underscores the essence of sound management of the wastes by adopting waste minimization strategies in any winery.

Table A.1: Significant effluent features, their sources, and environmental medium where they have potential to cause negative impacts.

Variable	**Source**	**Land (soil)**	**Water resources**[a]	**Ambient air**
Volume	influent[b]	✓	✓	
Organic carbon	product loss, cleaning water solids in WW[c]	✓	✓	✓
Salinity[d]	caustic soda, influent, product loss, ion exchangers	✓	✓	
pH	product loss, ion exchangers, incompletely neutralized acid or acid rinsewater, formation of carbonic acid	✓	✓	
Sulphur	Sulphiting process		✓	✓
Phosphorous	phosphate detergents	✓	✓	
	phosphoric acid	✓	✓	
Sodicity[e]	caustic washing, influent	✓		

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[a] Underground water, rivers, dams, streams, wells or boreholes

[b] Refers mainly water from rivers, dams or ground sources

[c] WW = wastewater

[d] Determined through measurement of electrical conductivity

[e] Relationship of sodium, calcium and magnesium concentrations

Source: Chapman et al., (2001), Chapman, (1996), EL Rayes Environmental Corporation, (1997).

Table A.2: Significant winery contaminants and their corresponding possible environmental impacts.

Variable	**Potential environmental impacts**
Organic carbon (BOD, COD)	depletion of dissolved oxygen during degradation, suffocation of aquatic life development of septic conditions (generation of odors).
Volume	water logging due to uncontrolled irrigation, poor aeration of soil, malodours.
Solids	clogging, reduced soil aeration and permeability to water, may damage equipment and treatment systems, suffocation of aquatic life, creates anaerobic sludge and conditions in water lagoons.
pH	high or low pH damages aquatic life (acidification of soils), reduces the availability of useful nutrients e.g. phosphorous and calcium, decimates microbial populations in the soil
Phosphorous	stimulates growth of undesirable aquatic life, causes water eutrophication and underground water pollution
Nitrates	formation of ammonia which is toxic to fish, pollution of underground water, stimulates growth of undesirable aquatic plants, causes water eutrophication decimates microbial populations in soil, acidification of soils due to Nitrates formation, high incidences of powdery mildew and botrytis fruit rot where high nitrogen presence in soils.
Salinity	reduces the quantity of water to organisms, salinization of soils and water
Sodicity	decline of soil structure quality leading to poor drainage,water logging, poor aeration, hardness, compaction, breakdown of clay, pore clogging and erosion.
Sulphur	Malodours in lagoons

Source: Chapman et al., (2001), Chapman, (1996), EL Rayes Environmental Corporation, (1997).

Appendix B

Environmental Legislative Guidelines

In many wine production regions globally, the most explicit legislative guidelines regarding discharging of a particular waste from the wineries concerns the wastewater. This is because of its potential to cause multiple environmental impacts in soil, water, and air. Secondly, it is the dominant waste stream and therefore given much attention. Therefore, in this section the guidelines regarding discharging of wastewater are presented for: Australia, South Africa and USA. Due to the wide variations in terms of ecosystem, soils and other environmental factors, the benchmarks vary greatly.

(a) Australia

For the application of wastewater from wineries for the irrigation of vineyards, the following water quality benchmarks should not be exceeded:

- Avoid volumes exceeding the needs of the vine for selected management options for fruit quality (to ensure that there is no soil structure loss, salinization, water logging, chemical contamination or erosion of the soil in the wastewater irrigation area).
- The BOD values should not exceed 2000 mg/L.
- The C:N:P should be in the range 30-15:1:0.5.
- pH is not less than 5.5 and not more than 8.5.
- Sodium Adsorption Ratio (SAR) should not exceed 3 as soils will be susceptible to sodicity.
- Salinity levels not exceeding 1.5 dS/m.

- The saturated conditions of the soil should exceed a period of 24 hours.
- All other soil parameters should be within 10% of the natural range as may fit the soil type.
- In addition winery wastewater **should not** be irrigated:
    1. In a manner which leads to surface runoff from the winery wastewater irrigation area at any time.
    2. Onto waterlogged areas, land within 50 metres of a creek or swamp or domestic or stock water bore, or land subject to flooding, steeply sloping land, or rocky or highly permeable soil overlying an unconfined aquifer.
    3. Using equipment which sprays the wastewater more than 1.5 metres into the air and creates significant quantities of fine droplets.
    4. Over an area which is within 50 metres of any residence on neighboring land or 10 metres of any type of publicly owned land.

(b) South Africa

The legislative guidelines applicable to the irrigation of vineyards using industrial wastewater (in this case from wineries) should meet certain quality benchmarks. These are:

1. A person can irrigate up to 500 m^3 of domestic or biodegradable industrial wastewater on any given day, provided the -
    (a) Electrical conductivity does not exceed 200 mS/m;
    (b) pH is not less than 6 or more than 9 pH units;
    (c) Chemical oxygen demand (COD) does not exceed 400 mg/l after the removal of algae;
    (d) Faecal coliforms do not exceed 100 000 per 100 ml; and
    (e) SAR does not exceed 5 for biodegradable industrial wastewater.
2. or irrigate up to 50 m^3 of biodegradable industrial wastewater on any given day, provided the -

   (a) Electrical conductivity does not exceed 200 mS/m;
   (b) pH is not less than 6 or more than 9 pH units;
   (c) Chemical oxygen demand (COD) does not exceed 5000 mg/l after the removal of algae;
   (d) Faecal coliforms do not exceed 100 000 per 100 ml; and
   (e) SAR does not exceed 5 for biodegradable industrial wastewater.

3. Other significant conditions wastewater irrigation should meet for the permit to be granted, irrigation should take place-
   (a) above the 100 year flood line, or alternatively, more than 100 metres from the edge of a water resource or a borehole which is utilized fro drinking water or stock watering; and
   (b) on land that is not or does not overlie major aquifer.

(c) United States of America

The California state has the highest area of viticultural farming in USA. Thus the California Water Quality Control Boards issued the legislative guidelines for the use of wastewater for irrigation with typical permit limits as follows;

- Average biological oxygen demand over 30 days ≤ 50 mg/L.
- Maximum biological oxygen demand in any single day ≤ 80 mg/L.
- Average total suspended solids over 30 days ≤ 50 mg/L.
- Maximum total suspended solids an any single day ≤ 80 mg/L.

NB: Wastewater treatment permits for wineries do not specify chemical oxygen demand, nitrates, nitrites, nitrogen (including ammonia) or phosphorous limits. However, the U.S. Safe Drinking Water Act specifies limits for nitrates in groundwater at ≤ 10mg/L, and nitrite limits of 1 mg/L.

Appendix C

Pollution Prevention Index of Smith and Khan

The pollution prevention index proposed and developed by Smith and Khan (1995) is presented in Table C.1. The pollution prevention index is calculated using the expression;

Table C.1: Pollution prevention index of Smith and Khan (1995).

Source reduction (SR):	Yes=1/no=0
Recycling (R):	Yes=1/no=0
Waste treatment	Yes=1/no=0
Ease of implementation (EI):	1=procedure change 2=retrofit equipment 3=new equipment 4= higher-purity solvent 5=material substitution
Percentage reduction (PR)	0-100%
Capital cost (CC) (1993$):	5=no cost ($0) 4=low cost (¡ $15,000) 3=moderate ($15,000¡cost¡$50,000) 2=high ($50,000¡cost¡$150,000) 1=very high cost (cost¿$150,000)
Payback (PB):	In years 0 to 9
Depth of solution (DS):	1000=company case study 0100=EPA case study 0010=consulting report 0001=option

$$PPI = SR\times10^{11}+R\times10^{10}+WT\times10^{9}+(6-EI)\times10^{8}+PR\times10^{5}+CC\times10^{4}+(9-PB)\times10^{3}+DS \quad \text{(C.1)}$$

Appendix D

Sensitivity Analysis

The sensitivity analysis was carried out in order to illustrate the functioning of the developed prototypes as well as identifying the most influential input variable in a given module. Each variable was varied over its possible transition interval while the other input variables were kept fixed at specific initiation values. The initiation value for each input variable in this case refers to a crisp value that upon fuzzification yields a degree of membership of 0.5 (μ=0.5) in the region where two fuzzy sets overlap. In this study, three or four fuzzy sets were used in representing an input variable (e.g. temperature variable had three fuzzy sets). For instance, for a variable that has been granulated into three fuzzy sets, the initiation values were found to be located around the 33.3 and 66.7 percentile regions with respect to its universe of discourse. For example, the crisp initiation values having a membership function of 0.5 for the grape temperature variable were 17.5^{o}C and 27.5^{o}C within the 33.3 and 66.7 percentile regions, respectively. On the other hand, a variable having four fuzzy sets, the initiation values were located within 25th, 50th and 75th quantile fuzzy overlapping regions.

Using a case study, we demonstrate the functioning of the prototype fuzzy expert system for determining the overall energy consumption by considering the module for computing the grape heat load (GHL). This objective was achieved by investigating the influence of each input variable on the overall GHL. Tables D.1, D.2, and D.3 summarizes the salient features owing to the changes of the input variables; grape temperature, temperature control and distance of grapes transportation on the overall GHL at 33.3 percentile region, respectively. Similar simulations were carried out at 66.7 percentile region as well as in situations where the initiation values were fixed in both regions simultaneously. The analytical results in Tables D.1 to D.3 are graphically presented in Figure D.1. Using the same procedure, the senstivity analysis was repeated at different regions of the input variables and the results obtained are explicated in Figures D.2 to D.4.

Table D.1: Relative sensitivity analysis of the GHL through the variation of temperature input variable while the initiation values of distance and temperature control variables were fixed at 33.3 percentile region.

Relative Variable Δ%	**Input Variables**			**Transferred Value**		**Computed Output**		
	T[a]**(°C)**	**TC**[b]	**D**[c]**(km)**	Max μ_{TC}	Max μ_D	**GHL**[d]	**ΔGHL**	**ΔGHL%**
-40	4	0.3	40	0.5	0.5	0.263	-0.189	-42.2
-30	8	0.3	40	0.5	0.5	0.263	-0.189	-42.2
-20	12	0.3	40	0.5	0.5	0.263	-0.189	-42.2
-10	16	0.3	40	0.5	0.5	0.313	-0.140	-31.0
0	20	0.3	40	0.5	0.5	0.452	0.000	0.0
10	24	0.3	40	0.5	0.5	0.452	0.000	0.0
20	28	0.3	40	0.5	0.5	0.597	0.145	32.7
30	32	0.3	40	0.5	0.5	0.770	0.318	70.4
40	36	0.3	40	0.5	0.5	0.770	0.318	70.4

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[a] Temperature
[b] TC: Temperature control
[c] D: Distance
[d] GHL: Grape heat load

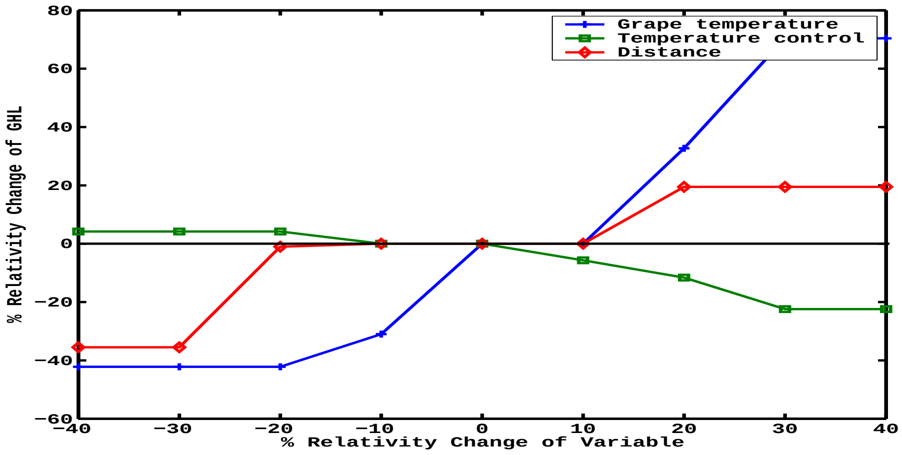

Figure D.1: The relative sensitivity analysis of the GHL due to the variation of all input variables. The transition interval for each variable was fixed at 33.3 percentile region.

From the results obtained in the cases discussed in the preceding paragraphs, we argue

Table D.2: Relative sensitivity analysis of the GHL through the variation of temperature control input variable while the initiation values of distance and temperature variables were fixed at 33.3 percentile region.

Relative Variable Δ%	**Input Variables**			**Transferred Value**		**Computed Output**		
	T[a]**(°C)**	**TC**[b]	**D**[c]**(km)**	Max μ_T	Max μ_D	**GHL**[d]	**ΔGHL**	**ΔGHL%**
-40	17.5	0.1	40	0.5	0.5	0.368	0.015	4.2
-30	17.5	0.2	40	0.5	0.5	0.368	0.015	4.2
-20	17.5	0.3	40	0.5	0.5	0.368	0.015	4.2
-10	17.5	0.4	40	0.5	0.5	0.353	0.000	0.0
0	17.5	0.5	40	0.5	0.5	0.353	0.000	0.0
10	17.5	0.6	40	0.5	0.5	0.332	-0.020	-5.7
20	17.5	0.7	40	0.5	0.5	0.311	-0.041	-11.7
30	17.5	0.8	40	0.5	0.5	0.274	-0.079	-22.4
40	17.5	0.9	40	0.5	0.5	0.274	0.079	-22.4

[a] Temperature
[b] TC: Temperature control
[c] D: Distance
[d] GHL: Grape heat load

Table D.3: Relative sensitivity analysis of the GHL through the variation of distance input variable while the initiation values of temperature and temperature control variables were fixed at 33.3 percentile region.

Relative Variable Δ%	**Input Variables**			**Transferred Value**		**Computed Output**		
	T[a]**(°C)**	**TC**[b]	**D**[c]**(km)**	Max μ_T	Max μ_{TC}	**GHL**[d]	**ΔGHL**	**ΔGHL%**
-40	17.5	0.3	15	0.5	0.5	0.274	-0.154	-35.5
-30	17.5	0.3	30	0.5	0.5	0.274	-0.154	-35.5
-20	17.5	0.3	45	0.5	0.5	0.421	-0.004	-1.0
-10	17.5	0.3	60	0.5	0.5	0.425	0.000	0.0
0	17.5	0.3	75	0.5	0.5	0.425	0.000	0.0
10	17.5	0.3	90	0.5	0.5	0.425	0.000	0.0
20	17.5	0.3	105	0.5	0.5	0.508	0.083	19.5
30	17.5	0.3	120	0.5	0.5	0.508	0.083	19.5
40	17.5	0.3	135	0.5	0.5	0.508	0.083	19.5

[a] T:Temperature
[b] TC: Temperature control
[c] D: Distance
[d] GHL: Grape heat load

that the sensitivity analysis gives an indication of the functioning of the grape heat load module and supplies some particular relative weight the input variables may have in the overall grape heat load contained in the grapes. However, the results also reflect that the

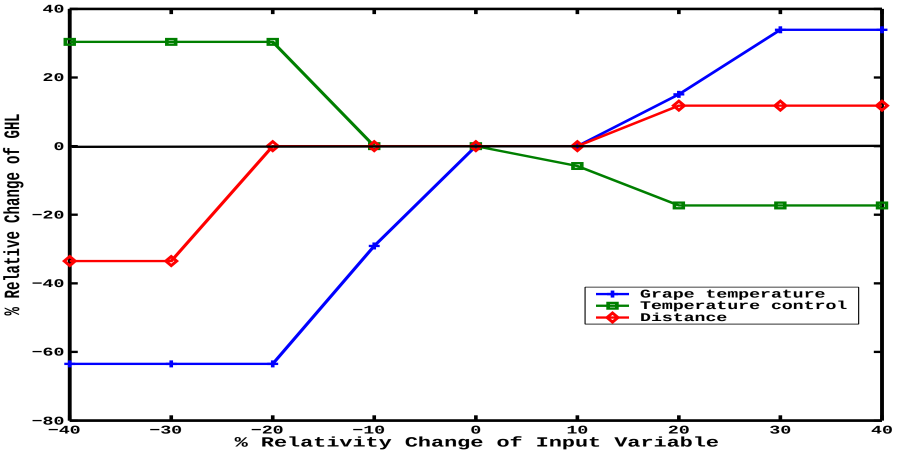

Figure D.2: The relative sensitivity analysis of the GHL due to the variation of all input variables. The temperature variable transition interval was fixed at 33.3 and 66.7 percentile regions while the temperature control and distance variables were fixed at 66.7 and 33.3 percentile regions, respectively.

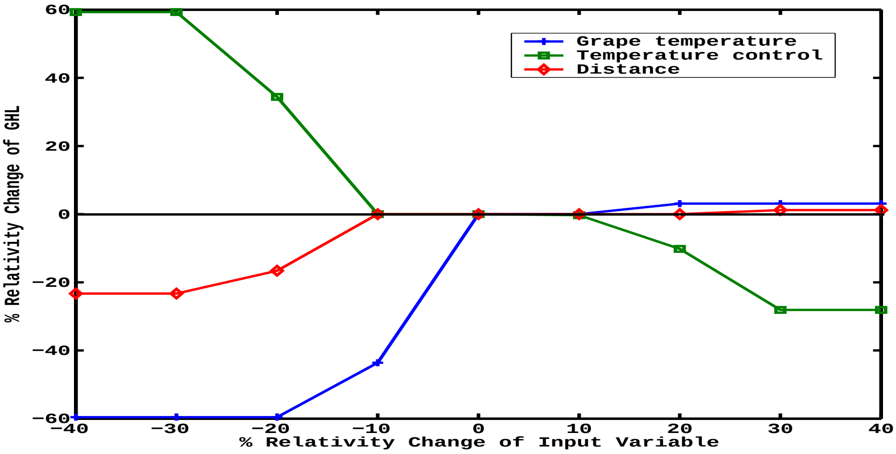

Figure D.3: The relative sensititvity analysis of the GHL due to the variation of all input variables. The temperature variable transition interval was fixed at 33.3 and 66.7 percentile regions while the temeperature control and distance variables were fixed at 33.3 and 66.7 percentile regions, respectively.

effective module output owing to the variation of a single input variable over its transition interval depends very much on the value of the other fixed variables. Therefore, the results presented here can be considered to generically illustrate the functioning of the grape heat load module in particular and generically in all other modules.

Two other observations can be derived which are specific for the GHL. Firstly, the temperature is the most influential input variable on the overall computation of GHL.

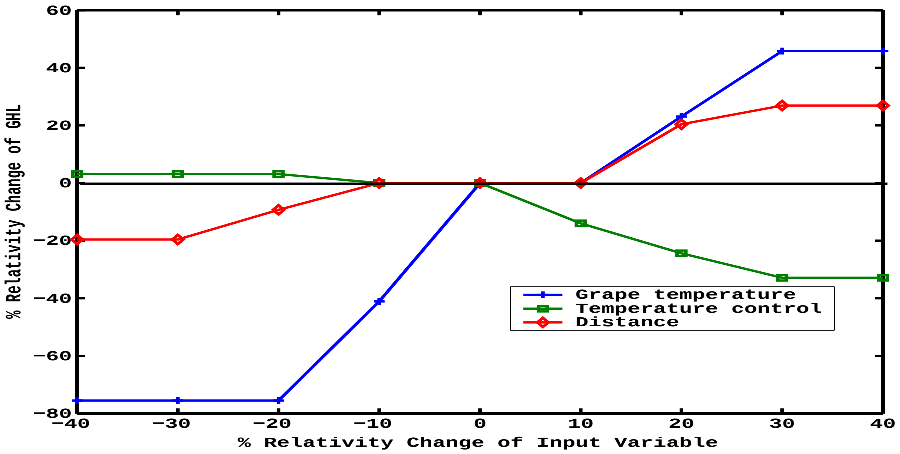

Figure D.4: The relative sensititvity analysis of the GHL due to the variation of all input variables. The transition interval for each variable was fixed at 66.7 percentile region.

This is an indicator that the temperature variable was given the highest relative weight during the design of IF-THEN rules in theGHL module. This can be clearly seen from the results presented in Figures D.1, D.2 and D.4. Within the 33.3 percentile region, the transportation distance is favorably short and the temperature control is poor, while at 66.7 percentile region, the distance is relatively long and the temperature control is good, the temperature input variable in both exerts the greatest influence on the grape heat load. In terms of decision-making and on the basis of these results, then it is clear that grapes harvesting should be done at low ambient environmental temperatures to reduce significantly the refrigeration load required at the maceration stage.

Secondly, the temperature control input variable has the least influence on the overall grape heat load, both under favorable and unfavorable conditions of the other two input variables (temperature and distance) as graphically illustrated in Figure D.1 and Figure D.4, respectively. In terms of decision-making in the light of this observation, the implication is that instituting temperature control mechanisms under the conditions that the grapes are harvested at low ambient temperatures and transported over a short distance or at high temperatures and being transported over a long distance may not be the optimal alternative in managing the grape heat load.