PROBLEM SOLVING IN CHEMICAL ENGINEERING: A STUDY OF THE SOLUTION OF MASS BALANCE PROBLEMS BY SECOND YEAR STUDENTS

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"It is the glory of God to conceal a matter; to search out a matter is the glory of the wise." - Proverbs 25:2

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May God, The Almighty bless you all!!!

SYNOPSIS

The success of engineers comes from their ability to solve problems. The educational goal of the Department of Chemical Engineering at the University of Cape Town (UCT) is to improve students' problem solving skills. Teaching problem solving can be effective if the teacher has knowledge of how students solve problems. Thus this research was conducted to investigate the strategies and skills students use to solve problems in the context of material balances.

A theoretical framework was developed in this study which represents a problem solving strategy applicable to the kind of problems students encounter in their study of chemical engineering. The strategy consists of the following stages: *defining the problem*, *analysing the problem*, *planning the solution*, *implementing the plan* and *evaluating the solution.* The framework includes the five stages given above, with the steps which may be taken during each stage and the skills which are required to implement them. An analytical tool for analysis of the results from the study was developed from the framework.

The study was carried out on fifteen-second year Chemical Engineering students from the University of Cape Town. Students were asked to solve two material balance problems similar to those they encounter in their material and energy balance course. Written solutions together with oral recordings of the students as they solved the two problems were examined with reference to the theoretical framework.

Results from the study revealed that students formulated solutions to the problems using stages similar to the ones described above. However students displayed very little evidence of *planning* and *evaluating* in the process of solving the problems. It was also found that students iterated between the different problem solving stages. Those students who solved the problems

successfully showed more iteration between the stages than the unsuccessful students.

The adoption of the theoretical framework developed in this study is recommended for teaching and developing students' problem solving skills. In the use of the strategy students should be encouraged to *plan* and *evaluate* their solutions. It is suggested that a way of assessing the use of strategies and particular stages like *planning* and *evaluating* be designed so that students are motivated to learn problem solving. It is also suggested that students be encouraged to iterate between the different stages of a strategy.

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1. INTRODUCTION

1.1 THE CONTEXT

Problem solving lies at the heart of success as a chemical engineer. The work of engineers involves solving problems of the environment, industry and society. In the solving of many engineering problems the integration of knowledge drawn from different subjects is required according to Zhang and Peterson (1997). Motivated by the fact that engineers are supposed to be problem solvers, Woods et al. (1979) did an in-depth study of what problem solving is and what challenges there are in developing skill at solving problems. Also, Sears and Dean (1983) believed that "engineers are problem solvers", so they did a study to find out how to understand and improve the teaching process of problem solving. The many studies that have been done clearly show that both students and teachers in chemical engineering are concerned with problem solving (Greenfield 1979). It is not only engineers who see the need to develop skill in problem solving. The teaching of science according to Reif et al. (1976) should not only involve the mere transmission of factual information but must include teaching students to use basic facts and concepts flexibly so that they can deal with new situations, predict various consequences and most importantly solve problems. Gabel et al. (1984) agree that an area of prime importance in teaching science is problem solving.

Chemical engineers usually work on plant operations, product application, contracting projects, process development or research. According to the Engineering Council of South Africa (ECSA 1997), in all the cases the core of the work consists of a combination of problem solving and management plus communication. Both management and communication are usually in relation with problem solving. It is clear that undergraduate students should be able to develop special techniques independent of a particular problem for tackling engineering problems.

The Chemical Engineering curriculum at the University of Cape Town (UCT) focuses on the development of technical expertise, problem solving, teamwork and communication skills. Problem solving is introduced in the introductory course, CHE104W in the first year of study. In the second year problem solving skills are specifically developed in a material and energy balance course, CHE 231F, that is supported by all the other courses required in second year. Many principles of the chemical engineering domain are first met in CHE 231F. To be a good problem solver one has to understand the concept involved. The CHE 231F course does not only teach problem solving skills but it also includes a focus on understanding key concepts in the context of material and energy balances.

1.2 MOTIVATION FOR THE RESEARCH STUDY

The motivation for this study was stimulated from a study I did in 1999 on third year students, in which I examined students' recovery from failure in Chemical Engineering (Dhliwayo et al. 2000). Although it was worrying that some students failed some or most of their courses, most of them were able to recover and move on. The focus of this study was thus to find the methods used by students to cope with failure. Results from the study suggested that events and problems in the learning environment forced students to adopt certain approaches to learning. These approaches were a deep approach, a surface approach and a smart approach. The deep approach is characterised by understanding of learned material and concepts, whereas the surface approach involves brushing through course material just to get a rough idea of the subject, and to memorise and learn methods of answering questions through attempt of tutorials and exam papers. The smart approach is characterised by good time management, organisation of tasks and finding ways of going around difficulties encountered without rectifying them.

A study by Case et al. (2000) identified different approaches adopted by students who were exposed to the context of material and energy balances. The approaches found in that study were a conceptual approach, where the intention is to understand concepts, an algorithmic approach, intended to remember calculation methods for solving problems and finally an information-based approach where the intention is to remember information that can be supplied in response to assessment questions. The conceptual approach and the information-based approach of the Case et al. (2000) study are similar to the deep approach and the surface approach of the Dhliwayo et al. (2000) study respectively.

It is desired for every chemical engineering student to become a successful engineer. For some time chemical engineering staff have been concerned about the success rates in their courses. At UCT some changes have been made to the curriculum including reducing content in some courses, introducing separate design courses in second year. All of these changes are aimed at developing problem solving skills of students (Fraser 2001). However, from my experience as an undergraduate student the only opportunity one had to demonstrate ones' competency was during tests and exams. There were few opportunities available to develop problem-solving skills. Thus I felt that students' failure to achieve was partly influenced by their lack of skill in solving problems.

Bransford and Stein (1984) suggest that problem solving can be learned but it frequently is not learned because it is not explicitly taught. Huffman (1997) argues that preparing students to become effective problem solvers and helping them to understand concepts are both difficult to achieve. My opinion is that it is difficult to teach problem solving largely because the skill becomes subconscious hence trying to teach problem solving without knowledge of how students solve problems does not help. The reason for this difficulty according to Sears and Dean (1983) is that the teacher has mastered the skill of solving problems and is not aware of all the elements of thought which lead to a successful solution. The present research project was therefore focussed on the following questions:

- What strategies do students use to solve problems in the context of material balances?
- Which skills do students have that help them solve problems?

- What improvements, if any, in problem solving did students make during the study of the CHE 231F course?
- What changes if any could be made to improve undergraduates' problem solving techniques and how can the changes be implemented?

1.3 AN OVERVIEW OF THE THESIS

Chapter 2 is a discussion of the ways that problem solving has been theorised in the literature. The discussion gives an overview of the definitions of problem solving in the literature and the skills required in solving problems successfully. Different strategies and heuristics used while solving problems are also examined. Following this discussion and also drawing on the strategies and skills from the literature and a discussion held with the chemical engineering lecturers at UCT, a theoretical framework to guide the analysis in the present study was developed.

Chapter 3 reviews research into how people actually solve problems. It starts by discussing research done previously to investigate the difference between expert and novice problem solvers and the difficulties encountered during problem solving. The methods that have been used by teachers to improve problem solving are addressed as well. Finally, the methods used in similar studies to gather information about problem solving are introduced and thereafter the method used in this study is developed.

Chapter 4 describes the sampling of students, experimental procedure, the two tasks developed as instruments in this study, and the method of analysing the data obtained. Chapter 5 contains the analysis of students' solutions of the two tasks. Strategies used by students to solve the tasks and comparisons of students' solutions are given in this chapter.

Chapter 6 discusses the results observed in this study. It focuses mainly on whether students use the same strategies as those found in the literature and whether one has to follow a specific strategy to solve a problem. Chapter 7 concludes the study.

2. WAYS OF THEORISING PROBLEM SOLVING

In this chapter I discuss how problem solving has been defined in the literature as well as the different approaches of problem solving that have been suggested. To solve problems there is a need for an organised procedure known as a strategy. Heuristics and problem solving skills also play a big role in the construction of a solution. A few examples of heuristics are given together with the skills needed to produce a solution successfully.

2.1 DEFINITION OF PROBLEM SOLVING

Woods et al. (1975) defined problem solving as the activity whereby a best value is determined for an unknown, subject to a specific set of conditions. Fogler (1983) adopted this definition by Woods for use when he designed a course in problem solving. According to Lieske (1983), problem solving is a state of mind. This state of mind is the satisfaction that a solver gets from being able to solve a problem. Finegold and Mass (1985) acknowledged that problem solving might refer to a broad range of activities but only defined problem solving as the solution of written problems.

All the three definitions given above describe what is involved in solving problems. However the definitions of Lieske and Finegold and Mass only focus on certain aspects of problem solving. Lieske (1983) talks about the feeling of achievement that occurs once a problem has been solved which does not involve the process of how the problem is solved. Finegold and Mass (1985) mention in their definition the solution to written problems, which excludes those problems that are not written. It is also not clear from their definition whether they are talking about how the solution is obtained or the nature of the solution. Although the definition of Woods et al. (1975) does not say anything about the feeling one gets on achieving a solution, I find the definition most useful to my study. The definition talks about a process where the solver considers the specific conditions of the problem in order to work towards a solution. It is clear from the Woods et al. (1975) definition that a solver is required to take action in order to solve a problem.

2.2 APPROACHES TO THEORISING PROBLEM SOLVING

Human problem solving has been a continuing concern of psychologists and they have developed different ways of investigating it. There are three well-established approaches, namely Behaviourism (Rubinstein and Firstenberg 1995), Gestalt psychology (Laurillard 1984; Schoenfeld 1985; Simon 1989) and Human information processing (Laurillard 1984; Rubinstein and Firstenberg 1995; Simon 1989).

The behaviourists view problem solving as a relationship between a stimulus and a response without speculating about the intervening process (Rubinstein and Firstenberg 1995; Schoenfeld 1985). What this means is that when faced with a problem, (a stimulus), the solver recalls a previously learned answer without having to construct a solution. If an answer is not readily available the solver must act in a way which helps recall what was previously learned.

Gestalt psychology describes human cognition in terms of the quality of perception and thinking, that is, it emphasises the structural quality of the way in which we perceive, think about, and feel the world around us. By emphasising this structural quality of human cognition, the Gestalt psychologists make the assumption that there are always some underlying structures within our perception of a situation, experience or task (Laurillard 1984; Schoenfeld 1985; Simon 1989; Wertheimer 1959).

The information processing approach to problem solving is focused on the process that intervenes between input and output and leads to a desired goal from an initial state (Rubinstein and Firstenberg 1995). This approach attempts to uncover the transformation rules that connect input and output (Simon 1989). For example, given a blueprint find the recipe; given the description of a natural phenomenon find the differential equations for the process that will produce the phenomenon (Laurillard 1984; Simon 1989).

The most useful theory of problem solving in a learning environment and in the context of engineering is the information processing approach. It is important for learners when given a problem to provide a solution that describes how the information given was used to obtain a solution. The Behaviourist approach may come into play in situations where the problem presented to a student has a solution, which is similar to another problem that was solved before. Relying on similar solutions may hinder problem solving rather than enhance it. The solver in that case does not face the problem with an open mind and might introduce to the new problem unnecessary constraints which could have been useful in the previous problem and may also disregard the information of the actual problem.

There is some agreement between the information processing approach and the definition of problem solving given by Woods et al. (1975). Both the definition and the approach include a process (activity by Woods et al. 1975) undertaken by the solver to obtain the desired goal from the initial state (Rubinstein and Firstenberg 1995). The process that occurs once given the input and the desired output is more valuable since it allows people to solve problems that they are not familiar with and to learn how to solve problems in general. The Gestalt psychology approach does not seem helpful in the context of engineering. This approach focuses on how the solver perceives a problem but does not clarify how a solution to the problem can be obtained from the perceptions made.

There are several key skills that can be learned and developed in order to be able to solve problems effectively. These key skills are for example being creative, being analytical and having the experience for judgement (the memorised experience of factors for order of magnitude feelings). It is important for the solver to have background knowledge relevant to the context of the problem. Also some useful tools in solving problems are strategies or organised procedures, and heuristics or rules of thumb (Lieske 1983; Woods et al. 1979). Strategies are a set of stages that could be used to solve problems whereas heuristics are tips that can be used at any stage of the strategy to help the solver achieve a solution. If these procedures used in problem solving are made explicit for students there is a possibility that they can be assisted in learning how to solve problems (Marton et al. 1984). The procedures are described in the sections below.

2.3 STRATEGIES FOR SOLVING PROBLEMS

According to Woods et al. (1975), a strategy is a set of stages that combine creative and analytical thinking. Fogler and LeBlanc (1995) describe a systematic approach to problem solving called a heuristic that helps guide the solver through the solution process and generates alternative solutions. This approach is also a set of stages but its difference from that of Woods et al. (1975), is that for each stage Fogler and LeBlanc (1995) provide in detail the means of achieving that stage. Bransford and Stein (1984) call the set of stages for generating solutions a model. In the current study I will adopt the name 'strategy' from Woods et al. (1975) to describe the systematic process followed by a solver to generate a solution for a given problem. Conwell et al. 1993 and Lieske 1983 agree with Woods et al. 1975 that a strategy is a complex process consisting of a large number of different skills with stages combining creative and analytical thinking. Table 2-1 shows various strategies that were compiled from literature studies undertaken in mathematics, physics, chemistry, engineering, design and general problem solving. Important aspects of these strategies will be discussed in the sections that follow. Table 2-1 is also found in Appendix 5 as a fold out.

2.3.1 Background of the different strategies

The common interest in developing strategies was to provide a systematic approach to problem solving that would yield an appropriate solution to a problem. In the business world, problem-solving strategies have been developed to assist in making decisions (Kepner and Tregoe 1965). Polya (1957) as a teacher and researcher recognised that there are a number of general problem solving techniques which mathematicians use all the time but seldom communicative. Polya's researches led him to develop a four-stage strategy for solving problems with a primary focus of using the strategy in mathematics.

Table 2-1 Problem Solving Strategies suggested in the literature

SOURCE	STRATEGY
Polya (1957)	Understand the problem – Devise a plan – Carry out the plan – Look back *Developed for mathematical problem solving.*
Woods et al. (1975)	Define the problem – Think about it – Plan – Carry out the plan – Look back *Modified version of Polya's strategy. Used in a McMaster University project to improve students' problem solving skills.*
Reif et al. (1976)	Description – Planning – Implementation – Checking *Strategy taught to encourage students to examine a problem before blindly calculating and to check their answers afterwards.*
Mettes et al. (1980)	Analysis of the problem – Transformation of the problem – The execution of routine operations – Checking the answer and interpretation of the results *Developed for a thermodynamics course, problems requiring the specification of the solution.*
Bransford and Stein (1984)	Identify the problem – Define and represent the problem – Explore possible alternatives – Act on the alternatives – Look back – Evaluate the effects of your activities *Strategy for improving problem solving and decision-making.*
Schoenfeld (1985)	Analysis – Design – Exploration – Implementation – Verification *Strategy served as a foundation for mathematics and liberal arts majors.*
Conwell et al. (1993)	Acceptance – Analysis – Definition – Ideation or Brainstorming – Selection – Implementation – Evaluation *Koberg and Bagnal strategy introduced to design students.*
Conwell et al. (1993)	Definition of Problem – Information Retrieval – Seeking Alternatives – Development Synthesis – Analysis – Cost/ Benefit Analysis – Reporting to clients *Harrisberger strategy introduced to design students.*
Fogler and LeBlanc (1995)	Define the problem – Generate solutions – Decide on the course of action – Implement the solution – Evaluate the solution *Designed for anyone who would like to improve their problem solving skills.*
Rubinstein and Firstenberg (1995)	Preparation – Incubation – Inspiration – Verification *Problem solving strategy known by psychologists.*
Huffman (1997)	Focus the problem – Describe the physics – Plan the solution – Execute the plan – Evaluate the solution *Strategy given to students in a study to investigate its effect on problem solving performance and conceptual understanding.*

The strategy by Woods et al. (1975) was developed to help students in solving ordinary homework problems they were given in different courses during their studies in chemical engineering. The strategy they gave to students was an extension of Polya's strategy (Woods et al. 1979). Instead of the stage *understand the problem*, Woods et al. (1975) had *define the problem* and *think about it* as stages before the *plan* stage. The extension was done based on the study of protocols by experts.

Reif et al. (1976) taught students their strategy after observations on how an individual student goes about solving problems indicated that students approached problems in very haphazard and ineffective ways. The major stages of the strategy are similar but not identical in context to those suggested by Polya (1957).

Mettes et al. (1980) studied articles which described problem solving in chemistry and chemical engineering to develop a systematic approach to problem solving for a thermodynamics course. The strategy was meant for solving problems that required a specification of the situation such as calculation of a specific temperature. Although this strategy was designed for thermodynamics it was believed that it could be adapted for use in other science and technology courses.

Bransford and Stein (1984) provided a strategy that they claim could be used in all types of problems and which is also suitable for anyone who wants to learn problem solving. Their strategy was formulated from research on thinking, learning and problem solving on high school, college, and graduate students; teachers; administrators and business leaders. Contributing to the Bransford and Stein (1984) strategy were studies by other researchers in areas such as psychology, education, philosophy and artificial intelligence.

Schoenfeld (1985) developed a strategy from detailed observations of good problem solvers in the process of working difficult and unfamiliar problems. This strategy represents the most systematic behaviour of good problem solvers. The strategy served as a foundation for two courses in problem solving. It was a guide for students to use when they did not know what to do next and was not a program that students were supposed to implement mechanically.

Conwell et al. (1993) adopted strategies to give students while they worked on a design project. The strategies were adopted from Bransford and Stein (1984), (Harrisberger 1982, cited in Conwell et al. 1993) and (Koberg and Bangal 1981, cited in Conwell et al. 1993). All the three strategies were accessible to students. The choice of strategies was arbitrary.

Fogler and LeBlanc (1995) studied problem solving techniques used in industry by investigating problem-solving strategies from more than fifteen companies. They carried out an extensive survey of new employees, experienced engineers and managers to collect information on the problem solving process. The strategy developed after these studies was believed to be robust enough such that it would be applicable to many types of problems. The strategy by Fogler and LeBlanc (1995) also drew on the pioneering work of Woods on problem solving.

The strategy by Rubinstein and Firstenberg (1995) was based largely on the experiences of scientists who solved difficult problems by inspiration. The four stages listed in Table 2-1 may take place in parallel rather than in series in some situations.

Huffman (1997) adopted the strategy in Table 2-1 from (Heller et al. 1992, cited in Huffman 1997) to teach students how to solve physics problems. The procedure described by the strategy was for solving real world, context-rich problems rather than simple textbook physics problems.

Noble (1983) found that the problem solver may have to loop backwards at any stage of the solution process to redefine the problem or develop new solution strategies if initial attempts fail. Bransford and Stein (1984) supported this stating that people may have to move through the strategy a number of times to arrive at a satisfactory solution. Fogler and LeBlanc (1995) emphasise *evaluation* is an ongoing process in the generation of a solution.

Good strategies are general but specific enough to be useful, flexible, simple and easy to remember (Woods et al. 1979). The compilation of strategies should serve as a guide to the problem solving process (Schoenfeld 1985). From Table 2-1, it can be seen that in some cases the strategies have different names for the same stage, such as *understand the problem* (Polya 1957), which is similar to *define the problem* (Fogler and LeBlanc 1995; Woods et al. 1975).

The strategies by Bransford and Stein (1984), the ones in Conwell et al. (1993), and Fogler and LeBlanc (1995), all have an additional stage, which involves seeking alternative solutions to problems. Finding or generating alternative solutions is a specific feature of solving open-ended problems, such as the ones encountered in design courses, in industry and in real life.

The stages that are common to most of the strategies in Table 2-1 are discussed in the sections below. The table will be subsequently used to synthesise the strategy which will form the basis of this study. In each stage we will examine the activities which characterise that stage.

2.4 STAGES USED IN PROBLEM SOLVING STRATEGIES

2.4.1 Define the problem

All strategies in Table 2-1 have *definition* as a stage except the ones by Reif et al. (1976), Mettes et al. (1980), Schoenfeld (1985) and Rubinstein and Firstenberg (1995). Polya (1957), Reif et al. (1976) and Huffman (1997) did not have *define* as a stage but had some forms of *define* which were *understand the problem*, *description* and *focus the problem* and *describe the physics* respectively.

According to Woods et al. (1975), *define* is the stage where the solver identifies the real problem, that is, what the problem is about. Reif et al. 1976, suggest that the solver lists explicitly the given and desired information and draw a diagram of the situation. Leibold et al. (1976) and Lieske (1983) suggested that *defining* was about drawing a diagram; defining the system; listing knowns and unknowns; giving any criteria or constraints. Leibold et al. (1976) had an extra sub-step, which involved choosing symbols.

In the strategy by Mettes et al. (1980), *define* is a stage in problem solving, where the solver gets an overall picture of the data and the unknowns. This is the stage where the solver should understand the problem well. The desired activities are reading the problem carefully; transforming the text into a scheme using pen and paper to develop an image of the problem situation and to get a schematic survey of the data and unknown; and identifying what is to be looked for. Here a drawing can be used to make things clear. More activities are writing down the unknown in symbols; estimating the answer (its probable sign, magnitude, and dimensions); and considering special cases.

Schoenfeld (1985) argues that during problem *definition* the solver gets a feel of the problem (what is given; what is asked for; why the givens are there and whether the goals seam plausible; what major principles or mechanisms seem relevant; what mathematical context the problem fits in). What is required of the solver is to draw a diagram; examine special cases; and to try simplifying the problem.

Fogler and LeBlanc (1995) suggest that the solver gets to understand and define the real problem during *definition*. From experienced solvers it was found that one must collect and analyse information and data. Collecting data may involve describing the problem; determining missing and irrelevant information; and drawing sketches. Other important activities in this phase are talking with people familiar to the problem; viewing the problem first hand (by inspecting the problem); confirming all findings (verifying that all data collected is correct by cross checking and cross referencing data).

According to Fogler and LeBlanc (1995), it is also helpful at this stage to find out where the problem came from and explore the problem. Exploring includes identifying all available information; recalling or learning pertinent theories and fundamentals; and collecting missing information. The other activities that are used during exploring are solving a simplified version of the problem; hypothesising and visualising what could be wrong with the current situation; and brainstorming to guess an answer. Recalling past or related experience; sketching a pathway that will lead to the solution; collecting more data or information are all part of exploring. After using some or all of the activities above, students can write a concise statement defining the real problem.

According to the explicit strategy by Huffman (1997) *defining the problem* involves translating the written words of the problem into a visual description. The following should be included: a sketch of the problem situation; the given information; a question about what has to be found; and a general approach that can be used to solve the problem.

To conclude, *define the problem* is a stage in problem solving where the problem should be understood as suggested by Fogler and LeBlanc (1995) and Mettes et al. (1980). This is where one identifies what the problem is about and what is to be found. Mettes et al. (1980) and Schoenfeld (1985) argue that *define* is when an overall picture of the data and the unknown provided in the problem statement are obtained. One of the main activities at this stage is to translate the words of the problem into a visual description, which can be in the form of a sketch or a diagram. Another important activity is to collect information given of what is known and unknown. As in the strategies of Leibold et al. (1976) and Mettes et al. (1980), essential information to collect includes that of criteria and constraints that give one the boundaries in which to solve the problem.

2.4.2 Analyse the problem

As described by Leibold et al. (1976), and Lieske (1983), during the *analysis* stage, the problem is converted into a problem that can be solved. Activities here are finding out what the attributes are; identifying the area of knowledge;

collecting information; flowcharting the solution. Some details of this stage outlined by Leibold et al. (1976) are consideration of a basis; redrawing a diagram to present a variety of views and different levels of simplicity; identifying reasonable assumptions; and through a flowchart beginning to deal with a series of sub-problems. Lieske (1983), in this stage suggests the following steps: identifying background knowledge and experience, simplifying the problem by making assumptions; considering implicit constraints and criteria; identifying all issues; collecting necessary information or resources; listing attributes; and calculating order of magnitude values.

There is some overlap in the activities mentioned under the *defining* stage with those mentioned in *analysis*. Estimating the answer mentioned by Mettes et al. (1980) in *definition* is similar to the activity of calculating order of magnitude values mentioned in *analysis* by Lieske (1983). The activity of recall and learning of pertinent theories and fundamentals were also stated by Fogler and LeBlanc (1995) as *define* activities while Lieske (1983) refer to these activities in *analysis* as identifying background knowledge and experience.

In the strategy by Mettes et al. (1980) *analysing* the problem entails converting the problem into a standard problem by linking the unknown and the data with given relations between quantities. This is done by writing down useful relations; splitting the problem into sub-problems; checking the relations found for their validity in the problem situation; and interrelating unknown and data by applying the relations to the problem situation.

According to Schoenfeld (1985) *analysis* involves the consideration of other problems in order to produce a solution. The solver considers here essentially equivalent problems, slightly modified problems and broadly modified problems.

Huffman (1997) suggested that the sketch made during *definition* is translated at this stage to a simplified physics description. This stage comprises of three parts, that is, a physics diagram; a definition of variables including the target variable; and selection of quantitative relations (principles or mathematical relations that can be used to solve the problem).

In conclusion, the *analysis* stage is concerned with the transformation of the problem into a form that can be solved. At this stage the solver should identify background knowledge (Leibold et al. 1976; Lieske 1983) and experience (Lieske 1983) relevant to the problem. The problem at this stage is simplified by making reasonable assumptions or by splitting it into manageable sub-problems (Huffman 1997; Mettes et al. 1980). The information of the data and unknown can be linked at this stage by formulating relations between the two.

2.4.3 Generate

Fogler and LeBlanc (1995) describe a stage where one *generates alternative solutions* to the problem. At this stage the solver requires some idea generating techniques so as to generate the best solution. Some of the techniques used at this stage are brainstorming and analogy, which are both discussed in section 2.5 of this thesis. Similar to *generate* is as stage by Bransford and Stein (1984) *exploring alternative approaches*. This stage involves an assessment of how the solver is reacting to the problem and a consideration of options that might be employed. Options to be considered are for example working backwards discussed in section 2.5 of this thesis.

Here the solver should be able to recognise the different mental and technical blocks when they appear in order avoid hindering the process of generating new ideas. This stage is useful in open-ended problems where there is no single solution to the problem and not necessarily in a situation where the problem has a unique solution.

2.4.4 Plan the solution process

Planning is a stage found in the strategies of Polya (1957), Woods et al. (1975), Schoenfeld (1985) and Huffman (1997). This stage, according to Woods et al. (1975), is where alternative paths as to how the problem could be solved are considered. Methods that could be used to achieve a solution are also organised at this stage. In the strategy by Huffman (1997) the physics description formulated during *analysis* is translated into mathematical relations that can be used to solve the problem at this stage. This step involves constructing specific equations; checking for sufficiency (comparison of the number of equations and variables to be solved); and outlining the mathematical solution. Most of what is considered during *planning* by Huffman (1997) is part of *analysis* in the other strategies described by Leibold et al. (1976), Mettes et al. (1980) and Lieske (1983).

2.4.5 Decide on the course of action

In the Fogler and LeBlanc (1995) strategy, *Decide on the course of action* is where decisions are made about which alternative to choose after generating many possible solutions. Alternative solutions are each analysed so as to make a decision. Once a choice has been made, *planning* should be done to ensure success of the choice by identifying things that could go wrong; the cause of each potential problem; the preventative steps and the steps of the last resort. The task of making decisions could be used also in closed-ended problems in situations where one is stuck or is faced with alternative routes to obtaining the solution.

2.4.6 Implement the plan

Some form of *implementation* was stated in all the strategies given in Table 2-1 except those by Conwell et al. (1993) and Rubinstein and Firstenberg (1995). The main purpose of this stage is to carry out the plan devised in the *planning* stage. According to Mettes et al. (1980), this stage is concerned with working out the solution that has been found already. By this it means that all the necessary relations suitable for providing the solution are available. The actions involved are writing down the routine operations and the answer in a well-organised way; checking very frequently whether all signs, powers and units are taken along; and checking whether results still make sense. Apart from the step-by-step execution of the solution, Schoenfeld (1985), in his strategy suggested that this stage involved local checking of the solution.

In the Huffman (1997) strategy, *implementation* is where the equations are combined algebraically according to the plan to produce an equation with a single unknown target variable. The known quantities are inserted into the equation to calculate the value of the target variable.

During *implementation* one first plans the activities that need to be done to solve the problem; then the progress of the critical tasks in the plan are monitored; and the solution checked if it meets the specified objectives and criteria (Fogler and LeBlanc 1995).

The stage of *implementation* involves the application of the plan formulated in the *planning* stage in order to solve the problem. It is the stage where the required is found according to the *definition*, *analysis* and *planning* that would have been done. At this stage the solution should be checked frequently to make sure the criteria prescribed in the problem statement are met.

2.4.7 Evaluate the solution

The last stage in most strategies is that of *evaluation*. According to Mettes et al. (1980) looking at the answer and retracing the way the problem has been solved is used for checking if the problem has been solved correctly and completely. Possible mistakes can then be tracked down and corrected. What is done here is checking the answer by comparing it with the estimation that has been made in the initial stages and checking if the answer is the correct one for the question asked. This stage also involves checking all sub-problems if they have been solved and looking back at the way the problem has been solved to improve problem-solving skills.

Schoenfeld (1985) suggests that at the *evaluation* stage one checks whether the solution passes specific tests (does it use all pertinent data, does it conform to reasonable estimates or predictions, does it withstand tests of symmetry, dimensional analysis and scaling). General tests are also conducted to find if the solution can be obtained differently; can be substantiated by special cases; can be reduced to known results; and can be used to generate something new.

This phase according to Woods et al. (1975) is about checking the reasonableness and the mathematics; checking criteria and constraints; studying related problems; identifying implications in engineering, everyday behaviour and deserted island; identifying and memorising order of magnitude numbers; developing successive approximation strategies; studying problem solving skills learned; communicating results. *Evaluation* according to Reif et al. 1976 involves checking if each preceding stage was valid and if the answer makes sense. Huffman (1997) agrees that the solution is checked to ensure that it is properly stated, reasonable and complete.

Evaluation is where the solver must check that all criteria in the problem statement were fulfilled and that none of the constraints were violated. The solver must also check if the problem has really been solved and if the solution obtained is the best; if the solution is novel or if it was merely an application of principles (Fogler and LeBlanc 1995). *Evaluation* according to Schoenfeld (1985) and Fogler and LeBlanc (1995) should be done at various points during the process of problem solving especially when major decisions are made.

2.5 PROBLEM SOLVING HEURISTICS

Heuristics are rules of thumb used within the stages of a strategy to aid the solving process (Woods et al. 1979). These provide general suggestions that help an individual to understand a problem better or to make progress toward a solution (Schoenfeld 1985). Heuristics increase the chances of finding the solution by offering suggestions about what to do next (Woods et al. 1979) but give no guarantee of reaching that solution (Mettes et al. 1980). Different heuristic techniques can be utilised during problem solving to aid the solution process. Students should be introduced to alternative tactics for solving problems successfully (Woods et al. 1979). However heuristics do not replace the subject matter knowledge or compensate easily for its absence. Often successful implementation of a heuristic depends heavily on a firm foundation of domain specific tools and techniques (Schoenfeld 1985). A large number of heuristics have been suggested to aid a problem solver who is stuck (Noble 1983; Polya 1957; Rubinstein and Firstenberg 1995; Schoenfeld 1985; Woods et al. 1979).

2.5.1 Analogy

An analogy is an idea from related or unrelated areas, which can be used to develop a solution for a problem. An analogy provides a model that serves as a guide to identify the elements of a problem as parts of a more complete problem (Rubinstein and Firstenberg 1995). As an example, ideas, rules, laws, facts and conventions from one discipline can be transferred to other disciplines (Fogler and LeBlanc 1995).

2.5.2 Brainstorming

Brainstorming is a technique for generating ideas that stimulates creativity (Fogler and LeBlanc 1995; Noble 1983; Woods et al. 1979). Problem solvers need to develop triggers that will keep the flow of ideas (Woods et al. 1979). The more ideas that are generated, the better the chances there are for an innovative workable solution to a problem (Fogler and LeBlanc 1995). Brainstorming is most relevant for open-ended problems that have more than one solution.

2.5.3 Discuss Difficulties

It is helpful to communicate difficulties to another person (Noble 1983; Woods et al. 1979). This may help to loosen constraints and change one's frame of reference resulting in the generation of outstanding creative solutions (Rubinstein and Firstenberg 1995).

2.5.4 Extreme cases

This is the consideration of extreme cases (Noble 1983; Woods et al. 1979). If it is not clear what is happening, its is suggested that one ask a series of "what if" questions which should be chosen to help understand the problems quickly. Often these questions explore the constraints, the obstacles and the data given (Moore et al. 1979). An example of an extreme case relevant to material balances is increasing the conversion of a process to 100%.

2.5.5 Generalisation and Specialising

Generalisation is the consideration of a set of objects that contains the object under consideration (Polya 1957). Specialisation involves the consideration of a smaller set of objects from a given set of objects being considered (Polya 1957). We can see that both these approaches are valid and helpful in the path to a solution.

2.5.6 Incubation

Incubation involves stopping active work on the problem and letting the subconscious continue the work (Fogler and LeBlanc 1995; Noble 1983; Woods et al. 1979). If the solution to the problem is not an emergency incubation can be done. This technique can be used when stuck with generating alternative solutions or just in general when stuck on a problem.

2.5.7 Simpler Problem and Sub problems

The solver can solve a simpler problem (Noble 1983; Woods et al. 1979). A simplified version of the problem can be solved in order to obtain an estimate to the answer (Fogler and LeBlanc 1995). Complex problems can also be divided into manageable sub problems (Woods et al. 1979).

2.5.8 Use of models

Models are simpler representations of real world problems (Rubinstein and Firstenberg 1995). The problem statement can be transformed to a transparent form that can clearly describe the problem situation as given in the problem statement. Mathematical or graphical pictorial models may represent the problem. Other models such as symbols and equations can also be used.

2.5.9 Working backwards and working forwards

In working backwards it is assumed that the solution has already been found and it is worked backwards from there to see how the goal can be reached (Fogler and LeBlanc 1995; Polya 1957). The problem is not started at the beginning then followed systematically step by step to the end goal (Rubinstein and Firstenberg 1995; Woods et al. 1979) as would be done when working forwards. Whether one uses a working backward or working forward heuristic depends on the type of information present in the problem statement.

2.6 SKILLS REQUIRED TO SOLVE PROBLEMS

To be able to solve problems successfully, the problem solver requires some prerequisite skills, which serve as tools and techniques that could be used in a particular situation if that knowledge is called for (Lieske 1983; Schoenfeld 1985). The most commonly needed skills and requirements are mentioned in brief:

- Basic knowledge: This is the basic knowledge pertinent to the problem, which enables the solver to understand the problem and develop feasible solutions. Such knowledge may simply include the relevant facts known by the solver, concepts, laws, constants and formulae essential for the solution (Finegold and Mass 1985; Fogler and LeBlanc 1995; Schoenfeld 1985; Woods et al. 1979).

- Creativity: Creativity can be used to generate new ideas for problems of invention (Conwell et al. 1993; Fogler and LeBlanc 1995). Creative thinking is divergent and often violates principles (Conwell et al. 1993).

- Critical thinking: Critical thinking seeks to assess worth or validity of something that already exists and applies accepted principles. It is convergent and involves analysis of basic assumptions (Conwell et al. 1993).

- Experience for judgement: This is the memorised experience of factors that provide order of magnitude feelings as to what assumptions can be made and how reasonable the answer is (Lieske 1983; Woods et al. 1979).

- Selection of suitable strategy: To utilise skills well, it is essential to have an organised approach to solving problems called a strategy (Fogler and LeBlanc 1995; Lieske 1983; Woods et al. 1979). In addition the ability to select and implement suitable domain specific strategies is also important (Schoenfeld 1985).

- Translation of problem statement: The problem solver must be able to translate a problem as stated into the solvers' internal languages meaningfully (Finegold and Mass 1985; Gabel and Bunce 1994).

Problem solving is a complex process where the solver considers conditions of the problem in order to construct a solution for the desired outcome. By the information processing approach the process of solving problems involves the transformation of inputs into the outputs required. Solving a problem requires one to be equipped with a strategy, knowledge of rules of thumb for guidance and special skills, some of which are specific to the domain of the problem.

2.7 DEVELOPMENT OF A THEORETICAL FRAMEWORK

To develop a theoretical framework for this study, I used the different problem-solving strategies from the literature illustrated in Table 2-1, from which the stages of problem solving were pulled out. The steps and skills under each stage shown in Table 2-1 were carefully selected from the discussion of stages in section 2-4. I also looked at the skills required to be able to solve problems successfully as discussed in section 2.6 of this thesis. I then drafted a theoretical framework and later presented it to the lecturers of the Chemical Engineering Department at the University of Cape Town, after which a discussion followed. The staff members agreed the stages contained in the theoretical framework were suitable for chemical engineering problems that students encounter. The theoretical framework that was synthesised from a combination of the literature already discussed in Chapter 2 and the responses from the chemical engineering staff members is illustrated in Figure 2-1 and is also given as a fold out in Appendix 6. The important processes of problem solving that students should follow were; *defining the problem, analysing the problem, planning the solution process, implementation of the plan, evaluation of the solution.*

The skills in Figure 2-1 came from the discussion of skills required in Section 2.6 and the descriptions of the stages in problem solving strategies, Section 2.4. The framework presented in Figure 2-1 was then used in the formulation of the research methodology and to construct a coding scheme for analysis of results. However, this does not necessarily mean that students who do not follow the theoretical framework exactly would fail to solve problems. Following the discussion and lecturers' experience, it was generally agreed that students who go use the proposed framework are likely to get the solution with fewer difficulties, but with a few exceptions.

In general, it was concluded that to be able to solve problems in any course, students must have thinking skills, which embrace creative thinking, lateral thinking, and structured thinking and have a critical approach to problems.

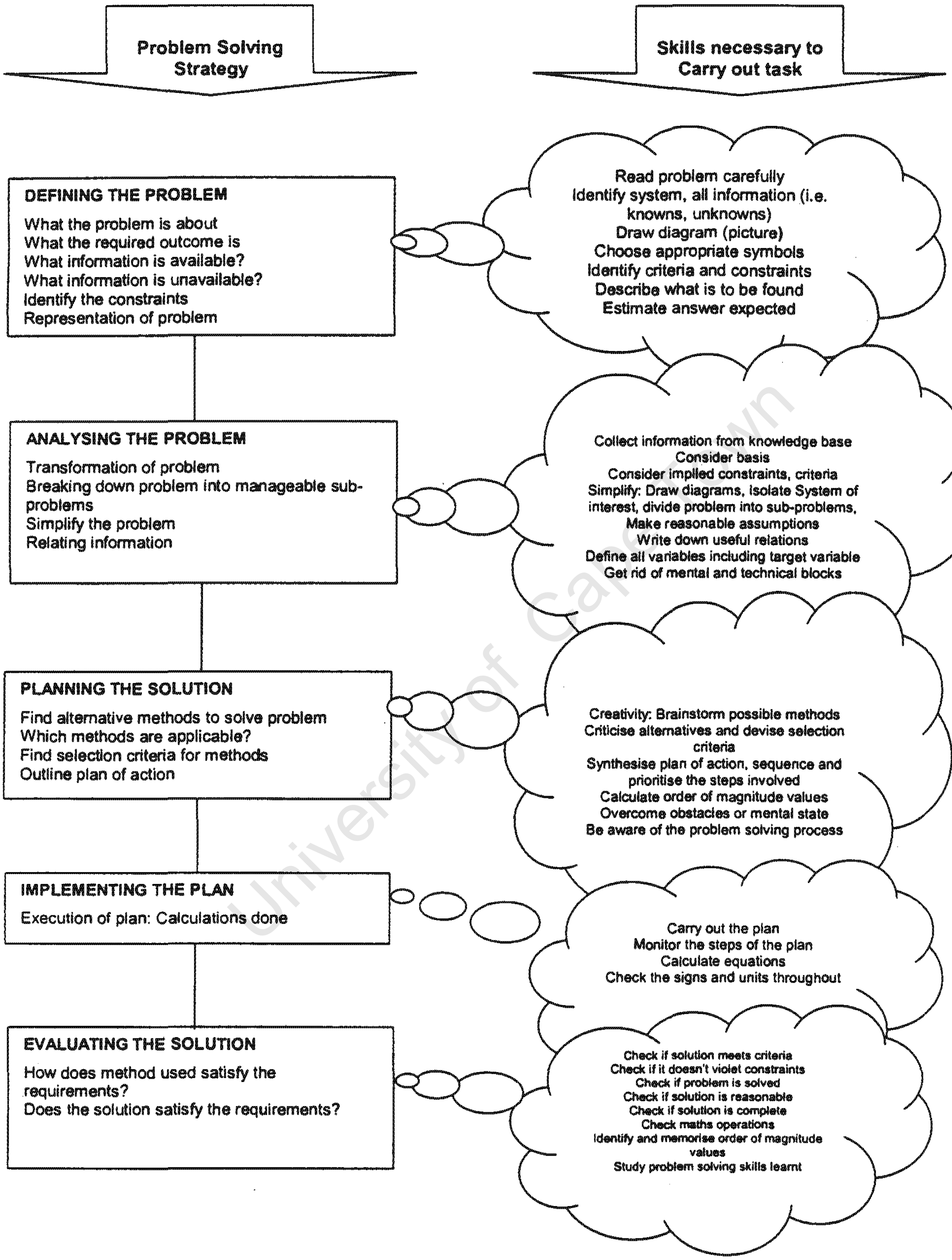


Figure 2-1 Theoretical framework for the study

3. RESEARCH ON HOW PEOPLE SOLVE PROBLEMS

What are the differences in the problem solving behaviour between experts and novices? Studies investigating these differences are discussed in this chapter. Some problem solving difficulties of problem solvers with different achievements in the domains of physics and chemistry are also highlighted. The attempts that have been made by different researchers to improve problem solving of students are discussed. Two approaches used to achieve this are teaching students the skills of experts or teaching students an explicit problem solving strategy.

3.1 EXPERT VERSUS NOVICE PROBLEM SOLVERS

Numerous studies have been done to identify the skills that experts use in solving problems and how they differ from those of novices (Dhillon 1998; Fogler and LeBlanc 1995; Larkin 1979; Simon 1989; Woods 1981; Woods 1989; Woods et al. 1979). The knowledge of experts' problem solving processes has been used to develop notes of procedures and skills for teaching students how to solve problems (Larkin 1979; Woods et al. 1979).

In his review of problem solving, Woods (1983) found that since 1975 the chemical engineers at Twente University in the Netherlands were focused on improving problem solving in the context of a chemical engineering thermodynamics course. The studies involved included that done by Mettes et al. (1980,1981). Studies on experts as they solved thermodynamics problems while thinking aloud were done to find out what key skills these experts used to solve these problems. The strategy of the experts was converted into a teaching-learning strategy, which was used in the class to teach students.

In trying to find how one can help students to solve problems in physics more effectively, Larkin (1979) asked two experts to think aloud as they solved five mechanics problems. These experts were professors of physics and had both taught lower division mechanics. The five problems were all taken from the physics textbook which students used. For comparison, Larkin also asked a novice, a student who had completed one quarter of physics, to solve the same problems given to the experts.

Two differences were identified between the experts and the novice. Firstly, experts were found to engage in a qualitative analysis or re-description of the problem (this is a visualisation of the physical situation described in the problem statement and imagination of what could happen in that situation). The qualitative analysis was generated by application of physical principles stored in memory. The novice on the other hand jumped directly from a physical situation described in the problem statement to quantitative equations. Secondly, in the memory of experts, physical principles are stored in a group or a chunk, a stimulus that has become familiar from previous repeated exposure and hence is recognisable as a single unit. Experts can thus solve problems considerably faster and more accurately than novices because when one principle is applied during problem solving, many other principles related to it will immediately become available to the expert (Larkin et al. 1980).

Also in physics, Dhillon (1998) studied the problem solving behaviour of thirteen participants (1 university lecturer, 2 doctoral students, 4 masters students, and 6 first-year undergraduates), all from the same physics department. The study was to identify the problem solving activities within the broader strategies, depict the expert and novice problem solving styles using the activities and to relate the activities to the general methods used by participants and those reported in literature. The lecturer (who had taught mechanics for over 20 years), the two doctoral students and one masters student (who had tutored mechanics for a number of years) were classified as experts. The other three masters students (who had just started their studies) and the four physics undergraduate students were classified as novices. Conducting think-aloud and pen-and-paper sessions plus recording observations of what was not verbalised and interviews for clarification of data were used for data collection.

Dhillon (1998) found that the experts declared and related quantities, clarified information and drew diagrams more than the novices did. In addition they constantly checked their work and logic as they progressed. On the other hand, novices used symbols, referred to examples and analogously deduced surface information when they encountered difficulties within the problem solution. The novices had difficulty relating quantities that did not have an obvious relationship. Instead they used symbols to infer similarities and connections between quantities.

In summary, unlike experts, novices have difficulty in relating quantities and jump into calculations without analysing problems qualitatively. Experts store their information in memory in chunks thus are able to apply principles that are related when solving problems. The experts tend to declare and relate quantities, clarify information and draw diagrams more than the novices do. Novices have difficulty relating quantities that do not have an obvious relationship while the experts can.

3.2 DIFFICULTIES WITH PROBLEM SOLVING

Other studies in problem solving literature investigated difficulties experienced while solving problems. Finegold and Mass (1985) examined solutions to physics problems and Adigwe (1991,1992) examined solutions to chemistry problems. The difficulties identified guided teachers in their preparation of problem solving instruction.

Finegold and Mass (1985) examined solutions to physics problems carried out by grade twelve high school students. The aim was to determine the differences in strategies employed by good problem solvers and poor problem solvers. Teachers classified students as good problem solvers and poor problem solvers according to the following descriptions. Good problem solvers were students who excelled in problem solving and whose final graduating grades in physics were at least 90% while the poor problem solvers were defined as students experiencing difficulties in solving problems and whose final graduating grades were above 60%. Students were asked to think aloud as they solved four physics problems.

The study showed that compared to poor problem solvers, good problem solvers translate the problem statements more correctly, plan their solutions more fully and in greater detail before carrying them out while poor problem solvers tend to solve without *planning*. Good problem solvers complete their solutions in less time and spend relatively more time on translation and *planning* than do poor problem solvers. However it was also shown that good problem solvers do not rely more heavily on algebraic solutions than do poor problem solvers and that good problem solvers do not tend to check their solutions significantly more than poor problem solvers do.

Adigwe (1991) attempted to identify persistent problem solving difficulties that pre-service chemistry teachers may experience in chemistry. Each teacher was given three written problems constructed to assess their problem solving capability, and knowledge of relevant chemistry and mathematics. The performance of the subjects in the three tests was used to categorise the teachers into high or low achievers and to identify those who were successful and unsuccessful in solving the problems.

Data generated from the study revealed that a significant difference existed between the successful and the unsuccessful solvers in their capabilities to identify understand and work within the problem conditions. The successful solvers were more capable of constructing problem-solving plans than the unsuccessful solvers. There were no differences in the ability to estimate possible answers to the problems between the two groups. The unsuccessful students were incapable of utilising all the information given and applying it correctly to generate necessary information to solve the problems. Successful solvers showed that they logically analysed and organised their work but the unsuccessful ones were likely to have problems in initiating problem solving approaches and had no solutions or incomplete solutions. Most of the pre-service teachers failed to *evaluate* their problem solving processes, there was no difference between the two groups in this regard.

In a follow up article Adigwe (1992) reported on the problem solving difficulties of 240 chemistry teachers. The teachers were given three tests that were designed to assess their problem solving capability, chemistry knowledge and mathematical capabilities. The performances in the three tests were determined and were used to categorise the teachers as high achievers and low achievers. It was not mentioned in the 1992 study whether the tests given were the same as those in the 1991 study.

Successful solvers were more able to identify, understand and work within the problem conditions or restrictions. However there were no significant differences found between the two groups on interpretation of data provided, descriptions of unknowns, descriptions of basic concepts, use of principles laws and rules involved in the problem. The unsuccessful solvers were unable to construct reasonable plans for the problem solving process. The two groups differed greatly in their ability to execute operations in problem solving. The low achievers showed a lack of logical analysis and organising skills, thus most of them had non-systematic approaches to initiate problem solving or had no solution at all. When there were solutions they were found to be incomplete. The successful solvers made correct application of information and generated necessary correct information for solving the problems. Both successful and unsuccessful solvers checked for the structural errors in their problem solving but however differed in their checking for correctness of problem solving plans and for executive errors, both of which were more common among the successful problem solvers. The problems of these teachers were similar to the problems of the pre-service teachers.

The differences between people with the same exposure to concepts are that the poor problem solvers do not translate problem statements correctly and that the solutions of the good problem solvers are *planned* in detail before carrying out the plan. The poor solvers spent less time on constructing their plans. The common problem found between the poor and the good problem solvers is that the two groups did not check their solutions.

3.3 HOW PROBLEM SOLVING ABILITY CAN BE IMPROVED

Many papers have been written on how to improve problem-solving abilities of students. Most researchers suggest that problem solving can be learned (Bransford and Stein 1984; Larkin et al. 1980). If students have available the processes that experts use to solve problems, perhaps then the students themselves could solve problems more effectively (Larkin 1979).

3.3.1 Effect of teaching expert's skills

Ten students were trained on how to apply seven physical principles needed to solve one type of Direct Current-circuit problem in physics by Larkin (1979). Five of the students were trained on how to do qualitative analysis and chunking. Qualitative analysis was taught by showing students some qualitative representation of principles. To teach chunking it was suggested to students by grouping principles on a chart that when certain principles are applied it is generally useful to proceed by applying the other specified principles. Students were then asked to think aloud as they solved three DC-circuit problems. Of the five students taught expert procedures, three solved all three problems and two solved two problems. Among the five students that did not receive training four solved at most one of the three problems. In this study acquainting students to experts' processes of qualitative analysis and chunking improved their problem solving.

In a similar study, Mestre et al. (1983) studied the problem solving behaviour of a group of forty-two students who were doing beginning college physics. Some students were taught to practise performing qualitative analysis of problems that involved integrating principles, concepts and procedures. The second group was taught a formula based approach for analysing problems while the third group was not taught at all. After the teaching, all students solved the same twenty-five problems on mechanics. Students who were treated with qualitative analysis of problems improved their performance of problem solving more than the other students did.

To find out how effective a new introductory course in chemical engineering was in raising students' awareness of problem solving processes in the context of material balances, Ko and Hayes (1994) introduced at the beginning of the course the McMaster six-step problem solving strategy that was pioneered by Woods. The strategy had the following steps: *I want to and I can, Define, Explore, Plan, Do it* and *Look back*. The stages in this strategy are similar to those by Woods et al. (1975) except the first stage *I want to and I can* which is basically an attitude that the solver must have in order to be able to solve problems. The instructor applied the McMaster strategy as well as the guidelines given in the prescribed book for the course when solving class examples. The students chosen for the study were first year students on the introductory course, second year students who had done the course and third year students who had not done the course. The data collected included a self-evaluation in which the students rated their own awareness of problem solving on a scale of 0 to 10.

Results showed that awareness of problem solving procedures was greater after the course compared to at the beginning of the introductory course. A questionnaire was used to find out what students thought about problem solving in chemical engineering, difficulties they experienced in solving problems, and methods used by students when they were stuck on problems. From the questionnaire, Ko and Hayes were able to differentiate four types of problem solving methods that they judged as being relevant to the materials of the course. These were creating external representation of problem information, making use of external sources of knowledge, drawing inferences from knowns, and re-representing the problem. Among the four problem solving methods, it was seen that the second year students had advantages over the other two groups in the first, second and fourth methods and less in the third method. Other methods mentioned by the students were, '*Take a break*', '*Ask for help*' and '*Work in groups*'. The third years scored highest on *Ask for help* and *Work in groups*. The first years did not mention *Working in groups* at all and they scored the least on *Asking for help*.

It was concluded that the second years that had completed the course were aware of many more problem-solving procedures compared to the first and third year students. The second year students seemed to show a difference from the other groups in the ability to create external representations, to use external sources of information and to re-represent the problem space, but showed a weakness in the ability to draw conclusions from what is known. The course was unable to increase awareness of drawing inferences from knowns. The strategies of *asking for help* and *working in groups* become more important as students progressed with their degree. The research showed that chemical engineering principles could be used to raise awareness of problem solving.

3.3.2 Effect of explicit instruction of strategies and heuristics

Woods et al. (1975) used a voluntary non-credit tutorial to improve students' problem solving skills. In this study Woods became a student again and attended all lectures with the students and gave them guidance on solving homework problems assigned each week. Students were introduced to a five-step strategy; *define, think about it, plan, carry out plan* and *look back*. In the tutorial sessions students had the opportunity to learn from each other as well as from Woods. Students also learned how to solve problems and became aware of problem solving skills and problem solving as an essential activity and one that can be improved. On the other hand it was possible for the researchers to learn how students solved problems and obtain first hand information on the problem solving training provided by the lecturers in different courses and to identify student difficulties.

From the lectures it was found that the professors provided hints on solving problems. However students did not make use of these hints because they lacked the skills of learning. Common learning difficulties found were *planning* and scheduling time, taking lecture notes that reflected what was said in the lecture and identifying the major ideas, laws and definitions. Students did not take note of most of the lecturers' discussions on problem solving, as this information was verbal and not written. Students had difficulty in identifying problem solving suggestions from lecture notes.

Accomplishments from the study were students' awareness of problem solving skills and possible strategies, reasonable proficiency at *defining the problem*, exposure to techniques for improving creativity and for the *think about it* stage of the strategy for ordinary well defined homework problems, exposure to application in open ended problems.

Senior students had the same general difficulties experienced by first years. These difficulties were faulty identification of the unknown, poor diagrams, inappropriate choice of symbols, inability to correctly define the system, and defining the problem so as to inhibit creativity.

Reif et al. (1976) argued that even when students know all the relevant facts and principles necessary for the solution of a problem, they may be unable to solve it because they lack any systematic strategy for guiding them to apply such facts and principles. They taught some students a simple problem solving strategy with the following steps: *description*, *planning*, *implementation* and *checking*. This strategy was explained to students and was demonstrated in the case of a few physics problems. Students were then provided with practice and feedback on a variety of problems of the kind in a physics introductory course. After the instruction, students were given other physics problems to solve aloud. The students who received the explicit instruction made greater use of diagrams, and made intelligent use of algebra before putting numbers into equations compared to students who did not receive the instruction. The protocols of the students who received the explicit instruction showed that students did more extensive *planning* and that students had greater success in attaining solutions than those students who did not have the instruction. Even when students did not attain the correct solution those who were taught a problem solving strategy had a tendency to use reasoning and steps relevant to the solution while many of the other students quickly got lost and started going down blind alleys.

Schoenfeld (1979) investigated the effect of explicit instruction of heuristics on college mathematics students. He divided a group of seven students into two groups. The two groups of students were given a five question pre-test of mathematical problems to solve while thinking aloud. After the pre-test all seven students were given twenty practice problems including the five of the pre-test. In the practice sessions, students worked on each problem for 15 minutes or until it was solved. When finished a solution was presented to them together with a tape where they listened to the solution. Four of the students were told on the tape how five heuristics could be used for solving problems. During all practice sessions plus the post-test session, the list of heuristics given below was placed in front of the four students. The heuristic was as follows: *draw a diagram if at all possible, if there is an integer parameter, look for an inductive argument, consider arguing by contradiction, consider a similar problem with fewer variables, try to establish sub-goals*. There was some improvement in the problem solving performance of the four students who received heuristic instruction. All students who got instruction on the heuristic had more problems that were completely solved in the post-test than the pre-test whereas only one student without the heuristic instruction solved one more problem completely in the post-test compared to the pre-test. The non-heuristic students also jumped into algebraic computations. Students who relied on the heuristics from the beginning solved the problems more correctly and faster than the ones who used the strategies much later in their solution processes. I think the finding cannot be conclusive since the sample used was small.

Huffman (1997) investigated the effect of teaching high school students an explicit strategy on students' conceptual understanding of physics and problem solving ability. He used a pre-test/post-test, quasi-experimental design to compare a group of students that received explicit instruction with one that was taught an ordinary textbook strategy. Half of the students were taught how to use an explicit problem solving strategy while the other half were taught how to use a textbook solving strategy. The explicit strategy had the following steps: *focus the problem, describe the physics, plan the solution, execute the plan*, and *evaluate the solution*. The textbook strategy had the steps *draw a sketch, define known and unknown quantities, select equations, and check the answer.* All the participants were then taught about Newton's law. At the end of the instruction, examining the students' solutions to physics problems compared the problem solving performance and conceptual understanding of students. Students in the explicit group showed improvement in the quality and completeness of their physics representations. There was no difference between the two groups on organisation of solutions, mathematical execution and in conceptual understanding of Newton's law.

3.3.3 Experience on application of Problem Solving Strategies

In learning to use the Woods et al. (1975) problem solving strategy *define, think about it, carry out the plan, look back*, Leibold et al. (1976) experienced difficulties especially with the *define* and *think about it* stages. Often the group did not know the correct meaning of the words in the problem. It was a common error for students to read what they thought and not what they were asked in the problem statement. In their statement of the unknown, students had the tendency to include possible solutions, constraints and criteria. In some cases what was identified as unknown was a set of equations to be solved for the unknown. Most of the time students did not draw diagrams or drew poor ones. In addition students forgot the system that is the process being described in the problem statement. This means that at different instances during solving problems students described a system different from the one that was initially defined at the beginning of the solving process. Students often made the problem very complicated by trying to use all the information they had. Understanding the meaning of criteria was very difficult for the students as well as acquiring quantitative experience about the real world to be able to make judgement. Ability to analyse and synthesise was also found to be very poor.

Example problems can be used to develop problem solving skills as well as knowledge if a problem solving strategy and heuristics are utilised. For example once a problem statement is read, students are asked to determine the given facts, what is being asked for, and to draw a diagram (Noble 1983).

Teaching expert skills and problem solving strategies seems to improve students' problem solving skills and problem solving procedures. In addition to improving problem solving abilities, the awareness of problem solving skills and strategies is also increased through teaching.

3.4 RESEARCH METHODS USED IN PROBLEM SOLVING STUDIES

Different methods have been used to carry out research on problem solving in engineering and science. The data collection instruments that have been used are thinking aloud sessions (Adigwe 1991,1992; Larkin 1979; Simon and Bhaskar 1977; Woods et al. 1979), questionnaires (Ko and Hayes 1994) and written solution methods with pre-test/post-test design (Huffman 1997). Different methods were used for different purposes. The think aloud sessions were mainly used to investigate how novices and experts solve problems. Questionnaires were used to find out what subjects thought about problem solving and the written pre-test/post-test design was used to test the effectiveness of an instruction method in improving problem solving skills of subjects.

3.4.1 Thinking Aloud Methods

Thinking aloud methods have been used extensively in the study of problem solving, (Adigwe 1991,1992; Dhillon 1998; Larkin 1979; Simon and Bhaskar 1977; Woods et al. 1979). During think aloud sessions, the subjects' verbalisations are recorded to form a protocol. A protocol is a transcript of the subjects' verbalisations during the course of problem solving (Adigwe 1992; Newell and Simon 1972; Schoenfeld 1985). The protocol may also include some remarks of the experimenter (Newell and Simon 1972). Think aloud methods were also used in conjunction with pen and paper methods where the subjects were given a piece of paper to write down their solutions as they think aloud (Dhillon 1998; Finegold and Mass 1985).

The main use of thinking aloud methods has been to investigate the problem solving processes of experts and novices. For example, in physics, Larkin (1979) examined the problem solving processes of experts compared to those of novices, Woods et al. (1979) studied protocols of an expert solving beginning physics problems as well as open ended trouble shooting plus design problems and about 200 novices solving trouble shooting problems. In addition, in the area of engineering, Simon and Bhaskar (1977) recorded protocols of an expert solving thermodynamics problems. The think aloud method has also been used in investigating the differences between two groups of students, good problem solvers and bad problem solvers (Adigwe 1991,1992; Finegold and Mass 1985). Common difficulties in solving chemistry problems were identified by recording protocols (Adigwe 1992).

Woods et al. (1979) engaged professors who were regarded as experts and students who were novices in think aloud sessions. The professors and students all solved freshman physics problems, open-ended problems and trouble shooting problems. This study was done to find out how problem solving could be taught to improve students' ability to solve problems. It was possible in this study to follow the approaches used by students to solve problems as well as the approaches of experts such that notes were developed for teaching problem solving.

Larkin (1979) also studied protocols of experts and novices in an effort to find problem solving methods that could help students solve physics problems more effectively. The subjects were asked to think aloud as they solved problems from a physics textbook. Their comments were tape-recorded and transcribed for detailed study.

The inquiry by Woods et al. (1979) and Larkin (1979) made it possible for them to identify the methods used by experts and novices to solve problems. The information obtained from their studies was made into notes that were used to teach students good problem solving skills. Another study by Simon and Bhaskar (1977) utilised think aloud procedures to investigate the problem solving behaviour of a teaching assistant while solving chemical engineering thermodynamics problems. The thermodynamic problems were typical of the problems that students were given in the course.

In general think aloud methods were used to:

- Identify problem solving activities within the broader strategies used in solving problems.
- Examine the differences in problem solving processes of experts and novices.
- Identify difficulties encountered when solving problems among successful and unsuccessful problem solvers.

3.4.2 Questionnaire methods

Using their own method, Ko and Hayes (1994) only asked students to talk about how they would solve a problem without engaging in the process. In their study, they asked the students to rate their awareness of problem solving processes on a scale of 0 to 10 (0 not aware at all and 10 being very aware). These ratings were carried out both at the beginning and end of the course. They also designed a questionnaire where students responded to three questions. The first question asking students to imagine advising a high school student about problem solving in chemical engineering; secondly to recall a problem previously solved then describe difficulties encountered and how they were overcome and lastly students were asked to describe methods they use when in trouble during problem solving.

3.4.3 Pen and paper method with Pre-test and Post-test design

Huffman (1997) used a pre-test and post-test quasi-experimental design to investigate the effect of explicit problem solving instruction on students' conceptual understanding of physics. Half the students were taught how to use an explicit strategy while the others used a textbook strategy to solve problems. Students were given two problems to solve in a problem-solving test where they were given 50 minutes to solve each problem. The quality of the solutions was judged by comparing them to experts' skills. Such skills were detailed qualitative descriptions of problems, mathematical solutions that match the qualitative descriptions, logical, well-organised solutions and correct mathematical executions. To measure these general characteristics a scoring system was designed. The scores showed gains in the characteristics of solutions for the explicit group more than for the textbook group.

3.4.4 Method used in the present study

Each of the methods discussed above has advantages and disadvantages that will be discussed in the context of this study. Thinking aloud sessions have a disadvantage in that students are asked to talk as they solve the problems yet in situations where they commonly encounter problems, that is, tests, exams and tutorials, they solve them quietly. There is a risk that students may concentrate their efforts on verbalisation rather than solving the problem, which may interrupt their thinking process.

Ko and Hayes (1994) recognised that the method they used had problems since they studied what students said about problem solving and not what they do when they solved problems. Students were only saying what they thought they would do while solving problems rather than solving the problems themselves. One may look like a genius in talking, which may lead the hearer to think that person would produce a good solution. On the other hand a student who has a language problem would be disadvantaged. Since Ko and Hayes (1994) indicated that they had taught the students about problem solving before the administration of the questionnaire there could be a possibility that in responding to the questionnaire they were just recalling the course contents rather than engaging on the actual problem being asked.

Pre-test and post-test designs have their own disadvantages. The assessment of the students' solutions was done satisfactorily in Huffman's study. However the treatment that was done, that is, teaching some students an explicit strategy and teaching others a textbook strategy put the students who got the textbook strategy instruction at a disadvantage since this method did not teach conceptual understanding. This kind of research is also biased because the students themselves can see that they have been split and some students may inform the other group of their methods. One half of the students may be slowed down in their learning process and this may even impact their future studies while the other half of the students will always be more up to scratch with their concepts. Such students would always have an upper hand with regards to the context used in the study.

For the purposes of the present study, a combination of think-aloud and pen-and-paper methods was found to be most useful and posed no threat to the academic development of students, both those who were involved and those who were not involved in the study. The research could not potentially disadvantage any students by teaching others how to solve problems properly and not teaching the others as was done by Huffman (1997). Unlike the research by Ko and Hayes, the think aloud method gives the students a chance to demonstrate how they actually solve the problems. In addition, with pen and paper, the students have an option of presenting the solution, which means that those who have a problem with language would not be disadvantaged. They can write down or even draw pictures although other students may not draw pictures if they would have understood the content of the problem. This method is able to provide valuable information on how students engage with the problems they are given to solve.

4. RESEARCH DESIGN

This chapter examines the research design for this study starting by discussing how students who participated in the current study were selected. The procedure in which the data was collected is also discussed as well as the data collecting instruments. The instruments were two tasks set in the context of material balances. The main features of the tasks are given plus model solutions to each of the two tasks.

4.1 SAMPLING OF STUDENTS

This research was conducted during the first semester of 2001. Fifteen students were selected from the second year class of 2001 for the inquiry. All students were at that time doing CHE 231F the Material and Energy Balances course for the first time. Repeat students, that is, those that had failed the course before and were doing it again, were excluded from this investigation. With the students' previous experience of material and energy balances they were expected to be at a different level of understanding concepts and problem solving compared to the new second years. The experience of repeat students may have amplified the problem solving ability of the sample, which the new CHE 231 students at that level may not have. There was also a risk of giving students who were repeating problem-solving tasks that they may already have seen. This could provide false evidence of their problem solving capabilities.

The students in the sample were selected by purposive sampling (Lincoln and Guba 1985) to obtain a sample comprising students of mixed gender and of different levels of achievement. All students in the class were categorised into three groups based on their performance in all their first year chemical engineering courses. Those students who had an average of 75% and above were in one group, those with between 60% and 75% were in another group while those with less that 60% were in another. Since the percentage of female students in the class was small, the three categories were further classified based on gender. Two or three from each subcategory were then randomly selected for the study.

For purposes of reporting, pseudonyms were given to the participants. Table 4-1 shows the students chosen and the groups they were in.

Table 4-1 The Profile of students

Pseudonyms	1st Year achievement	Sex
Kudzi	>=75	M
Tawa	>=75	M
Fadzi	>=75	F
Rudo	>=75	F
Gari	>=60	M
Kuda	>=60	M
Vimbi	>=60	F
Ranga	>=60	M
Tandi	>=60	F
Tasu	>=60	M
Fari	<60	M
Munya	<60	M
Saru	<60	F
Tafi	<60	M
Chipo	<60	F

4.2 EXPERIMENTAL PROCEDURE

Prior to the problem solving sessions the participants were approached informally and were asked to participate in the study. Students were also informed that the aim of the session was to determine how they solve material balance problems. A statement explaining the purpose and importance of the study preceded each problem solving session. The pre-session statement is given in Appendix 1. During the session students were given instructions on what they were expected to do. These instructions are also found in Appendix 1. The sessions took place in a quiet seminar room and lasted from 20 to 60 minutes. Timing of the duration of the solving process was not done since timing information was not critical to the study.

Two private sessions were held with each individual student and one problem was attempted each time. The sessions were eight weeks apart. An extended time between the sessions was decided on since there was a possibility that some development in the problem solving skills might have taken place in this period. The problems were sufficiently similar that the second task could have been task one. At the time when the Task 2 session was conducted, students had already written two class tests in material balances (CHE 231F) thus we could safely say students had prior knowledge of how to solve problems before tackling Task 2.

Students were asked to think aloud while solving each problem and were allowed to use a calculator with which they were familiar. They were also given pencil and paper to write their solutions. Students' verbalisations were tape recorded and later transcribed into protocols. In addition to the students' written records, notes were taken during the sessions by the researcher. Thus written and oral records of the problem solving processes were obtained.

Although students were asked to think aloud as they solved the problems some students did not find it easy to talk. In those cases the researcher made observations of students' movements and made a written record. Mini interviews were then held immediately after the problem solving session to clarify the observations made.

4.3 THE EXPERIMENTAL TASKS

In this section I will first discuss the general material balance equation so that it is clear how the problems that were given to students could be solved. Secondly, each problem given to the students in the problem solving sessions will be discussed, giving a model solution and thereafter the method for analysing the students' solutions.

The two tasks given to each student were set in the context of material balances since when the study was conducted the students had been introduced to material balances in their introductory course CHE104W. The students were also at that time of the study in the middle of CHE 231F, the material and energy balance course. In their material balance course students had been taught about the general conservation equation expressed as shown in equation (4-1):

INPUT – OUTPUT + SOURCES – SINKS = ACCUMULATION **Equation 4-1**

This equation holds for all conserved quantities (energy, mass and momentum). The input and output terms in the conservation equation represent the flow of material across the boundary of the system. The source and sink terms refer to the generation and consumption of mass within the system boundaries (e.g. chemical reactions which either produce or consume a given species). The accumulation term accounts for an increase or decrease of the conserved quantities within the boundaries of the system as time increases. If there is no change in any of the variables with time the system is said to be at steady state.

For the two problems considered in this study, there are no reactions taking place, therefore the sink and source terms are equal to zero. The systems are in a steady state since there is no accumulation of mass within the system boundaries. The material balance equation takes therefore the form:

INPUT = OUTPUT **Equation 4-2**

Both problems were taken unmodified from a material and energy balances textbook (Felder and Rousseau 1986). The two problems are typical of the problems that students are given in their tutorials, tests and exams. These problems involve common processes of making juice and jam rather than the traditional hydrocarbon chemical processes. Students meet juice and jam in their everyday lives more than they do hydrocarbons. The situations posed are typical of the problems that an ordinary jam or juice maker has to solve in the operation of the processes.

The problems were selected to explore various problem-solving activities of students. In each case the word evaporation is a keyword that alerts the subject to the fact that water is removed from the system. To solve the two problems students are expected to visualise the process being described and translate the information into a form that they understand. Solving both problems requires logic and common sense and only requires basic knowledge of material balances. The problems are comparable and both require quantitative and qualitative solutions. In each case the physical systems were described without the use of diagrams so that students could develop diagrams if they considered diagrams necessary for them to understand the problem. The problems solving tasks plus detailed explanations are given in Appendix 2.

4.3.1 Task 1: Jam Production

Strawberries contain about 15% (by mass) solids and 85% water. To make strawberry jam, crushed strawberries and sugar are mixed in a 45:55 mass ratio, and the mixture is heated to evaporate water until the residue contains one-third water by mass.

a. Calculate how many pounds of strawberries are needed to make 1lb jam.

b. Is the following statement true or false? The mass of the strawberries and sugar added is equal to the mass of the jam formed.

c. As the seasons change, a different fruit is used in the jam making. Peaches contain about 20% by mass solids (excluding stone). Will the ratio of fruit to sugar added decrease, remain the same or increase if jam of the same specification is to be produced? Explain.

In this problem students were asked to find the amount of strawberries needed to produce one pound of jam. The first thing expected in chemical engineering problems is to read and extract information given in the problem and translate it into a diagram form. For someone to solve the problem, a person should have background knowledge of how to construct flow diagrams and how process units are put together. A probable diagram for this problem can be represented by either figure below:

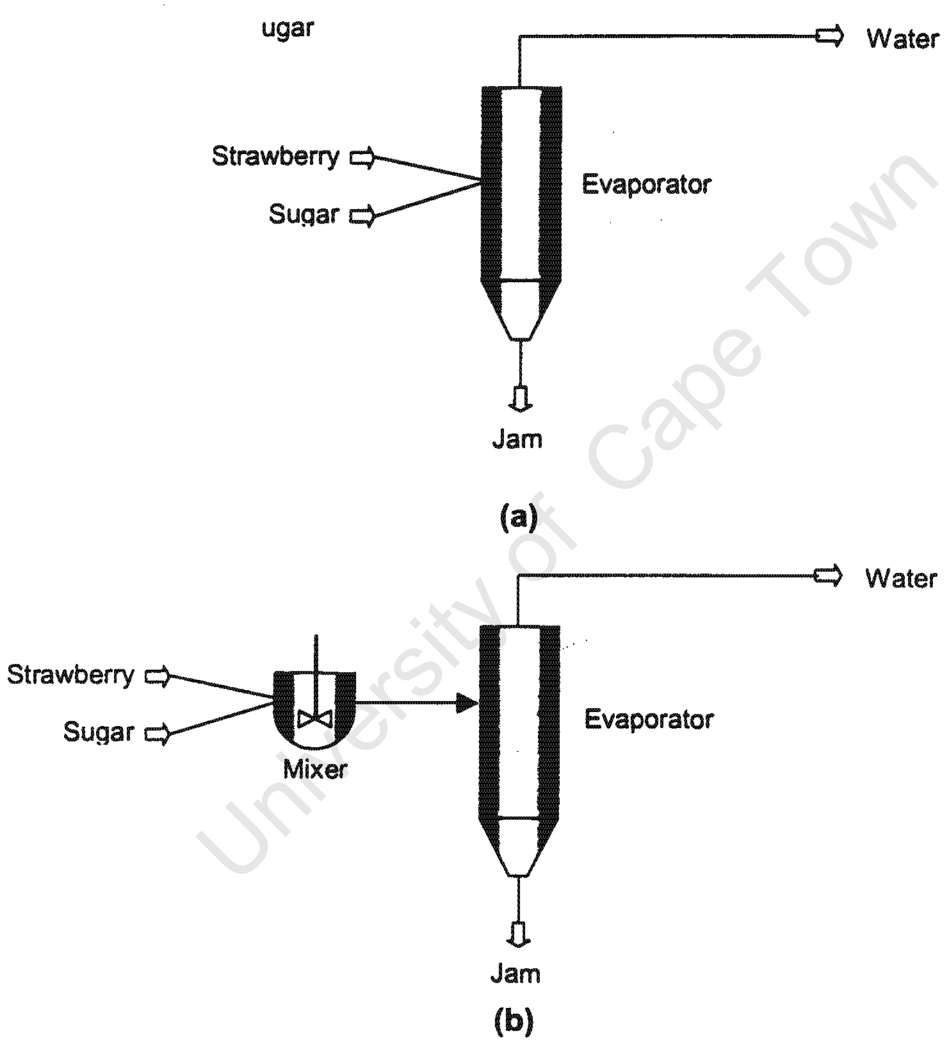


Figure 4-1 Process diagrams for Jam production

In Figure 4-1(a) strawberries and sugar are added directly into the evaporator, which means that the evaporator becomes both the mixer and the evaporator. In Figure 4-1(b), strawberries and sugar are mixed in a mixer first before they are fed into the evaporator.

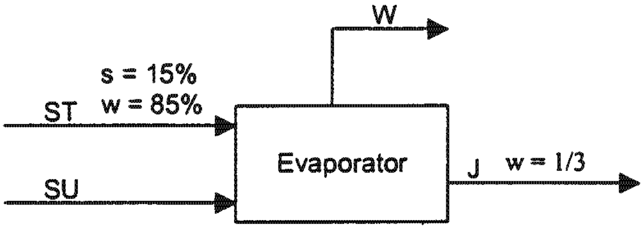
To start solving part (a) of this problem, that is, to find the amount of strawberries that makes one pound of jam there is need to choose a basis. "A basis is a reference chosen by a student for the calculations you plan to make in any particular problem, and a proper choice of basis frequently makes the problem much easier to solve" (Himmelblau 1992). In this problem there are four possible bases. The easiest choice of basis would be to take one pound jam, which is the product required out of the process. A second choice could be for example 100 pounds strawberries, a third 100 pounds sugar, and a fourth could be 100 pounds of both sugar and strawberries.

Part (b) of Task 1 is a conceptual question. If a person understood the problem they were supposed to realise that the water being evaporated is coming from the strawberries since they are made up of solids and water.

Part (c) is a bit ambiguous as far as the jam specification is concerned. The student has to show flexibility and understanding of the problem and be able to analyse the situation at hand with an open mind.

The basis of calculations chosen determines the approach followed in solving a problem. A number of model solutions were produced using different bases. It would thus be important to identify how many students used a particular basis and whether their approach is the same or different. One model solution is presented below in Table 4-2 that shows the stages of solving the problem according to the five-stage strategy of Figure 2-1. Another model solution is in Appendix 3.

Table 4-2 Jam production model solution (Basis = 1 pound jam)

DEFINE	From the problem statement the diagrams in figure (4-1) may represent the process described. I will call the strawberry stream ST, the sugar stream SU, water stream W and the jam stream, J; s = solids and w = water. 
ANALYSE	Basis: 1 pound jam Overall balance: Strawberry + sugar = water + jam i.e. $ST + SU = W + J$ Since the amount of jam formed is known as 1 pound, the balance becomes: $$ST + SU = W + 1$$ Species balance: In strawberry there are 15% solids and sugar consists of solids only. Water does not contain any solids but the jam contains 2/3 solids, which included the sugar, and the solids from the strawberries. Since the ratio of strawberry and sugar streams is 45:55, then it means that ST/SU = 45/55, thus SU = ST (55/45) We now have SU in terms of ST. Solids balance: $sST + sSU = sJ \quad \Rightarrow \quad 0.15 * ST + ST\left(\frac{55}{45}\right) = \frac{2}{3}$
PLAN	In order to calculate the amount of strawberries needed to produce 1 pound of jam I would need to do an overall balance around the process. Wait a minute; this will give me the total flow rates of each stream. There are still a lot of unknowns in the balance above thus we can try to do species balances over the whole process. The species in this process are solids and water. Well so it is now possible to find the amount of strawberries.
IMPLEMENT	$0.15 * ST + ST\left(\frac{55}{45}\right) = \frac{2}{3} \quad \therefore \quad ST = \frac{2}{3\left(0.15 + \frac{55}{45}\right)} = 0.486\,\mathit{pounds}$
EVALUATE	Water balance: $wST = W + wJ \Rightarrow 0.85ST = W0.33(1) \therefore W = 0.08\,\mathit{pounds}$ But $ST + SU = W + J \Rightarrow 0.486 + 0.486\left(\frac{55}{45}\right) = W + 1$ $\therefore W = 0.08\,\mathit{pounds}$

4.3.2 Task 2: Juice Production

Fresh juice contains 12 weight percent solids and the balance is water, and concentrated juice contains 42% solids. Initially a single evaporation process was used for the concentration, but volatile constituents of the juice escaped with the water, leaving the concentrate with a flat taste. The present process overcomes this problem by bypassing the evaporator with a fraction of the fresh juice; the juice that enters the evaporator is concentrated to 58% solids and the product is mixed with the bypassed fresh juice to achieve the desired final concentration of solids.

a. Calculate the amount of concentrated juice produced per 100kg fresh juice fed to the process, and the fraction of the feed that bypasses the evaporator.

b. The volatile ingredients that provide the taste are contained in the fresh juice that bypasses the reactor. You could get more of these ingredients in the final product by evaporating to (say) 90% solids instead of 58%; you could then bypass a greater fraction of the fresh juice, and you would thereby obtain an even better tasting product. Suggest possible drawbacks to this proposal.

The first thing expected in this problem is to visualise the process involved and to draw a diagram (Figure 4-2), which shows all the input and output streams as given in the problem statement.

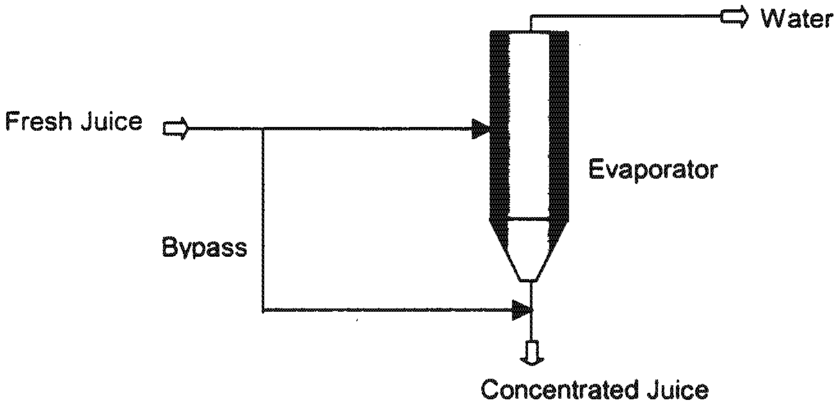


Figure 4-2 Process diagram for Juice Production

To solve part (a), students had to realise that the evaporator removes water from the fresh juice and that no solids of the juice will be evaporated with the water. It was also important for students to note that the vapours of flavour that leave the evaporator with water do not contain any solids This means that all the solids in the fresh juice end up in the concentrated product.

Here a student was expected to have knowledge of bypass operations in processes. When students were given this problem they seemed unfamiliar with a bypass process. Students were asked if they were familiar with the recycle process. Fortunately they understood how the recycle works in a system. The recycle process is simply the opposite of a bypass process thus with the aid of the diagram below I illustrated to the students how bypass differs from recycle.

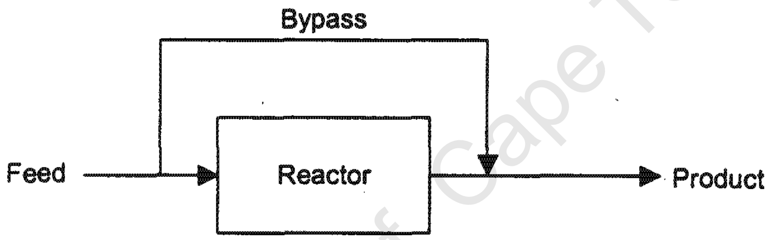


Figure 4-3 Illustration of a bypass process

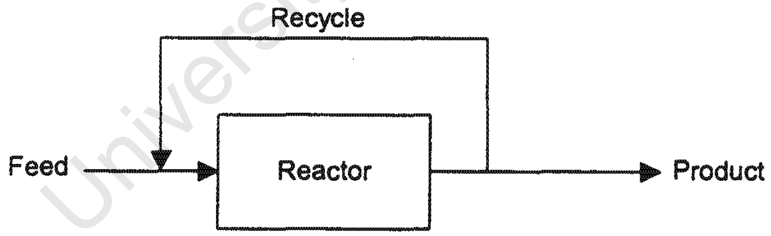


Figure 4-4 Illustration of a recycle process

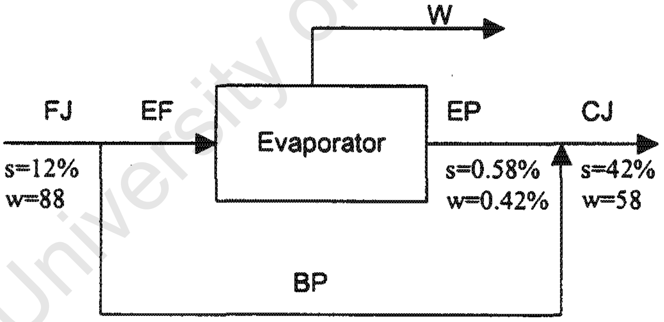
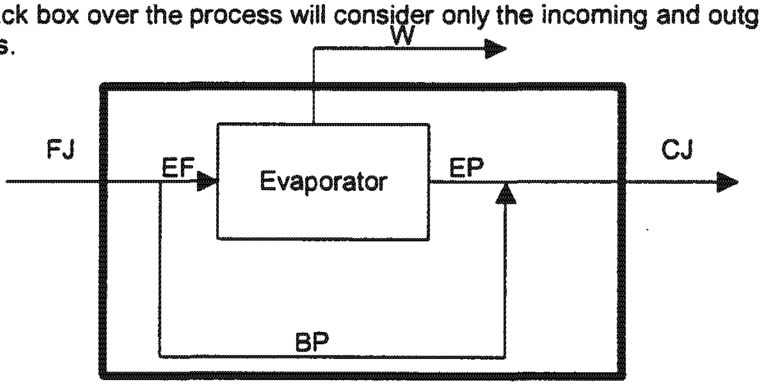
It was made clear to the students that this diagram was only an example and not the proposed diagram for the given problem.

As far as the bypass is concerned, the students were supposed to realise that when the fresh feed is split to the bypass stream and the feed to the evaporator, the proportion of solids and water in each of the streams remains the same. That is the composition of the bypass, and the feed to the evaporator remains equal to that of the fresh juice entering the process.

In part (b) of the problem, the amount of solids to be left in the juice after evaporation has increased from the 58% of part (a) to 90%. This means that more fresh juice would have to be bypassed to produce a juice mixture of the required concentration, 42% solids. Here a student was expected to analyse the effects of altering the juice process in that way. This required the student to put him or herself in the position of the "juice producer" so as to discover the changes that would result from implementing this proposal.

A model solution for the juice production process is shown in Table 4-3. A second model solution using a different basis is found in Appendix 3.

Table 4-3 Juice production model solution (Basis = 100kg Fresh juice)

DEFINE	So the process of interest is the one with a bypass. Symbols for the streams are: Fresh Juice, FJ; Evaporator Feed, EF; Bypass, BP; Evaporator product, EP; Water, W; Concentrated Juice, CJ; s=solids; w=water.  I need to find concentrated juice produced by 100kg fresh juice and the fraction of feed that is bypassed.
ANALYSE	Basis: 100 kg Fresh juice(FJ) The black box over the process will consider only the incoming and outgoing streams. 

	Overall Balance: $FJ = W + CJ$ Since the amount of fresh juice is known the equation becomes: $100 = W + CJ$. I still have two unknowns here. Solids balance: $0.12(100) = 0(W) + 0.42CJ$ Evaporator balance: $EF = W + EP \ldots$ (1) Solids balance: $0.12(EF) = 0(W) + 0.58(EP) \ldots$ (2) Water balance: $0.88(EF) = W + 0.42(EP) \ldots$ (3) Since we now know how much is in CJ and also FJ the overall balance can be used to find W. Balance around the splitter: $FJ = EF + BP \Rightarrow 100 = EF + BP$ (4)
PLAN	I will do a black box calculation (overall balance) to find the amount of concentrated juice. Now to find the fraction of the bypass I would have to find stream BP. The fraction of the bypass would be found by: $\frac{BP}{FJ}$
IMPLEMENT	Now the amount of CJ is $CJ = \frac{0.12(100)}{0.42} = 28.57kg$ From overall balance: $100 = W + 28.57$, thus $W = 71.43kg$ Subtracting equations (2) and (3), we get: $\frac{0.88}{0.12}0.12EF = \frac{0.88}{0.12}0.58EP - (0.88EF = 71.43 + 0.42EP)$ $\Rightarrow 71.43 = 3.833EP \therefore EP = 18.634kg$ Substituting values in (1): $EF = 71.43 + 18.634$ Substituting EF in (4): $BP = 100 - EF \Rightarrow 100 - (71.43 + 18.634)$ Thus $BP = 9.936kg$, The fraction bypassed is $\frac{9.936}{100} = 0.0994$
EVALUATE	There are so many equations in this part. Let me just see if they are all right. To check the bypass stream let me use the balance at the mixer: $EP + BP = CJ$. CJ=28.57kg so this must equal the sum of EP and BP which is $18.634 + 9.936 = 28.57$ Thus the answer for the bypass is correct.

4.4 ANALYSIS OF DATA

4.4.1 Development of a Coding scheme

A number of researchers have used coding schemes to analyse data collected (Adigwe 1991; Dhillon 1998; Finegold and Mass 1985; Gabel et al. 1985; Lucas 1980, cited in Schoenfeld 1985; Simon and Bhaskar 1977). Some modified schemes to suit their purposes (Adigwe 1991; Gabel et al. 1984; Lucas 1980, cited in Schoenfeld 1985). The analysis done by Larkin (1979) and Woods et al. (1979) was done to identify useful strategies that could be used to in teaching problem solving. Other analyses involve documenting the effectiveness of problem solving strategies, searching for correlation between the frequency of use of strategies and problem solving success (Adigwe 1991,1992; Dhillon 1989; Finegold and Mass 1985). Coded protocols by Simon and Bhaskar (1977) were analysed to discover regularities in problem solving behaviour.

Simon and Bhaskar (1977) developed a semi-automated coding system, SAPA for protocols. SAPA is an interactive programme that supports the coder in analysing protocols. The scheme is highly specific, it was designed for chemical engineering thermodynamics, and thus the programme is not relevant to other disciplines. The advantage of this method according to Simon and Bhaskar (1977) is that it has a higher reliability and validity than the manual coding schemes. The scheme assumes the protocols will be made up of the processes such as producing a relevant equation, evaluating a variable, solving an equation. The coder in this scheme could depart from the sequence of the scheme in order to imitate the actual sequence of the protocols.

(Lucas 1980, cited in Schoenfeld 1985) described the modification of a protocol originally developed by (Kilpatrick 1967, cited in Schoenfeld 1985) in mathematics education to analyse problem solving behaviour. Kilpatrick's coded data was used for statistical analysis to explore the correlations between problem solving success and the frequency of occurrences of certain problem solving processes. Lucas's scheme was designed to record and evaluate the many actions which could occur during a problem solution. Some of the activities the scheme checked for were: the kind of notation used; the number of diagrams drawn; whether or not the diagrams accurately represented problem conditions; the number and kinds of modifications; whether or not the subject recalled a related problem or applied its methods or results. The other factors considered in Lucas's coding scheme include the frequency of checking; the kind of checking; the type of errors made and a count of the instances in which errors were noted. Additional factors are methods by which solutions were produced such as analysis, synthesis, trial and error, reasoning by analogy; the equations, relations and algorithmic processes of the solution; separating or summarising data; looking back; trying a different mode of attack.

To determine the general problem solving skills used by high school students in solving chemistry problems, Gabel et al. (1984) adopted and modified a coding scheme from (Nurrenbern 1979, cited in Gabel et al. 1984). The modified scheme had the following categories: reading/organising; recall; production (systematic, arithmetic, non-systematic, no answer); strategy (algorithmic, algorithmic reasoning, trial and error); structural errors (misinterprets, disregards, misapplies); evaluation; comments about solution; executive errors. Gabel et al. (1984) argued that in the adopted coding scheme the subcategories were not suitable for the general categories thus they modified the scheme.

The analysis done by Adigwe (1991) employed a coding scheme, which was a modified version of that used by Gabel et al. (1984). The scheme (Adigwe 1991) consisted of the following main categories: problem understanding, construction of problem solving plans, executive operations in problem solving, structural errors in problem solving, and evaluation of problem solving processes.

Analysis of protocols by Finegold and Mass (1985) was based on the assumption that there would be differences between good problem solvers and bad problem solvers. Such differences could be examined as they might occur during the four stages of the problem solving strategy described by Polya (1957), *understanding the problem*, *planning the solution*, *carrying out the plan* and *examining the solution*. Time spent on *planning* and on the solution was also included in the coding scheme. Questions relating to the four stages and time spent on *planning* and on the solution were formulated:

-Did the students translate the problem correctly?
-Did the students plan the solution before carrying it out?
-Did the students solve algebraically?
-Did the students check the solution?

-How long, in minutes did the student spend on the solution?
-What proportion of the solution time was devoted to planning?

The coding of protocols by Dhillon (1998) depended purely on the protocols themselves. The coding began by reading the transcripts from the beginning and when the first activity was encountered it was noted. Reading the transcript would continue until another activity was discovered and then named.

To develop a coding scheme for the study at hand I assumed that the solving processes employed by students would correspond to the five stages of the theoretical framework of Figure 2-1. The scheme developed is shown in Table 4-4. The first four transcripts were analysed using the framework by reading line by line to identify activities then classifying them into the broad categories of the framework. The basic activities identified first were, for example, whether all the conditions described by the problem were noted, and if a diagram was drawn.

Those activities that were not in the framework but were specific to the problem or the context of material balances were introduced into the coding scheme. Such activities were:

- Describing the process correctly with a diagram;
- Describing basic concepts relevant to the problem which falls under background knowledge in analysis;
- Assessing the plan.

The scheme formulated from the theoretical framework and the first four protocols was then applied on the rest of the protocols and when another activity was discovered it was added in to Table 4-4. Examples of what was added in are:

- Whether the student produced a solution at all,

- If the solution was complete
- Characterisation of the solution.

The coding scheme, Table 4-4, is also reproduced in Appendix 7 as a fold out. All the transcripts were coded twice to make sure all the processes of problem solving were considered in the analysis.

The first five main categories of the coding scheme correspond to the stages of the theoretical framework in Figure 2-1. The subcategories of the scheme represent steps under each stage of the theoretical framework. The coding scheme in Table 4-4 shows the set of questions used to identify the steps in each stage. The scheme described below applies to problems where the solver is asked to find a quantitative solution to the problem. What the problem is asking the solver to find will be called the *required outcome* in this thesis.

4.4.2 Classification of quality of solutions

The problem solutions by the students were classified into three different groups namely good, partial and bad solutions. A good solution gives the correct answer to the problem, while a partial solution is close to the correct answer but has some errors. These errors could be in the formulation of equations or in the calculations. A bad solution is either fundamentally or conceptually wrong meaning that the solution will be far from realistic. Fundamental errors are those associated with the basic principles in a process while conceptual errors are those associated with the understanding of a situation.

Table 4-4 Coding categories and the associated questions

1. Defining the problem

1.1. Where all problem conditions noted?

1.2. Were the conditions described correctly?

1.3. Did the student draw a diagram?

1.4. Does the diagram correctly describe the process?

1.5. Were symbols used for representation of variables?

1.6. Was the required outcome noted?

2. Analysing the problem

2.1. Did the student choose a basis?

2.2. Was the basis used correctly with the problem conditions?

2.3. Were problem conditions linked to the required outcome correctly?

2.4. Were relations between knowns and unknowns correct?

2.5. Were these relations checked for their validity?

2.6. Were all relations translated into the correct equations?

2.7. Did student describe any basic concept related to the problem?

3. Planning the solution

3.1. Is there evidence of planning?

3.2. Did student assess the plan?

3.3. Is the plan well structured?

3.4. Is the plan relevant to the problem solution?

4. Implementing the plan

4.1. Does implementation follow the plan exactly?

4.2. Is the implementation checked for errors?

4.3. Was the student able to produce a solution at all?

4.4. Was the solution complete?

5. Evaluating the solution

5.1. Was the solution checked?

5.2. Were the intermediate calculations checked?

6. Characterisation of the solution

6.1. Was the student successful?

6.2. Were answers to other questions correct?

6.3. The solution was Good (G), Partial (P), or Bad (B)

5. RESULTS

5.1 INTRODUCTION

This chapter presents the analysis of how students solved the two tasks they were given using the categories in the coding scheme developed in Chapter 4. The results focus on students' responses to parts (a) of the two tasks they were given. The chapter discusses the success of students in providing correct solutions to the problems and the activities the students used in order to obtain solutions. The broader strategies used by students in solving the problems will also be discussed. Ways in which the two tasks were solved are compared to identify any similarities or differences in methods used.

5.2 TASK 1: JAM PRODUCTION

Complete tabulated responses to questions in categories of the coding scheme may be found in Table 5-1. An example of how transcripts were coded is found in Appendix 4, the coding of Kudzi's transcript. Table 5-2 shows the number of students who executed activities in each category of the coding scheme.

Under *defining*, all fifteen students noted the process conditions, while only eight of them stated the required outcome. In *analysis* all students chose a basis, while only two checked relations for validity. Only five students showed any evidence of *planning*. All their plans were relevant and four of them were well structured. The only students to assess their plans were the two who checked relations for validity. Those students with plans all followed them exactly. Only two (one of whom had also checked relations for validity) checked for errors during *implementation*. Only five students checked their solutions and only four were observed to have checked their calculations. As for the characteristics of the solution, there were seven good, six bad and two partial solutions produced for Task 1.

Table 5-1 Responses to questions of the coding scheme in Task 1

Student	Kudzi	Tawa	Vimbi	Ranga	Rudo	Chipo	Gari	Fadzi	Tasu	Munya	Tandi	Fari	Kuda	Saru	Tafi
Define the Problem															
Were all problem conditions noted?	y	y	y	y	y	Y	y	y	y	y	y	y	y	y	y
Were the conditions described correctly?	y	y	y	y	y	Y	y	y	y	y	n	y	y	n	y
Did the student draw a diagram?	n	y	y	y	y	Y	n	y	y	y	y	y	y	y	y
Does diagram correctly describe the process?	-	y	y	y	y	Y	-	y	y	y	n	n	y	y	n
Were symbols used for representation of variables?	y	y	y	n	y	Y	y	y	y	y	y	y	n	y	y
Was the required outcome noted?	y	y	y	n	y	Y	n	y	y	n	n	n	n	y	n
Analyse the problem															
Did student choose a basis?	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y
Was basis used correctly with problem conditions?	y	y	y	y	y	y	y	y	y	n	n	n	y	n	n
Were problem conditions linked to the required outcome correctly?	y	y	y	y	y	y	y	n	y	y	n	n	n	n	n
Were relations between the knowns and unknowns correct?	y	y	y	y	y	y	y	y	n	n	n	n	n	n	y
Were these relations checked for their validity?	y	n	n	n	y	n	n	n	n	n	n	n	n	n	n
Were all relations translated into the correct equations?	y	y	y	y	y	y	y	n	y	n	y	n	n	n	y
Did student describe any basic concept related to problem?	n	y	y	y	n	y	n	n	y	y	y	n	n	n	n
Planning the Solution															
Is there evidence of planning?	y	n	y	n	y	n	n	y	y	n	n	n	n	n	n
Did student assess the plan?	y	-	n	-	y	-	-	n	n	-	-	-	-	-	-
Is the plan well structured?	y	-	y	-	y	-	-	y	n	-	-	-	-	-	-
Is the plan relevant to the problem solution?	y	-	y	-	y	-	-	y	y	-	-	-	-	-	-
Implementation of the Plan															
Does implementation follow the plan exactly?	y	-	y	-	y	-	-	y	y	-	-	-	-	-	-
Is the implementation checked for errors?	y	-	n	-	n	-	-	n	y	-	-	-	-	-	-
Was the student able to produce a solution at all?	y	y	y	y	y	y	y	y	y	y	y	y	y	y	n
Was the solution completo?	y	y	y	y	y	y	y	y	y	n	y	y	y	y	n
Evaluation of the Solution															
Was the solution checked?	y	y	n	n	y	n	y	n	y	n	n	n	n	n	n
Were the intermediato calculations checked?	y	y	n	n	n	n	y	n	y	n	n	n	n	n	n
Characterisation of the Solution															
The solution was Good (G), Partial (P), or Bad (B)?	G	G	G	G	G	G	G	P	P	B	B	B	B	B	B
Was student successful?	y	y	y	y	y	y	y	n	n	n	n	n	n	n	n
Was the answer to question (b) correct?	y	y	y	y	y	y	y	y	n	y	n	y	n	n	y

Key: y=yes, n=no, G=good, P=partial, B=bad;

Question (b) is the conceptual question

Table 5-2 Number of students who executed activities in each category of the coding scheme: Task 1 (total number of students =15)

Activity	Number of students
Defining	
Noted problem conditions	15
Problem conditions described correctly	13
Student drew a diagram	13
Diagram correctly described the process	10
Symbols used for representation of variables	13
Required outcome noted	8
Analysis	
Student chose a basis	15
Basis used correctly with problem conditions	15
Correct links of problem conditions to required outcome	9
Correct links between knowns and unknowns	9
All the relations checked for validity	2
All relations translated into correct equations	10
Student described any basic concept related to the problem	7
Planning	
Planning the solution	5
Student assessed the plan	2
The plan well structured	4
The plan is relevant to the problem	5
Implementation	
Implementation follows the plan exactly	5
Implementation was checked for errors	2
Students able to produce a solution	14
Complete solutions	13
Evaluation	
Solution was checked	5
Intermediate calculations were checked	4
Characteristic of Solution	
The solution is good	6
The solution is partial	2
The solution is bad	6
The required outcome produced	7

5.2.1 Defining the Problem

Generally students carried out most of the activities set out in Table 5-1 while *defining the problem* to be solved.

Noting problem conditions

In this category the student was familiarising himself or herself with the problem. Here one wants to know what is involved in the process and what is happening to the different components of the system, what quantities or proportions the inputs and outputs are. Thirteen students drew diagrams. Six of them first wrote all the information given on a piece of paper before drawing a diagram to which the information was transferred. The other seven students put all information directly onto diagrams. Two students, Kudzi and Gari, did not draw diagrams. Gari presented information in tables, which divided the solids from the water. Seven students verbalised their information gathering, for example the following statement by Kudzi:

> Okay, umm, strawberries contain 15% solid and 85% water. Crushed strawberries and sugar are mixed in that ratio. ...Of this 15% solid and 85% water this is gonna make up 45 parts and then sugar crushed strawberries and sugar... So the sugar is gonna make up 55 parts sugar, sugar mass ratio mass, so umm the mixture is heated to evaporate water until residue contains 1/3 water by mass. (Kudzi)

The verbalisations of students as the example illustrated above consisted of the information given for the strawberries and the sugar inputs as well as the jam product. The verbalisation by Ranga showed some understanding of the problem but he had a misinterpretation where he said: "1/3 of the water we had will go to the jam".

Drawing a diagram

As stated above, all students except two drew diagrams to represent the process described. Three of the students drew diagrams that misrepresented the process. The process could be represented as illustrated in Figure 4-1. Students could either draw a diagram with a mixer or one without. Both diagrams describe the process well. Most students (10) drew the diagram without a mixer while only three drew the one with a mixer. Three of the students without mixers had one input stream into the evaporator, which contained a mixture of strawberries and sugar. This means that the strawberries and sugar were mixed elsewhere and brought to the process mixed already in the right proportions.

The two incorrect diagrams reproduced below show that the students did not understand the process involved, that is, what is happening to the mixture of strawberry and sugar. Both diagrams had the product of the process, jam, separated into two streams. In addition to separating the product stream, the diagram produced by Tafi did not have the stream of evaporated water coming out of the process. The diagrams produced by Tandi, Fari and Tafi are shown below:

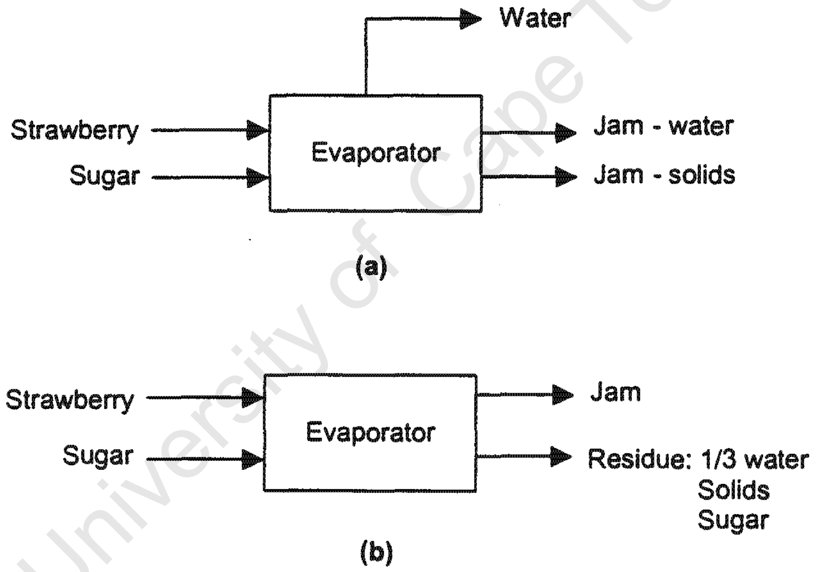


Figure 5-1 Diagrams drawn by Tandi and Fari (a) and Tafi (b)

Use of Symbols

In general students used symbols appropriately to represent variables. Only two students, Kuda and Ranga, did not use symbols, instead variables were represented by their full names. Of the students who used symbols, eleven of them had a symbol for the strawberries, for which they had to solve. Quite a number of students had symbols for sugar and jam. Only one student gave symbols to the strawberry solids and water (including the strawberry water).

Stating the Required outcome

About half (8) of the students stated what the problem required them to find. The following is a statement by a student who verbalised what was to be found.

> I will try to choose a suitable basis based on what I have been asked for, in this case strawberries to produce one pound of jam (Fadzi)

The above statement by Fadzi as well as those by Tasu and Tawa were given right after the problem was read. Most of the other students only mentioned what they were supposed to find much later on in their problem solving processes. For Vimbi and Kudzi, the problem statement was mentioned after all the unknowns of the problem had been found.

Chipo also attempted to calculate the unknowns before she stated the problem requirements. She however encountered problems with the strawberries and sugar mass ratios and decided to do the other parts of the problem. The second and third parts of the problem seemed equally demanding for her so she went back to do part (a) and at this stage stated the outcome required. Saru and Rudo mentioned the main requirement of the problem by just reciting words in the problem statement. All verbalisations of the required outcome were correct and stated clearly what the problem was looking for.

5.2.2 Analysing the Problem

All students chose a basis to eliminate some of the unknowns of the problem. Students had been introduced to the idea of choosing a basis in their first and second year chemical engineering courses, and most did this with ease. Chipo however had problems deciding what basis to use. Initially she chose 100 pounds strawberries. She however struggled to use the ratio of strawberries to sugar, which was 45:55. She then tried to use one pound of jam but this did not seem to be much easier to work with.

> The problem is my basis.... Because once I get a proper basis I can just work with that to get somewhere. The thing is I know what I wanna do but I just can not do it. In both cases I know what to do, I need to just know what's right, where do I go how do I start doing? (Chipo)

The table below gives a picture of the number of students who chose a particular basis for their calculations.

Table 5-3 The number of students who chose a certain basis

Basis	100 lbs ST & SU	100 lbs ST	1 lb. J	44 lbs ST	1 kg ST	55 lb. ST
Number	3	3	6	1	1	1

Note: ST = strawberries, SU = sugar, J = Jam

From Table 5-3 it can be seen that one pound of jam was the most popular choice of basis. This is also the basis where the calculations give the exact amount of strawberries required. All the other bases needed scaling of calculations at the end. The problem with one pound of jam as a basis is that students found it difficult to work from the product stream to the input stream of the process. Students who chose the other bases ran a risk of making mistakes during scale up or down of values to get the quantities to the required proportional amounts.

Stating Principles relevant to the task

The essential principle stated by a few students was that *the mass into the process is equal to the mass out*. This is a statement of the material balance equation (4-2) in Chapter 4. The students were also required to use this equation to formulate relations needed to calculate the amount of strawberries required. As can be seen in Table 5-2, in the subcategory “correct links of problem conditions with the required outcome”, about half of the students failed to do so. This showed that although students stated the relevant principle it was not properly integrated into the problem.

5.2.3 Planning

In the *planning* stage the students clarified for themselves what they had to do in order to solve the problem. Only five students were identified as following this stage. Few students mentioned their intention or even how the steps were going to follow each other. Students generally jumped straight into the calculations. Of those that did verbalise *planning*, a representative quote is below:

> So we would have to work out of this 92.625 solid strawberries make up. Yah you work out the percentage of solid strawberry of the total and you work that back to obtain the strawberries. (Kudzi)

The statement by Kudzi is about organising the sequence of calculations involved after some calculations of unknowns had been complete.

5.2.4 Implementation

Most students produced complete solutions to the problem although some of them were not correct. Complete solutions are those where the steps followed reach a stage where a solution is provided. Only one student did not get a solution and only one more had an incomplete solution. For those that did not attain a solution, the main reason was they couldn't make a start on a solution. Tafi for example had two equations written down relating jam with the strawberries and sugar but could not proceed further. Initially Chipo was not sure how to tackle the problem. After choosing the basis and having used it to find the feed materials she reached a point where she did not know where to continue so she said:

> I know what to do here but I don't know how to do it. Work backwards from, to find out how much water I have in my strawberries.... Is there anyway of working backwards to getting the water in your strawberries seeing that you have the water that's leaving? (Chipo)

During *implementation*, Kuda and Fadzi disregarded some valuable information of the problem thus their equations were not complete.

5.2.5 Evaluation

After doing calculations, students just put down their pens saying they had finished. A few looked back at their calculations to make sure they were all correct. Even the relationships that were formulated were not reviewed before most students applied them. Checking was mainly done by just re-punching numbers into the calculator. If the answer obtained was the same as before it was considered correct. Below is an example of a quotation by Tasu as he checked his calculations:

> Okay let me just check that. Umm okay well, no,no,no, is equal to zero. And check that gives me the correct ratio so it is correct. (Tasu)

Tasu's checking involved doing a calculation from the answer to find the initial variables then finding their ratio if it was still the same as the one provided in the problem statement. In Gari's case, checking seemed to depend on the magnitude of the values he was expecting. If any of the figures obtained from calculations seemed wrong, he would check the calculations made to confirm the answer was right.

5.3 CHARACTERISTICS OF THE SOLUTION

Although all students chose a basis, some of them could not use it to calculate problem conditions. The main reason was that several students failed to use the ratios of species provided in the problem statement. These students produced partial solutions. When students used a basis correctly, they got a solution of good characteristic or had partial solutions. The students who were unable to answer the conceptual question correctly had either partial solutions or bad solutions. Some of the students did not apply the simplified material balance equation correctly in formulating relations between the knowns and the unknowns, thus their solutions were either partial or bad.

5.4 SUCCESS IN SOLVING THE PROBLEM

Success in solving the problem will be defined in this thesis as the production of the correct answer for the problem-solving task given.

Table 5-4 shows the number of students who performed activities and whether they were successful or unsuccessful in achieving the required amount of strawberries. As shown in Table 5-1, all the students who had good solutions were successful and all those with partial and bad solutions were not successful in finding the required outcome.

Table 5-4 Numbers of students who executed a certain activity and their success in solving Task 1.

Activities	Successful	Unsuccessful
Diagram drawn [13]	5	8
Diagram not drawn [2]	2	0
Diagram describing process correctly [10]	5	5
Diagram NOT describing process correctly [3]	0	3
Required outcome stated [8]	5	3
Required outcome NOT stated [7]	2	5
Basis linked correctly to conditions [10]	7	3
Basis NOT linked correctly to conditions [5]	0	5
Required outcome linked correctly to conditions [9]	7	2
Required outcome NOT linked correctly to conditions [6]	0	6
Relations of knowns and unknowns correct [9]	6	3
Relations of knowns and unknowns incorrect [6]	0	5
Relations checked for validity [2]	2	0
Relations NOT checked for validity [13]	5	8
Relations translated into correct equations [10]	7	3
Relations NOT translated to correct equations [5]	0	5
Described basic concept [7]	4	3
Did NOT describe basic concept [8]	3	5
Evidence of planning [5]	3	2
NO evidence of planning [10]	4	6
Solution evaluated [5]	4	1
Solution NOT evaluated [10]	3	7

The numbers in the square brackets in the table indicate the number of students who executed the activity.

The following activities in Table 5-4 seem to indicate the conditions for unsuccessful solutions: diagram not describing process correctly, basis not linked correctly to conditions, required outcome not linked correctly to conditions, relations of knowns and unknowns incorrect, relations not translated to correct equations.

Drawing a diagram did not seem to have an effect on the success in solving the problem, since the two students who did not draw diagrams were able to solve the problem successfully. However a good diagram was not always associated with successful solving as of the ten students who drew good diagrams only five were successful. The three students with wrong diagrams were successful and had bad solutions as shown in Table 5-1.

The students who linked the required outcome to the problem conditions correctly were capable of solving the problem. Those who failed to link the required outcome to the problem conditions may not have been clear as to what they were looking for since they had not stated the purpose of the problem and were thus unsuccessful.

Students who described good relations between the known and the unknown were able to solve the problem while those who made the wrong relations could not solve the problem. In seven out of ten cases where students had correct equations, they were able to obtain the right answer.

It is not clear how *planning* affected the solving of the problem. This is because a considerable number of students who did not show evidence of *planning* were able to solve the problem. On the contrary a large number of those who were not observed to *plan* were unsuccessful in solving the problem. Students may have *planned* in their heads.

Of the students who were unsuccessful in solving the problem, most of them did not *evaluate* their solutions. Those who did some checking on their solutions were able to rectify their mistakes and had a greater chance of solving the problem successfully.

Some of the students who failed to solve the problem disregarded information that they could not fit into their problem solving process. Kuda for example disregarded some information about the inputs to the problem. When asked to say what he was thinking as he solved the problem Kuda said the following:

> ... when I looked at the first part of the problem I didn't think that, like I thought this is actually not important. (Kuda)

Examples of students who made errors in the construction of their solutions are as follows: Fadzi who was unsuccessful and produced a partial solution linked the required outcome and the problem conditions incorrectly by leaving out one variable in the relationship. In Saru's case all relations formulated were wrong since she had not described the problem conditions correctly thus she was unsuccessful and had a bad solution. For Tasu it was carelessness on his part as he wrote down and used the wrong value for the known, strawberries were in the ratio 45:55 with sugar but he worked with a ratio of 44:55.

It can be seen from combining Table 4-1 and 5-1 that of the nine male students who participated in the study, four solved Task 1 correctly and five did not. Three of the six female students solved Task 1 while the others did not. These results show that success in solving problems is independent of gender. As for the students' achievement in first year, out of the four students who had average marks greater than or equal to 75, three were successful in solving the task but one was not. Of the students with average marks greater than or equal to 60 three were successful and the other three were not. Of those with marks less than sixty, one was successful and four were not successful. Students' chances of success decreased with decrease in their first year marks.

5.5 SEQUENCES USED BY STUDENTS WHILE DOING TASK 1

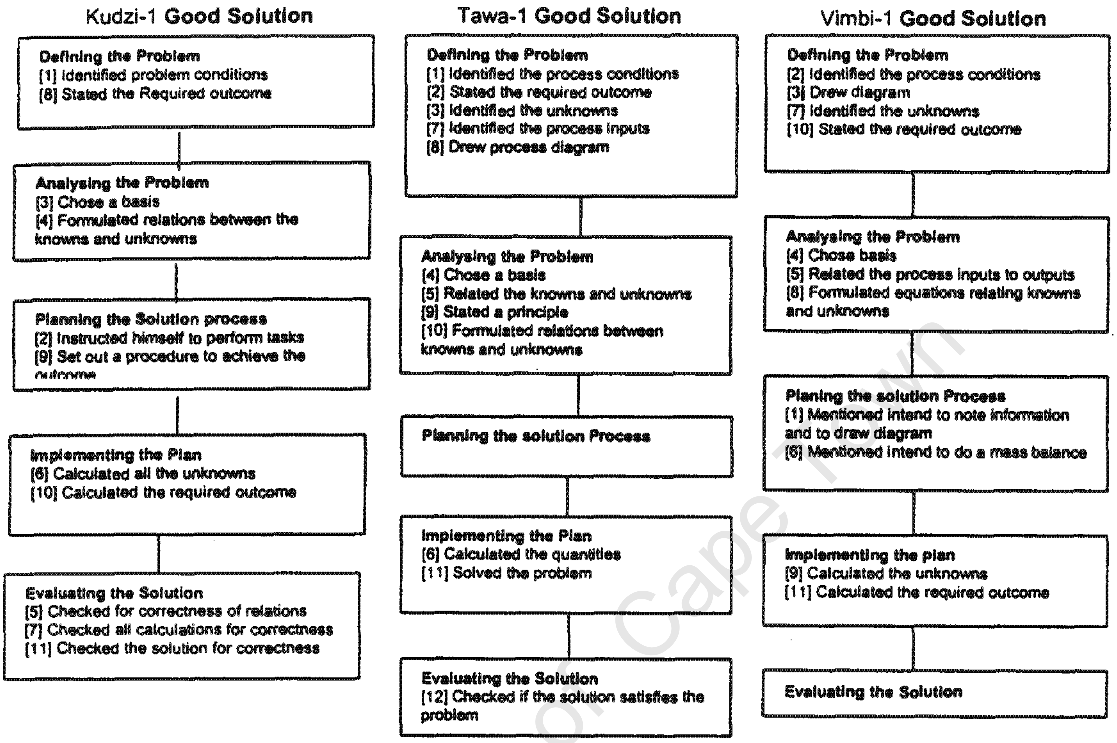
The problem solving processes followed by students have the general components of the problem solving strategy set out in the theoretical framework (Figure 2-1). However the sequence in which the activities are undertaken is not ordered as in the literature. This means that the strategies do not always follow the sequence *define*, *analyse*, *plan*, *implement* then *evaluate*, supporting the finding by Noble (1983) that the solver may loop backwards at any stage of the solution process. Bransford and Stein (1995) also state that people may move through a strategy a number of times to create a satisfactory solution. These processes described by Noble and Bransford and Stein result in iterations within the strategy being used for solving a problem. The sequencing of activities for each student is shown in Table 5-5.

Students had a tendency to jump into calculations immediately after jotting down information. The sequence of activities by eight of the students started with identifying the problem conditions. Four other sequences started with *planning* which was just mentioning the intention to do certain activities. The other three students started with drawing diagrams. There are various patterns in the sequence of events at the beginning of the solving process. In five cases the initial sequence was identifying conditions, drawing diagrams, and choosing a basis. Four of the students (Munya, Fari, Kuda, Tafi) with this starting sequence produced bad solutions and were unsuccessful while the other person (Ranga) had a good solution and was successful.

Chipo, Tasu, and Tandi had their own beginning sequence which started with drawing a diagram followed by identifying problem conditions then choosing a basis. The only difference between this sequence and the previous one is that it starts with drawing a diagram while the other starts with identifying conditions. The third step of both sequences was choosing a basis. The three students with the latter sequence produced all the three types of solutions Chipo produced a good one, Tasu a partial solution (unsuccessful) and Tandi a bad solution (unsuccessful). Sequences of Tasu and Chipo clearly showed that they stated the required outcome in the solutions after doing some calculations aimlessly.

Table 5-5 The sequencing of activities as students solved Task 1

Note: Numbers in square brackets indicate order of solution.



Kudzi-1 **Good Solution**

Defining the Problem
[1] Identified problem conditions
[8] Stated the Required outcome

Analysing the Problem
[3] Chose a basis
[4] Formulated relations between the knowns and unknowns

Planning the Solution process
[2] Instructed himself to perform tasks
[9] Set out a procedure to achieve the outcome

Implementing the Plan
[6] Calculated all the unknowns
[10] Calculated the required outcome

Evaluating the Solution
[5] Checked for correctness of relations
[7] Checked all calculations for correctness
[11] Checked the solution for correctness

Tawa-1 **Good Solution**

Defining the Problem
[1] Identified the process conditions
[2] Stated the required outcome
[3] Identified the unknowns
[7] Identified the process inputs
[8] Drew process diagram

Analysing the Problem
[4] Chose a basis
[5] Related the knowns and unknowns
[9] Stated a principle
[10] Formulated relations between knowns and unknowns

Planning the solution Process

Implementing the Plan
[6] Calculated the quantities
[11] Solved the problem

Evaluating the Solution
[12] Checked if the solution satisfies the problem

Vimbi-1 **Good Solution**

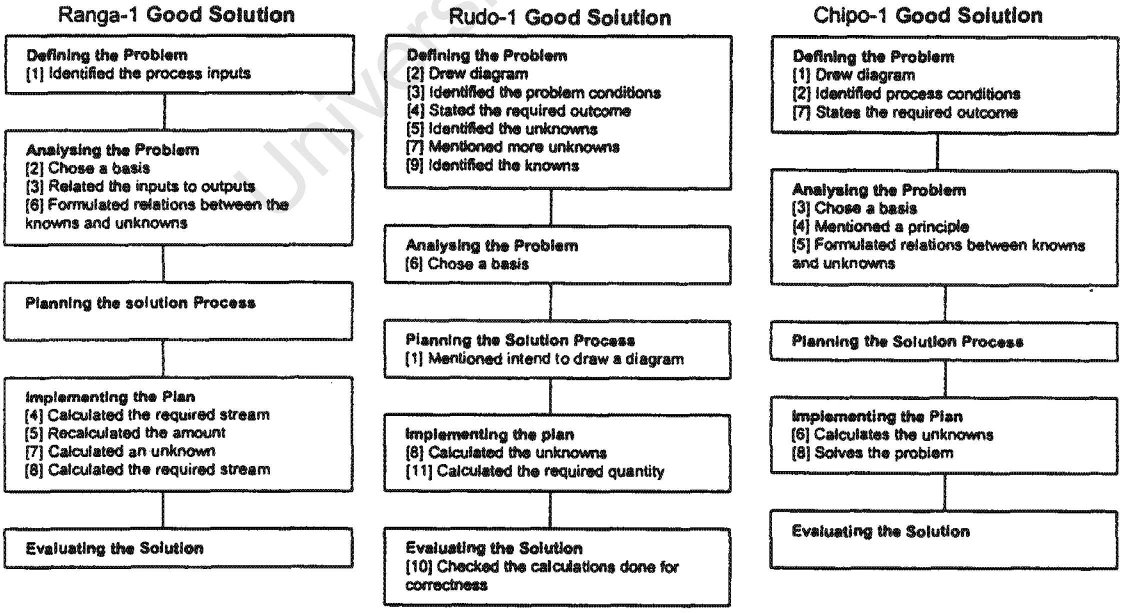
Defining the Problem
[2] Identified the process conditions
[3] Drew diagram
[7] Identified the unknowns
[10] Stated the required outcome

Analysing the Problem
[4] Chose basis
[5] Related the process inputs to outputs
[8] Formulated equations relating knowns and unknowns

Planing the solution Process
[1] Mentioned intend to note information and to draw diagram
[6] Mentioned intend to do a mass balance

Implementing the plan
[9] Calculated the unknowns
[11] Calculated the required outcome

Evaluating the Solution



Ranga-1 **Good Solution**

Defining the Problem
[1] Identified the process inputs

Analysing the Problem
[2] Chose a basis
[3] Related the inputs to outputs
[6] Formulated relations between the knowns and unknowns

Planning the solution Process

Implementing the Plan
[4] Calculated the required stream
[5] Recalculated the amount
[7] Calculated an unknown
[8] Calculated the required stream

Evaluating the Solution

Rudo-1 **Good Solution**

Defining the Problem
[2] Drew diagram
[3] Identified the problem conditions
[4] Stated the required outcome
[5] Identified the unknowns
[7] Mentioned more unknowns
[9] Identified the knowns

Analysing the Problem
[6] Chose a basis

Planning the Solution Process
[1] Mentioned intend to draw a diagram

Implementing the plan
[8] Calculated the unknowns
[11] Calculated the required quantity

Evaluating the Solution
[10] Checked the calculations done for correctness

Chipo-1 **Good Solution**

Defining the Problem
[1] Drew diagram
[2] Identified process conditions
[7] States the required outcome

Analysing the Problem
[3] Chose a basis
[4] Mentioned a principle
[5] Formulated relations between knowns and unknowns

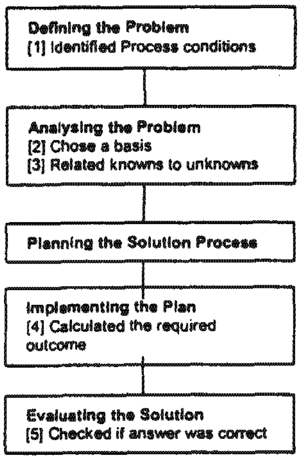
Planning the Solution Process

Implementing the Plan
[6] Calculates the unknowns
[8] Solves the problem

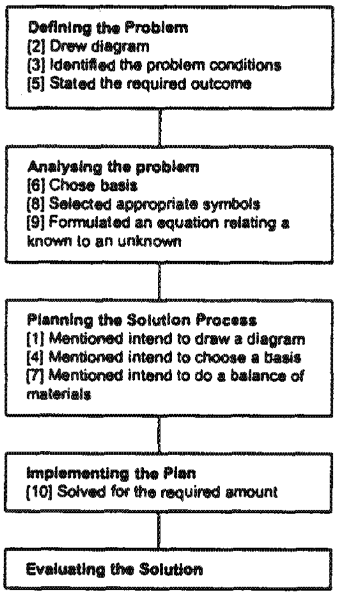
Evaluating the Solution

The sequencing of activities as students solved Task 1 Table 5-4 (continued overleaf)

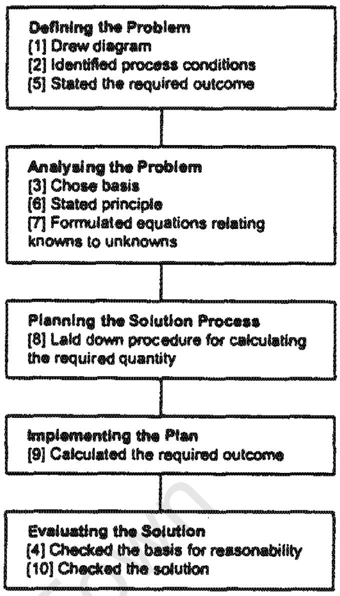
Gari-1 **Good Solution**



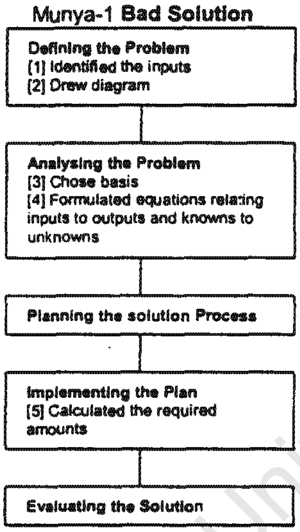
Fadzi-1 **Partial Solution**



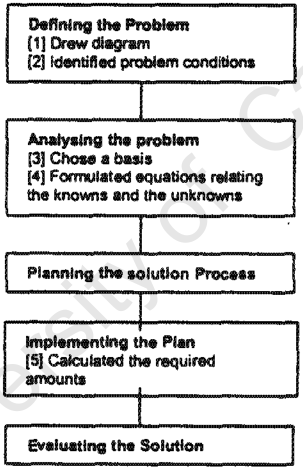
Tasu-1 **Partial Solution**



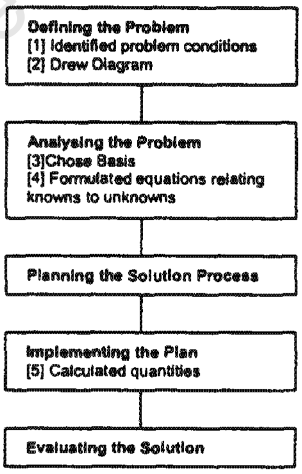
Munya-1 **Bad Solution**



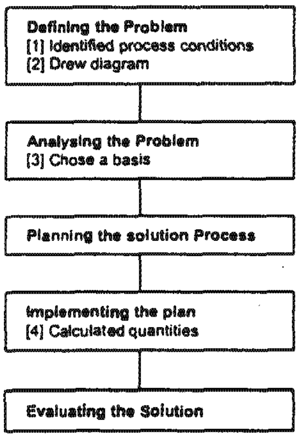
Tandi-1 **Bad Solution**



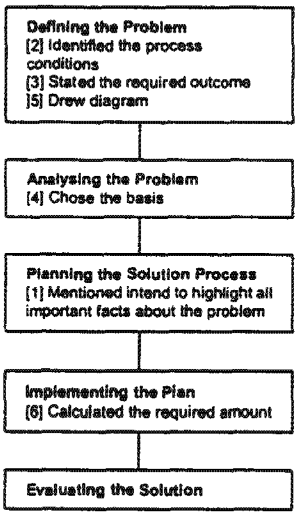
Fari-1 **Bad Solution**



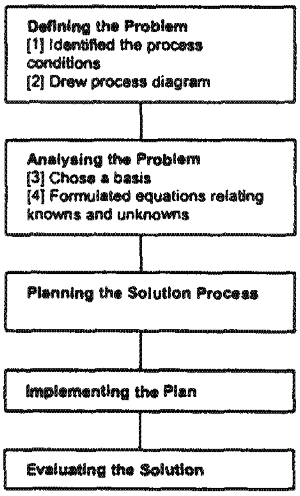
Kuda-1 **Bad Solution**



Saru-1 **Bad Solution**



Tafi-1 **Bad Solution**



In nine occasions choosing a basis was followed by formulation of relations between knowns and unknowns. In four of these cases finding what was required by the problem followed the formulation of relations. In two cases calculations of the unknowns of the problem followed the formulation of relations.

After the first three to five activities the order in which the activities were done did not have any particular pattern as most students had their unique sequence of activities. In total there were fifteen activities used by all students to solve the problem. The least number of activities carried out in a strategy was four. In the two cases with only four activities the students (Tafi and Kuda) did not produce correct solutions to the problem. The maximum number of activities performed by one student to solve this problem was eleven (by Kudzi who had a good solution). In five cases some activities are repeated.

The broad stages of a strategy were also visited at least once by a large number of students (9), producing an iterative way of solving problems. Table 5-5 also shows the sequencing of the broader strategies. Eleven times the process of solving the problem started with the *define* stage. In eight of these cases, *defining the problem* was followed by *analysis*, which was followed by *implementation. Planning* was the beginning stage four times in three of which it was followed by *defining* then by *analysis*. There is iteration between the steps of the strategies used by students. Iteration was evident in nine solutions as shown in Table 5-5. In eight of the cases where iteration was present, the *define* stage, was visited up to three times and the *analysis* and *implementation* stages were visited up to twice.

The strategies used by six of the successful students had iterations while one of them was linear: Tawa, Vimbi, Ranga, Rudo, Chipo had strategies which showed iterations while Gari had a linear strategy. A little linearity between the *define* and *analysis* stages showed in the strategies of Ranga, Chipo, Vimbi, Tawa and Rudo. The unsuccessful students, for example Munya, Tandi, Fari and Kuda, had strategies that were much more linear than the strategies of the successful students. In relation to this, the bad solutions were much more linear in their sequences than the good ones, where there was more iteration between the stages.

5.6 TASK 2: JUICE PRODUCTION

The first requirement of Task 2 was to find the amount of juice produced from 100 kg fresh juice. This is represented by Subtask 2.1. The second requirement, to find the fraction of the bypass, is represented by Subtask 2.2. The responses of Task 2 to questions in the categories of the coding scheme are presented in Table 5-6. Table 5-7 illustrates the number of students who performed activities suggested by the coding scheme. Under each category, subcategories are listed against the number of students who performed the activity.

In *defining* all fifteen students noted problem conditions and did it correctly. All of the fifteen also drew diagrams and used symbols to represent variables. A few students undertook stating the required outcome. Choosing a basis involved all fifteen students and the basis was used correctly with problem conditions by all of them. Only one student checked the validity of the relationships formulated during *analysis*. Three students were observed as *planning*. Of these three only one assessed the plan designed. All the three followed their plans exactly in *implementation*. The fifteen students involved in the study all produced solutions to the given problem. There was however no evidence of checking the solution but five students were involved in checking intermediate calculations. Six good, seven partial and two bad solutions were produced in Task 2.

5.6.1 Defining the problem

Noting problem conditions

All students drew diagrams when they solved Task 2. They were able to identify and describe the problem conditions correctly. In identifying problem conditions, nine students drew diagrams after reading the problem then put down all the information provided. The other six students listed information down before drawing diagrams then filled in the information on the diagrams.

Ten students verbalised their process of identifying information. Verbalisations of Kuda and Rudo are given as examples:

So we have got a bypass and we have a reactor which is an evaporator. And we have got 58% there, 58% solids. And the product is mixed with the bypassed fresh juice to achieve the desired final concentration of solid....so the desired is 42%.... (Kuda)

The juice that enters the evaporator is got 12% solids. And my product is mixed with the bypass fresh juice to achieve the desired...my product, you have got a mixer somewhere here, after the evaporator. ... Oh so your final product is the concentrated one,..., which is 42% solids.... We know from the evaporator 58%, umm evaporation process.... (Rudo)

Kuda's verbalisation only mentioned the composition of the evaporator product and the required juice product. It is also not clear from his statement what the 58% is and in what stream it is in. Kuda only states clearly the mixing of product stream and the bypass. From the statement one does not get a clear picture of what is happening in the process. The statement by Rudo includes the compositions of the bypass, the feed and the product streams. In her verbalisation it is clear what happens to each stream for example the product is mixed with the bypass fresh juice.

Drawing a Diagram

During the second task all students drew diagrams as mentioned above. They may have been partly influenced by the diagram that I drew at the beginning of this task to explain what a bypass in a process is. The correct diagram for the second task could be illustrated as shown in Figure 4-2. Twelve diagrams were correct and the other three drawn by Kuda, Saru and Tawa did not have the water stream coming from the evaporator.

Table 5-6 Responses to questions of the coding scheme in Task 2

Student	Kudzi	Tawa	Ranga	Munya	Fadzi	Saru	Vimbi	Rudo	Chipo	Tandi	Tasu	Fari	Tafi	Gari	Kuda
Define the Problem															
Were all problem conditions noted?	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y
Were the conditions described correctly?	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y
Did the student draw a diagram?	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y
Does diagram correctly describe the process?	y	n	y	y	y	n	y	y	y	y	y	y	y	y	n
Were symbols used for representation of variables?	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y
Was the first required outcome noted?	y	y	n	n	n	n	n	y	n	n	y	n	n	n	n
Was the second required outcome noted?	n	y	n	n	n	y	n	y	y	n	y	n	n	n	n
Analyse the problem															
Did student choose a basis?	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y
Was basis used correctly with problem conditions?	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y
Were problem conditions linked to Subtask 2.1 correctly?	y	y	y	y	y	y	y	y	y	y	y	y	y	n	n
Were problem conditions linked to Subtask 2.2 correctly?	y	y	y	y	y	y	n	y	y	y	y	n	y	n	n
Were relations between the knowns and unknowns correct?	y	y	y	y	y	y	y	y	y	y	y	y	y	n	y
Were these relations checked for their validity?	n	n	n	n	n	n	n	n	n	n	n	n	n	n	y
Were all relations translated into the correct equations?	y	y	y	y	y	y	n	n	y	y	n	y	y	n	y
Did student describe any basic concept related to problem?	n	y	y	y	y	n	y	y	n	y	y	y	n	n	n
Planning the Solution															
Is there evidence of planning?	n	y	n	n	y	n	n	n	y	n	n	n	n	n	n
Did student assess the plan?	-	n	-	-	n	-	-	-	y	-	-	-	-	-	-
Is the plan well structured?	-	y	-	-	y	-	-	-	y	-	-	-	-	-	-
Is the plan relevant to the problem solution?	-	y	-	-	y	-	-	-	y	-	-	-	-	-	-
Implementation of the Plan															
Does implementation follow the plan exactly?	-	y	-	-	y	-	-	-	y	-	-	-	-	-	-
Is the implementation checked for errors?	y	n	y	n	y	n	n	y	y	n	y	n	n	n	n
Was the student able to produce a solution at all?	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y
Was the solution complete?	y	y	y	y	y	y	y	y	n	n	y	y	n	y	y
Evaluation of the Solution															
Was the solution checked?	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
Were the intermediate calculations checked?	y	n	y	n	n	n	n	y	y	n	y	n	n	n	n
Characterisation of the Solution															
The solution was Good (G), Partial (P), or Bad (B)?	G	G	G	G	G	G	P	P	P	P	P	P	P	B	B
Was student successful with Subtask 2.1?	y	y	y	y	y	y	y	n	y	y	y	y	y	n	n
Was successful with Subtask 2.2?	y	y	y	y	y	y	n	n	n	n	n	n	n	n	n

Key: y=yes, n=no,; G=good, P=partial, B=bad;

Question (b) is the conceptual question

Table 5-7 Number of students who executed activities in each category of the coding scheme: Task 2 (total number of students =15)

Activity	Number of students	Activity	Number of students
Defining		**Planning**	
Noted problem conditions	15	Planning the solution	3
Problem conditions described correctly	15	Student assessed the plan	1
Student draw a diagram	15	The plan well structured	3
Diagram correctly describing the process	12	The plan is relevant to the problem	3
Symbols used for representation of variables	15	**Implementation**	
First required outcome noted	4	Implementation follows the plan exactly	3
Second required outcome noted	5	Implementation was checked for errors	6
Analysing		Students able to produce a solution	15
Student choose a basis	15	Complete solutions	12
Basis used correctly with problem conditions	15	**Evaluation**	
Correct links of problem conditions to 1st required outcome	13	Solution was checked	0
Correct links of problem conditions to 2nd required outcome	11	Intermediate calculations were checked	5
Correct links between knowns and unknowns	14	**Characteristics of the solution**	
All the relations checked for validity	1	The solution was good	6
All relations translated into correct equations	11	The solution was partial	7
Student described any basic concept related to problem	9	The solution was bad	2
		The first required outcome was found	12
		The second required outcome was found	6

Use of Symbols

All students used symbols in their solutions. These symbols were used to represent streams of the process.

Stating the Required outcome

Very few students stated both the requirements of the problem. Only four students mentioned they were to find the amount of concentrated juice while three stated that they had to find the fraction of the bypass. This suggests that students probably started doing calculations before they knew what they were really supposed to be doing. It was only after doing a lot of calculations that most students like Chipo and Tasu asked themselves what they were required to do.

5.6.2 Analysing the problem

There are only two different bases chosen by students in this task. Fourteen students chose 100 kg of fresh juice as their basis. Calculations involved with this basis start at the input of the process to the output product. Rudo chose a different basis of 100 kg of the juice coming out of the evaporator.

Nine students mentioned that the *total mass in is equal to the total mass out* of the system. This statement was true since there was no accumulation in the process of juice production.

Most students were capable of using the problem conditions given to formulate good useful relations that could be used to achieve the required outcome. Thirteen of the students were able to make good relations that involved the required outcome of Subtask 2.1 of the problem and were also able to make good relations of knowns and unknowns.

5.6.3 Planning

Only three students showed evidence of *planning* their solutions.

So first choose a basis which they have given to us to be 100 kg fresh feed....So first thing is to get 42%. Then I do an overall balance of the whole thing. To get 42% solids out, that means that the 12kg of solids that come in need to come out and then 12 over the total amount of juice out must be equal to 42%. (Tawa)

The *planning* in the above example is focused on organising the sequence of the steps to be followed in the process of obtaining the solution. Tawa's *planning* was very specific to the problem.

5.6.4 Implementation

All fifteen students produced a solution to this task but three of these solutions by Tandi, Chipo and Tafi were incomplete. There were various errors made by students, which resulted in wrong answers to the problem. For example, instead of writing the following balance for the solids around the mixer, sBP + sEP = sCJ, Vimbi only considered the solids in the EP and CJ streams.

Kuda on the other hand assumed that the amount of solids in the product stream was equal to 0.42% of the solids in the feed stream. The correct relation is that the solids in the product stream constitute 42% of the total quantity in the product stream.

Tafi introduced extra unnecessary variables. Variables y and x were used to represent the water and the solids respectively. It seemed Tafi did not realise that the composition in the bypass stream was equal to that of the fresh feed stream as splitting the fresh feed produces the bypass.

5.6.5 Evaluation

None of the students showed that they *evaluated* their solutions. However five checked their intermediate calculations. An example where calculations were assessed is given below:

> Okay must re-check. Okay the water would have to be that, fresh feed minus the flowrate of solids in feed is the same as flowrate of solids in concentrated product. Umm yes, yes water 0,88 plus,... all right. So, so far okay. We have a steady state equation. That looks weird, why am I suddenly getting a different answer for the same calculation. Okay so it's not that. (Kudzi)

The *evaluation* done by Kudzi involves just re-punching the numbers into the calculator. This kind of checking is only able to get rid of calculation errors so it does not guarantee a correct answer. Such a case was found with Tasu who was using wrong numbers for his calculations, so when he recalculated his answers (using the same wrong numbers) he was unable to discover that the values being used were wrong:

> Therefore the bypass of 2.24 divided by 0,123 equals 16.643. Okay I have done a complete mass balance and it checks out. Oh well does it check out? It does indeed check out. (Tasu)

Rudo checked her calculations as well as the relation of water getting in and out of the system.

> I am just checking my answer I am not sure if it's the correct working... its correct, and then your input, ... I want to check if the same thing,... your water coming in, 88% so where is my going? 153.33 you see there is something wrong with my calculations. (Rudo)

5.7 CHARACTERISTICS OF THE SOLUTION

Students who had the correct relations between the problem conditions and what was to be found all produced good solutions. Most students' solutions had partial solutions because they did not succeed in finding the fraction of the bypass to the evaporator. One reason for failing to find the evaporator bypass was that some students formulated incomplete equations relating knowns and unknowns. Another reason for partial solutions was the production of incomplete solutions, that is solutions that did not provide the required outcomes. The two students who had bad solutions formulated incorrect relations between the knowns and the required outcomes.

5.8 SUCCESS IN SOLVING THE PROBLEM

Twelve students obtained the amount of concentrated juice (Subtask 2.1) correctly while only six students found the fraction of the bypass to the evaporator (Subtask 2.2). The fact that most students were able to solve Subtask 2.1 of the problem shows that students have the general skills for solving simple material balances.

Table 5.6 shows that all students with good solutions were successful in solving Subtask 2.1. Of the five students that had partial solutions four of them were successful while one was unsuccessful with solving Subtask 2.1. In relation to Subtask 2.2, all students with good solutions were successful while all those with partial and bad solutions were not successful.

Table 5-8 was constructed to show the number of students who performed certain activities and whether they solved the problem successfully or unsuccessfully. Some activities performed by students when solving problems did not seem to have an effect on their ability to solve the problems. As can be seen in the table most activities did not appear to affect Subtask 2.2 (only six students solved Subtask 2.2). The links between the activities performed by students and their success in solving the problem are not as clear as in Task 1. A considerable number of students who had correct relations and good diagrams were unable to provide correct solutions.

Table 5-8 Numbers of students who executed a certain activity and their success in solving Subtasks 2.1 and 2.2.

Activities	Suc	Unsuc	Suc	Unsuc
	Subtask 2.1	Subtask 2.1	Subtask 2.2	Subtask 2.2
Diagram drawn [15]	12	3	6	9
Diagram not drawn [0]	0	0	0	0
Diagram describing process correctly [12]	12	0	4	8
Diagram NOT describing process correctly [3]	2	1	2	1
Required outcome stated 2.1[4]; 2.2 [5]	3	1	2	3
Required outcome NOT stated 2.1[11]; 2.2 [10]	9	2	4	6
Basis linked correctly to conditions [15]	12	3	6	9
Basis NOT linked correctly to conditions [0]	0	0	0	0
Required outcome linked correctly to conditions 2.1[13]; 2.2 [11]	12	1	6	5
Required outcome NOT linked correctly to conditions 2.1[2]; 2.2[4]	0	2	0	4
Relations of knowns and unknowns correct [14]	12	2	6	8
Relations of knowns and unknowns incorrect [1]	0	1	0	1
Relations checked for validity [1]	0	1	0	1
Relations NOT checked for validity [14]	12	2	6	8
Relations translated into correct equations [11]	10	1	6	5
Relations NOT translated to correct equations [4]	2	2	0	4
Described basic concept [9]	8	1	4	5
Did NOT describe basic concept [6]	4	2	2	4
Evidence of planning [3]	3	0	2	1
NO evidence of planning [12]	9	3	4	8
Solution evaluated [0]	0	0	0	0
Solution NOT evaluated [15]	12	3	6	9

NB: Suc. is for successful and unsuc. is for unsuccessful.

The following activities as shown in Table 5-8 are strong indicators of lack of success: diagram not describing process correctly, basis not linked correctly to conditions, required outcome not linked correctly to conditions, relations of knowns and unknowns incorrect, relations not translated to correct equations. Two students (Tasu and Vimbi) translated relations that were to be used to solve Subtask 2.2 to wrong equations. These equations did not affect their solutions to Subtask 2.1. It appears that the water stream from the evaporator missing in the diagrams by Tawa, Saru and Kuda did not affect the success of Tawa and Saru of getting the correct required outcomes.

Drawing a diagram did not appear to affect the students' success in solving the two parts of Task 2. All students drew diagrams but among them three failed to find the amount of juice and nine of then did not succeed in finding the fraction of the bypass.

Students who linked the required outcomes correctly to the conditions stated in the problem statement and those who formulated correct relations were more likely to solve the problem successfully. Stating the required outcome did not seem to have an effect on the success in solving the problem. Subtask 2.1 appeared to have been affected by the nature of the links between the required outcome and the problem conditions more than Subtask 2.2.

Combining Table 4-1 and Table 5-6, it can be seen that of the nine male students who participated in the study, seven solved Task 2 successfully while the other two did not. Also among six females five solved Task 2 successfully but one did not. The results also show that the ability of the students to solve Task 2 was not a function of gender. During Task 2, three of the four students with average marks of greater than or equal to 75 were successful in both Subtask 2.1 and Subtask 2.2. Of the six students with marks greater or equal to sixty, four were successful in Subtask 2.1 while only one was successful in Subtask 2.2. Of the five students with average marks less than sixty, all were successful in Subtask 2.1 and only tow successful in Subtask 2.2. These results show there was better success for students with lower marks than in

Task 1. The reason for this difference in success is not clear as both groups had progressed further into their second year.

5.9 SEQUENCES USED BY STUDENTS WHILE DOING TASK 2

The sequencing of activities is shown in Table 5-9. Sequences of the strategies of the majority of the students started with *definition* followed by *analysis*. In the middle of solving the problem there was no clear pattern in the order of activities. In general the first activities in solving this problem involved identifying conditions, and drawing a diagram (both of which are under *defining*), and then choosing a basis (which is part of *analysis*). This seemed to be going this way because once the problem conditions have been found, the next question that comes to mind is "how am I going to use all this information?" After choosing a basis, students would formulate equations that related what they are supposed to find to the conditions of the problem identified already. When the problem has been analysed it is not always easy to tell what the next step should be. The students may jump straight to *implementation* or start with *planning* (which was done by only a few students). Participants usually jumped into the calculations the moment that they finished drawing their diagrams. None of the students checked their solutions at the end of their problem solving although some of them evaluated the intermediate calculations as they solved the problem.

The sequences started with drawing diagrams in six cases and with choosing a basis in two cases. Different patterns of sequencing of activities were obtained. Rudo and Tasu had the same sequence for their first six activities. Kudzi's first five activities were the same as those of Rudo and Tasu. In the above cases, identifying information, stating the required outcome, choosing a basis, formulating relations then calculating unknowns followed drawing a diagram. Rudo was unsuccessful with both subtasks and her solution was partial, Tasu was successful with Subtask 2.1 and also had a partial solution, and Kudzi was successful with both subtasks and had a good solution.

Table 5-9 The sequencing of activities as students solved Task 2

Note: Numbers in square brackets indicate order of solution

Kudzi-2 Good Solution

Defining the Problem
[1] Drew diagram
[2] Identified problem conditions
[3] Stated the 1st required outcome

Analysing the Problem
[4] Chose a basis
[5] Formulated relations between the 1st required outcome and conditions
[9] Related knowns to unknowns
[11] Related 2nd required outcome to knowns

Planning the Solution process

Implementing the Plan
[6] Calculated the 1st required outcome
[8] Calculated the unknowns
[10] Calculated other unknowns
[13] Calculated the 2nd required outcome

Evaluating the Solution
[7] Checked the calculations
[12] Checked the relations made

Tawa-2 Good Solution

Defining the Problem
[1] Identified the process conditions
[2] Drew process diagram
[3] Stated the first required outcome

Analysing the Problem
[4] Chose basis
[6] Related the knowns and 1st required outcome
[8] Stated a principle
[10] Formulated relations between knowns and 2nd required outcome
[11] Related knowns and unknowns
[13] Formulated second equation for 2nd required outcome

Planning the solution Process
[5] Laid out procedure for calculating 1st required outcome

Implementing the Plan
[7] Calculated the 1st required outcome
[9] Calculated an unknown
[12] Calculated another unknown
[14] Calculated the 2nd required outcome

Evaluating the Solution

Ranga-2 Good Solution

Defining the Problem
[2] Drew process diagram
[3] Identified the process inputs

Analysing the Problem
[1] Chose a basis
[4] Related 1st required outcome to problem conditions
[6] Formulated relations between the knowns and unknowns
[7] Related 2nd required outcome to problem conditions
[9] Stated a principle

Planning the solution Process

Implementing the Plan
[5] Calculated the 1st required outcome
[8] Calculated the unknowns
[11] Calculated the 2nd required outcome

Evaluating the Solution
[10] Checked the calculations made

Munya-2 Good Solution

Defining the Problem
[1] Identified the inputs
[2] Drew diagram

Analysing the Problem
[3] Chose basis
[4]Stated principle
[5]Formulated equation relating the 1st required outcome and conditions
[7] Related knowns to unknowns
[9] Related the 2nd required outcome to problem conditions

Planning the solution Process

Implementing the Plan
[6] Calculated the 1st required outcome
[8] Calculated the unknowns
[10] Calculated 2nd required outcome

Evaluating the Solution

Fadzi-2 Good Solution

Defining the Problem
[1] Drew diagram
[3] Identified the problem conditions

Analysing the problem
[2] Chose basis
[5] Stated a principle
[6] Formulated an equation relating the knowns and the 1st required outcome
[8] Related the knowns and unknowns
[9] Formulated equation for 2nd required outcome
[10] Estimated the answer from equation
[12] Formulated new correct equation for 2nd required outcome

Planning the Solution Process
[4] Laid out procedure for calculations

Implementing the Plan
[7] Calculated the 1st required outcome
[13] Calculated the 2nd required outcome

Evaluating the Solution
[11] Checked the equations made

Saru-2 Good Solution

Defining the Problem
[1] Identified the process conditions
[2] Drew diagram

Analysing the Problem
[3] Formulated equations between knowns and unknowns
[4] Chose the basis
[5] Related the 1st required outcome to knowns
[8] Related the 2nd required outcome to conditions

Planning the Solution Process

Implementing the Plan
[6] Calculated the 1st required outcome
[9] Calculated the 2nd required outcome

Evaluating the Solution
[7] Checked if required outcome is reasonable

The sequencing of activities as students solved Task 2 Table 5-9 (continued overleaf)

Vimbi-2 Partial Solution

Defining the Problem
[1] Drew diagram
[3] Identified the process conditions

Analysing the Problem
[2] Chose basis
[4] Stated principle
[5] Related the knowns to unknowns
[6] Formulated equations relating knowns and 1st required outcome
[9] Related 2nd required outcome to knowns

Planing the solution Process

Implementing the plan
[7] Calculated the 1st required outcome
[8] Calculated the unknowns
[10] Calculated the 2nd required

Evaluating the Solution

Rudo-2 Partial Solution

Defining the Problem
[1] Drew diagram
[2] Identified the problem conditions
[3] Stated the required outcome

Analysing the Problem
[4] Chose a basis
[5] Related the required outcomes with the knowns and unknowns
[8] Formulated equation between the 1st required outcome and knowns
[10] Related the 2nd required outcome to knowns

Planning the Solution Process

Implementing the plan
[6] Calculated the unknowns
[9] Calculated the 1st required outcome
[11] Calculated the 2nd required outcome

Evaluating the Solution
[7]Checked the calculations made

Chipo-2 Partial Solution

Defining the Problem
[1] Identified process conditions
[2] Drew diagram
[11] Stated the 2nd required outcome

Analysing the Problem
[3] Chose a basis
[6] Formulated relation between knowns and unknowns
[9] Related 1st required outcome to knowns
[12] Related 2nd required outcome to

Planning the Solution Process
[4] Laid down procedure for doing calculations.

Implementing the Plan
[7] Calculated the unknowns
[10] Recalculated the unknowns

Evaluating the Solution
[5] Evaluated procedure
[8] Checked calculations made for correctness

Tandi-2 Partial Solution

Defining the Problem
[1] Identified problem conditions
[2] Drew diagram

Analysing the problem
[3] Chose a basis
[4] Stated a principle
[5] Formulated equations relating the knowns and unknowns to the 1st required outcome

Planning the solution Process

Implementing the Plan
[6] Calculated the 1st required outcome
[7] Calculated the unknowns

Evaluating the Solution

Tasu-2 Partial Solution

Defining the Problem
[1] Drew diagram
[2] Identified process conditions
[3] Stated the 1st required outcome
[8] Stated the 2nd required outcome

Analysing the Problem
[4] Chose basis
[5] Formulated equations relating unknowns and knowns

Planning the Solution Process

Implementing the Plan
[6] Calculated the unknowns
[7] Calculated the 1st required outcome

Evaluating the Solution
[10] Checked calculations made

Fari-2 Partial Solution

Defining the Problem
[1] Identified problem conditions
[2] Drew Diagram

Analysing the Problem
[3] Formulated equations relating knowns and unknowns
[4]Chose Basis
[5] Formulated equation relating 1st required outcome and problem conditions
[7] Related knowns to unknowns
[9] Related 2nd required outcome to knowns

Planning the Solution Process

Implementing the Plan
[6] Calculated the 1st required outcome
[8] Calculated unknowns
[10] Calculated the 2nd required outcome

Evaluating the Solution

Tafi-2 Partial Solution

Defining the Problem
[1] Drew process diagram
[2] Identified the process conditions

Analysing the Problem
[3] Chose a basis
[4] Formulated equations relating knowns and 1st required outcome
[6] Related the 2nd required outcome to knowns

Planning the Solution Process

Implementing the Plan
[5] Calculated the 1st required outcome

Evaluating the Solution

Gari-2 Bad Solution

Defining the Problem
[2] Drew diagram
[3] Identified process conditions

Analysing the Problem
[1] Chose a basis
[4] Related 2nd required outcome to knowns
[5] Related knowns to unknowns
[7] Related knowns to unknowns
[9] Reformulated equations between required outcomes and knowns

Planning the Solution Process

Implementing the Plan
[6] Calculated an unknown
[8] Calculated another unknown
[10] Calculated the required outcomes

Evaluating the Solution

Kuda-2 Bad Solution

Defining the Problem
[1] Identified process conditions
[2] Drew diagram

Analysing the Problem
[3] Chose a basis
[5] Related knowns to unknowns
[8] Related 1st required outcome to knowns
[9] Related 2nd required outcome to knowns

Planning the solution Process

Implementing the plan
[7] Calculated unknowns
[10] Calculated the 2nd required outcome
[11] Calculated the 1st required outcome

Evaluating the Solution
[4] Checked if conditions described correctly
[6] Checked the relations

Another six-step sequence used by Munya who was successful in both subtasks and Tandi who was successful in Subtask 2.1 was to identify conditions first, draw a diagram, choose a basis, state a principle, formulate relations and lastly solve for the required amount. The first three activities of this sequence were the same as those of Chipo and Kuda. Fadzi and Vimbi also had the same beginning sequence of three activities, which were drawing a diagram, choosing a basis then identifying conditions.

Saru and Fari also had a six step sequence at the beginning of their problem solving process which was identifying conditions, drawing a diagram, formulating relations, choosing a basis, formulating relations, then finding the problem requirement.

Within the common three to six step beginning sequences, formulation of relations was followed by solving for the required outcome or by solving for the unknowns. On five occasions, formulating relations then solving for the required outcome followed calculating unknowns.

The maximum number of activities used by students to solve the problem was sixteen with nine being the maximum number of different activities done by any student and five being the minimum. Some activities such as formulating relations, calculating unknowns, and solving for the required usually appeared more than once in the sequences. For Task 2 there were two requirements, which resulted in these activities to be revisited. The way the activities done were sequenced resulted in the iterations between the strategies and different sequencing of the strategies in solving the problem as shown in Table 5-9.

All strategies used by students who were successful in both Subtask 2.1 and Subtask 2.2 had iterations. The strategies of Tawa, Kudzi, Munya and Saru, who were successful in both subtasks, showed some linearity between the *define* and *analysis* stages. Fadzi, Ranga and Vimbi (who was only successful with Subtask 2.1) had more iteration in their strategies than the rest of the successful students. Tasu, Fari, Tandi and Tafi had linear strategies and were only successful with Subtask 2.1.

Students that were successful in Subtask 2.2 were Kudzi, Tawa, Ranga, Munya, Fadzi, and Saru, the rest were unsuccessful.

5.10 COMPARISON OF STUDENT SOLUTIONS FOR TASK 1 AND TASK 2

Generally, more students undertook the activities of *defining* and *analysing* in Task 2 than in Task 1. The number of students involved in *planning* and *implementation* was not very different between the two tasks.

5.10.1 Defining the problem

Noting Problem Conditions

In both tasks, six students followed the approach of listing information down first before drawing a diagram. Nine students drew diagrams first in the second task compared to seven in the first task.

Compared to Task 1, Task 2 had three more students who verbalised their information gathering process. In both tasks students were able to extract from the problem statement the right information of the inputs and outputs to the process. Information obtained was for the types of inputs and outputs, their quantities as well as their functions in the process described.

Drawing a diagram

From the students' written records of both tasks, it seems that generally students found drawing a diagram of a process helpful to the understanding of the problem. Both processes described in the two tasks involved evaporation and in the participants' responses to the tasks, there were cases of students leaving out the evaporated streams in the diagrams. It would seem in these cases that students did not understand what evaporation implied or that the information or word evaporation was disregarded or unnoticed in identification of information.

The difference in the errors made by students in the two tasks is that in Task 1, the product stream, which was jam, was divided into two streams. In Task 2, this error was not made by any of the students although the product, which was juice also, had two components, solids and water. What might have confused students in Task 1 was the statement about the residue, which was referring to the jam product. Otherwise, most students drew diagrams that described the process in the questions correctly.

Use of symbols

Students generally made use of symbols in their solutions. Nevertheless, in Task 2, symbols were mainly used to represent the process streams while in Task 1, symbols also represented the components of streams which were strawberry solids and strawberry water. This difference in where symbols were applied may be attributed to the fact that the juice process had only one feed to the process while the jam process had two feeds (sugar and strawberries). Symbols apparently simplified and made the solutions to the tasks clearer.

Stating the required outcome

Verbalisation of a statement of what the problem was asking the students to do was uncommon in both tasks. For those who mentioned what they were supposed to do, most of them did so only after doing calculations of unknowns. The verbalisations showed that students were clear about what they were supposed to do.

5.10.2 Analysing the problem

When tackling both tasks, all participants chose a basis, giving them a starting point in their solution. In the first task, students chose six different bases. Nine students chose bases that allowed them to work from the process inputs to the outputs even though the question asked them to find one of the inputs. In Task 2, students only chose two different bases. The basis that was chosen in this case was for working from the givens, which in this case are the inputs to the process, to the required output of the process.

In both solutions students stated correctly that the mass into the process would be the same as the mass out. More students were able to formulate correct relations between the required outcome and the problem conditions using the basis in Task 2 compared to Task 1.

5.10.3 Planning

Very few students showed evidence of *planning* when attempting either task. It does not mean however that most students did not *plan* as they could have done this in their minds.

5.10.4 Implementation

In both tasks, few students had incomplete solutions. The common errors made during *implementation* in the both tasks were disregarding some of the given information during calculations and misinterpretation of problem statements. In task two a specific error was the introduction of unnecessary variables thus making the solution more complicated.

5.10.5 Evaluation

In both tasks, *evaluation* was not a common stage in the solving processes demonstrated by students. The common method of checking the solution was just to re-enter numbers into the calculator, and when the answer was the same as before it was then considered correct. This method did not help Tasu in Task 2 to eliminate errors as he had used wrong values for the calculations in the first place.

5.10.6 Characteristics of the solutions

Partial or bad solutions in both tasks were mainly produced in situations were the relations formulated between the problem conditions and unknowns were incorrect. In Task 1 the difficulty that students encountered that led to bad or partial solutions was the failure to manipulate the ratios of process inputs in their calculations. The common difficulty in Task 2 that mainly lead to partial solutions was the failure of students to find the fraction of the juice that bypassed the evaporator.

5.10.7 Success in solving the problem

In Task 1, of the thirteen students who drew diagrams, five successfully solved the problem while in Task 2 all the twelve that had the right diagram solved the problem. As shown in Table 5-4 and Table 5-8, it appeared that students could successfully achieve the right solution for the problems whether they drew diagrams or not. Nevertheless when the diagram drawn was wrong, the solutions obtained for Task 1 were wrong. In Task 2, two students managed to obtain the right solutions with wrong diagrams.

In Task 1, of those participants who stated the required outcome, few were able to get the answer to the problem. Even some students who did not state the required outcome had correct answers. The same situation was found for Task 2. Basically, stating what was required by the problem did not have an effect on whether the answer obtained was correct or not.

In both cases students who linked the required outcome to the conditions got correct answers. The only difference between the two tasks was that more students had wrong relations in Task 1 and thus could not solve the task correctly. The same observation was made with regard to relations of knowns and unknowns, in Task 1.

The solutions of both tasks showed that the following conditions seemed to be strong indications of lack of success: diagram not describing process correctly, basis not linked correctly to conditions, required outcome not linked correctly to conditions, relations of knowns and unknowns incorrect, and relations not translated to correct equations. However the condition of diagram not describing process correctly did not seem to affect success in Task 2 as much as Task 1.

In general the solutions to Task 2 were much better than the solutions to Task 1. Many students who had bad solutions in Task 1 produced either good or partial solutions in Task 2. Of the seven students with good solutions in Task

1, three produced partial solutions, one produced a bad solution while the other three still had good solutions in Task 2.

5.10.8 Sequences used by students

The sequences of problem solving activities by many students in Task 1 started with identifying problem conditions. Four sequences started with *planning* and three other sequences started with drawing diagrams. In Task 2 drawing was observed in six cases as the starting activity. In two occasions, sequences started with choosing a basis while in seven occasions the sequences started with identification of information.

Six students in Task 2 started with a diagram while only three did that in Task 1. The two students who had not drawn diagrams in Task 1 both had good diagrams for Task 2. Choosing a basis was observed as the first activity in two sequences of Task 2 but such a beginning was not observed in Task 1. *Planning* became the starting activity in Task 1 in four occasions but never the beginning activity in Task 2. Kudzi had a good problem solving strategy as he produced good solutions on both occasions although there was no evidence of *planning* in the second task.

In Task 2 most students had five to six common step sequences at the beginning of the solving process compared to Task 1 beginning with common sequences of only three steps. In both tasks, there was some iteration of activities between stages in the strategy. In Task 1 all those students who produced good solutions did many iterations, except one whose solving process was linear. Of those students who produced partial solutions half had iterations but the other half did not have any. Those who produced bad solutions did not show any iteration processes in their solutions. Iteration was also evident in Task 2 but it was not as clear as it was in Task 1 that the successful students produce more iteration than the unsuccessful ones. However there were different sequences of activities as well as the stages of the problem solving strategies of students. In some of the partial solutions there was evidence of iteration but in others there was not.

5.10.9 Heuristics Used

In both tasks, students made use of models to simplify the problem statement by drawing diagrams and using symbols. The researcher in trying to explain how a bypass process works in Task 2 used an analogy of a recycle process, which the students were already familiar with. Calculations involved in Task 1 could follow a working backward heuristic where calculations are done from the answer to the givens. Only six students took a basis that required working forwards from the givens to the answer in the first task. In Task 2, more students chose a basis that allowed them to work forwards towards the answer than in Task 1 where students preferred to work backwards. It looks like students worked with either working backwards or forwards heuristics depending on the information provided in the problem statement. The first task gave students the exact quantity of the product (jam), which in calculations would involve working backwards to the required feed strawberries. In Task 2 with the feed juice provided as information, the calculations involved working forwards to the required product.

6. DISCUSSION

6.1 GENERAL

Think-aloud problem-solving sessions were used successfully in this study to obtain information on how students solve problems. Transcripts of verbalisations by students provided information such as the kind of data students obtained from the problem statements, and students' interpretation of the problem statements. Indication of where students experienced difficulties and how they tackled them was also identified from the transcripts. Transcripts also showed the activities done by students and how the activities were sequenced.

Written solutions by students showed the diagrams students drew, the calculations that were done by students and also the kind of information that was employed in solving the tasks. Field notes by the researcher pointed out the activities that students carried out while silent during the problem solving sessions. The field notes were used after the solving session to ask students specific questions on how they performed activities.

In Task 1, three students (Munya, Tandi and Kuda) did not verbalise their problem solving process while in Task 2 only Munya did not verbalise. In these cases, written solutions were the main source of data. These students seemed to be uncomfortable to think aloud in the presence of the researcher. In Task 1, Munya asked the researcher to do other things besides watching him solving the problem and Kuda simply said he would not speak. In Task 2, Munya said he would try to verbalise but he asked the researcher to leave the room. Kuda and Tandi verbalised their whole solving processes in Task 2. The researcher's notes were important in these cases in getting information on the thought processes that were involved when constructing the solution after the students had solved the tasks.

It was felt that asking students what their thought process was after they had tackled the tasks did not give accurate information about what really happened. This is because the information obtained from the students largely depends on what is remembered and the time interval between the solving process and the interviews. In this study the interval was short as the interviews were done immediately after the solving process. It seemed that students felt they had to tell the researcher what they perceived the researcher considered correct and also to explain the actions they had taken. In the interviews after solving problems students would realise they made mistakes in their calculations and attempt to correct them. Thus the explanations on how the problem was solved were done with a frame of mind different from the one when the problem was being solved.

6.2 STRATEGIES USED BY STUDENTS

Students who had strategies with all the five stages described in Figure 2-1 (*defining the problem, analysing the problem, planning the solution, implementing the plan, evaluating the solution*) had either good or partial solutions. There were four students in Task 1 and one in Task 2 who had a four-stage strategy (*defining the problem, analysing the problem, planning the solution, implementing the plan*) without the *evaluation* stage. Two of the four students with the four-stage strategy in Task 1 had good solutions, one had a bad solution while the other had a partial solution. The one in Task 2 with the same four-stage strategy had a good solution. In Task 1, those who had a three-stage strategy (*define*, *analyse*, *implement*) were mostly unsuccessful and their solutions were bad. In Task 2 students with the same strategy were mostly successful but had partial solutions.

6.3 STAGES OF STRATEGIES AND SKILLS USED

6.3.1 Defining the problem

In this study, students were able to extract the right information from the problem statement that enabled them to identify all the necessary information to describe the problems. This was evident in the verbalisations made by students as they gathered information.

The students in the present study were capable of translating the problem statements since they identified information and described it correctly. Adigwe (1991) and Finegold and Mass (1995) suggest that students who are capable of translating problem statements are good problem solvers or successful problem solvers (based on their performance in problem solving in their exams). In this study the success of students in solving problems did not clearly show a relation to their first year marks.

Drawing diagrams

In both tasks, most students drew diagrams to represent the problems but (similar to Leibold et al. 1976) some drew poor ones or did not draw diagrams at all. The participants of this study appear to have an important skill that experts have of drawing diagrams, according to the research by Dhillon (1998) in physics, where experts tended to draw diagrams more than novices did.

Use of symbols

Most students used symbols in their solutions. In the Dhillon (1998) research on experts and novices, novices only used symbols when they encountered difficulty within the problem solution. On the contrary, in this study students used symbols for representing process streams and variables from the start. The function of symbols thus was to simplify the problem as suggested in the strategies by Leibold et al. (1976) and Mettes et al. (1980), by making the calculations clear.

Stating the required outcome

Very few students stated what was required by the problem. Students may have stated the desired goal in their minds, but there was no verbal or written evidence that they did this. It was clear with some students though that they only thought about what they were supposed to find after making attempts to solve for other unknowns. Leibold et al. (1976) indicated that students had problems with stating the unknown as they included unnecessary constraints in the statement. Those students who did verbalisations in this study stated clearly and correctly what was to be found, implying that they understood what was required of them.

6.3.2 Analysing the problem

Choosing a basis

All students chose a basis. The basis chosen allowed them to work backwards or forwards (Fogler and LeBlanc 1995; Polya 1957). No research in the literature was found to investigate the use of a basis in calculations. The choice of basis in the two tasks seemed to depend on the nature of the information given rather than whether the calculations to be done required working backwards or forwards.

Stating relevant principles

To solve problems successfully students required basic knowledge of material balances (Fogler and LeBlanc 1995; Schoenfeld 1985; Woods et al. 1979). Students showed they knew how to balance the materials within a process in order to find the quantities required. The basic knowledge that students accessed from their knowledge base (Woods et al. 1975) was the material balance equation. This relationship seemed to have helped the students develop relations between the knowns and unknowns and between the required outcomes and the known information, both of which were later translated into equations. As expected, most students did not have difficulty relating quantities (Dhillon 1998).

6.3.3 Planning

Research by Adigwe (1991,1992) and Finegold and Mass (1985) showed that unsuccessful problem solvers were not capable of constructing plans in detail before carrying them out. In this study there was little evidence in *planning* and thus no conclusions can be drawn about the effect on solving problems successfully.

6.3.4 Implementation

The work by Adigwe (1991,1992) and Finegold and Mass (1995) revealed that unsuccessful problem solvers had problems in initiating problem solving approaches and had no solutions. *Implementations* in this study were mostly complete with a few incomplete ones, especially in Task 1.

6.3.5 Evaluation

In the current study, the evidence of *evaluation* by students was minimal. Adigwe (1991,1992) and Finegold and Mass 1995 found that both successful and unsuccessful solvers did not check their solutions. Experts checked their work and logic as they progressed with their problem solving (Dhillon 1998).

Some of the skills described in the framework did not appear in the solutions of students. At the stage of *defining*, the results showed that no student made an estimate of the answer to be calculated. The estimate could have helped the students during *evaluation* to check if their answers were reasonable. Evidence of hidden criteria and constraints did not appear in the solutions since the tasks did not have these. In tasks where hidden criteria and constraints are present the solver who identifies them early in their problem solving is likely to solve the actual problem at hand. Assumptions were also not necessary for the two tasks, as there was enough information to initiate problem solving. The problems seemed to indicate to students clearly that the way to solve the tasks was through material balances. It was however impossible to identify whether students were aware of their problem solving process during *planning*. The students did not show any signs of looking back at their problem solving to learn from the process. In both *analysis* and *planning*, no evidence was shown of students getting rid of mental or technical blocks.

6.4 SUCCESS IN SOLVING PROBLEMS

The relationship between the strategies used by students and their success in solving the tasks plus the quality of the solutions are illustrated in Table 6-1 and Table 6-2.

Table 6-1 Relationship between strategy used, quality of solution and success in solving Task 1

Strategy	**Define** **Analyse** **Plan** **Implement** **Evaluate**	**Define** **Analyse** **Plan** **Implement**	**Define** **Analyse** **Implement** **Evaluate**	**Define** **Analyse** **Implement**	**Define** **Analyse**
Students with strategy	Kudzi; Rudo; Tasu	Vimbi; Gari; Fadzi; Saru	Tawa	Ranga; Chipo; Munya; Tandi; Fari; Kuda	Tafi
Successful in solving task	Kudzi; Rudo	Vimbi; Gari	Tawa	Ranga; Chipo	
Unsuccessful in solving task	Tasu	Fadzi; Saru		Munya; Tandi Fari; Kuda	Tafi
Good solution produced	Kudzi; Rudo	Vimbi; Gari	Tawa	Ranga; Chipo	
Partial solution produced	Tasu	Fadzi			
Bad solution Produced		Saru		Munya; Tandi; Fari; Kuda	Tafi

The following factors contributed to the nature of the solutions produced by students: The students (Tandi, Fari and Kuda) with bad solutions misinterpreted the problem statement and thus produced wrong diagrams for the process. Munya had the correct diagram but did not use his basis correctly. As seen in Table 5-1, the relationships made between the required outcome and the problem conditions plus those between the knowns and unknowns were wrong. Fadzi and Tasu who were unsuccessful made errors in their calculations. Fadzi left out one variable in her formation of the relationship between required outcome and problem conditions. Tasu introduced a new value for one of the knowns in his calculations.

Table 6-2 Relationship between strategy used, quality of solution and success in solving Task 2

Strategy	Define Analyse Plan Implement Evaluate	Define Analyse Plan Implement	Define Analyse Implement Evaluate	Define Analyse Implement
Students with strategy	Fadzi; Chipo	Tawa	Kudzi; Ranga; Saru; Rudo; Tasu; Kuda	Munya; Vimbi; Tandi; Fari; Tafi; Gari
Successful in solving task	Fadzi; Chipo	Tawa	Kudzi; Ranga; Saru; Tasu	Munya; Tandi; Fari; Tafi
Unsuccessful in solving Subtask 2.1			Rudo; Kuda	Gari
Unsuccessful in solving Subtask 2.2	Chipo		Rudo; Tasu; Kuda	Vimbi; Tandi; Fari; Tafi; Gari
Good solution produced	Fadzi	Tawa	Kudzi; Ranga; Saru	Munya
Partial solution produced	Chipo		Rudo; Tasu	Vimbi; Tandi; Fari; Tafi
Bad solution Produced			Kuda	Gari

The factors that led to the production of the different types of solutions are given here: Kuda and Gari had bad solutions since their relations of outcome to conditions were wrong. Gari's relations of knowns and unknowns were also incorrect. Kuda's diagram did not describe the problem statement correctly, showing that he had misinterpreted the task. Partial solutions were produced in Task 2 due to different reasons. Tasu had incorrect equations. Tandi, Chipo, and Tafi had incomplete solutions and had introduced unnecessary information to the task. Vimbi disregarded components in a stream leading to wrong relations between outcome and problem conditions. Fari also had incorrect relations between the required outcome and problem conditions.

The relationship between sequencing of stages in strategy and success that was found in this study was that the strategies with more iteration than others led to more in successful solutions, as shown in Table 5-5 and Table 5-9. It seems that when students go back to a previous stage of a strategy to perform an activity they can discover errors and therefore correct them before they carry on with their calculations.

In general the results presented in this thesis show that students had the basic knowledge required for solving the two tasks they were given but some of the students had poor approaches to problem solving.

6.5 IMPROVEMENTS IN SOLUTIONS PRODUCED FROM TASK 1 TO TASK 2

The results of this study showed some improvements in the solutions from Task 1 compared to those of Task 2. The general approach to solving Task 2 was better than that used to solve Task 1. This improvement in students' general approach could have been attributed to the time students had between Tasks 1 and 2 where they had learned more about material balances. A basis was used more correctly with conditions in Task 2 than in Task 1. The main difficulty with using a basis in Task 1 was the manipulation of the ratio of feed streams given in the problem statement. The basis in Task 2 was also more obvious than in Task 1.The task gave students the feed rather than the product as was in Task 1. In Task 2 more students linked required outcome with conditions correctly than in Task 1, therefore more equations formulated in Task 2 were correct in comparison to Task 1

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 METHODOLOGICAL

Think-aloud-pen and paper sessions, which have been used extensively in physics (Larkin 1979; Woods et al. 1979), were used in the present study to provide rich data on how students solved material balance problems in chemical engineering. Strategies and skills used by students could be identified. The research depended mainly on verbal data, which was recorded and then transcribed, but the written records of students' problem solutions and researcher's notes provided some additions to the data for when verbalisation was absent. Neither verbal nor written records could provide information on what was happening when the student was silent and not writing.

This might seem to suggest that for future studies the interviewer ask students specifically about the things that seem difficult to verbalise and write down. Students could be probed concurrently with their solving and thinking-aloud for specific information. However, probing may interfere with the solving process of the students. On the other hand, asking students about these specifics at the end of the task would depend on what is remembered and how well depending on the interval between solving the problem and recall it (Ericsson and Simon 1980). If the information required by a study is mainly what students think during their solving process, having pairs to solve the same problem would be useful as the two solvers would be communicating their thoughts to each other.

As students in the present study were asked to verbalise concurrently with solving problems, an additional cognitive load may have been imposed by the instruction to verbalise, as suggested by Ericsson and Simon (1980). However this additional cognitive load was most probably negligible since most of the students were relaxed and responded to the request to verbalise positively. The reason for this could have been that prior to the study, the author was known to the students as a tutor in their Introduction to Chemical Engineering course the year before.

The tasks given to students were difficult enough to extract a wealth of information on how problems are solved. Tasks were not too difficult for the students so that they all got stuck, but also not too easy for them to solve without a bit of a struggle.

7.2 STAGES IN STRATEGIES AND SKILLS USED

The strategies used by students to solve problems in this study validated the theoretical framework in Figure 2-1. All the stages of *defining the problem*, *analysing the problem*, *planning the solution*, *implementing*, and *evaluating* were evident in the students' solutions. *Planning* and *evaluating* were evident only in a few solutions. Students may not have *planned* explicitly because the two tasks did not require *planning* or the tasks were similar to the problems they had tackled prior to the study. It is also possible that *planning* may have been done during the time in the sessions when the students were silent, in which case it could not have been identified in the students' verbalisations or written solutions. The students who *evaluated* did it by just re-entering numbers into their calculators. This kind of *evaluating* is sufficient for checking calculation errors only. It therefore means that if the numbers that were calculated in the beginning were wrong, re-entering the same numbers does not eliminate other errors for example errors, in the formulation of equations.

During the *defining* stage, most students showed that they could translate the problem statement into correct visual representations as was indicated by their process diagrams. Students are encouraged to draw diagrams in their CHE 231F course and they seemed to have grasped the skill well by the time the problem solving sessions were conducted.

In the *analysis* stage, students could access information from their knowledge base on material balances and use it to transform the problem statement into equations in order to solve the problems. Some skills in the framework did not find use in solving of the tasks. There was no evidence of students estimating answers or making assumptions in their solving processes. It seemed students did not also look back at their solution to learn from the way they had solved the problems. None of the students showed evidence of getting rid of mental or technical blocks.

Between different stages of students' strategies there were iterations. When things did not work in the process of solving, the students might have gone back to earlier stages and continued once the difficulty had been eliminated. Students who solved the tasks successfully had more iteration between the stages than unsuccessful students did.

7.3 RECOMMENDATIONS

As a result of the findings of this study it is suggested that the theoretical framework developed should be adopted as a strategy to teach and develop students' problem solving techniques. Lecturers at UCT should encourage students to *plan* their solution to avoid doing unnecessary calculations and wasting time, which in tests results in students not being able to finish. *Evaluation* of solutions, which may get rid of any errors in calculations, as well as errors in problem formulation, should also be strongly encouraged. Instead of re-entering numbers in the calculators students must be encouraged to check every step of their solution process for relevance and correctness. Persuading students to *plan* and *evaluate* may not be easy. Thus it is suggested that the use of these two stages in their strategies be assessed in tests. In addition, students should also be encouraged to iterate between the stages while solving problems as this allows then to revisit previous stages and to resolve difficulties or to clarify things which are unclear.

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APPENDICES

APPENDICES

APPENDIX 1. PRE-SESSION STATEMENT AND SESSION INSTRUCTIONS

Pre – session statement

Thank you very much for setting time aside for this session.
I will not assume you know exactly why you are here. Here is an explanation. I am interested in finding out how students solve problems. I am a not interested in a particular student but a general idea of the skills that students have in problem solving.

Lecturers are trying their best to teach problem solving but they are not sure whether their efforts are effective.

I am not very good at listening and taking down notes so could I get permission from you tape-record this session. Your identity will be anonymous.

I will give you two problems to solve: one today and the other a few weeks from now. The problems are similar so the second one will be done to identify any changes in the way you solve problems.

I am intending to publish the findings in my Masters Thesis. You are welcome to read it when it is finished.

Session Instructions

I am interested in what you think about, and what information you are accessing when you find a solution to the problem. I am going to ask you to think aloud as you work on the problem given. What I mean is I want you to say everything you are thinking and doing from the time you first see the problem until you have found a solution.

Assume I am not here, that you are alone in this room speaking to yourself. It is important that you keep talking. I may ask you to talk if you are silent for a long time.

Do you understand everything? Do you have any questions? Please feel free to ask any questions anytime.

You can begin when you are ready.

Please do not discuss this problem with the other students since I am giving everyone the same problem. It is very important that students do not think about the problem before I meet them.

APPENDIX 2. PROBLEM SOLVING TASKS

Task 1: Jam Production

Strawberries contain about 15% (by mass) solids and 85% water. To make strawberry jam, crushed strawberries and sugar are mixed in a 45:55 mass ratio, and the mixture is heated to evaporate water until the residue contains one-third water by mass.

a. Calculate how many pounds of strawberries are needed to make 1lb jam.

b. Is the following statement true or false? The mass of the strawberries and sugar added is equal to the mass of the jam formed.

c. As the seasons change, a different fruit is used in the jam making. Peaches contain about 20% by mass solids (excluding stone). Will the ratio of fruit to sugar added decrease, remain the same or increase if jam of the same specification is to be produced? Explain.

In this problem students were asked to find the amount of strawberries needed to produce one pound of jam. The first thing expected in chemical engineering problems is to read and extract information given in the problem and translate it into a diagram form. For someone to solve the problem, a person should have background knowledge of how to construct flow diagrams and how process units are put together. Figure 4-1 can represent a probable diagram for this problem.

In Figure 4-1(a) strawberries and sugar are added directly into the evaporator, which means that the evaporator becomes both the mixer and the evaporator. In Figure 4-1(b), strawberries and sugar are mixed in a mixer first before they are fed into the evaporator. In the case of this problem, both diagrams will give the same solution as the information given states that "strawberries and sugar are mixed in a 45:55 mass ratio". Thus you can either mix them before or add to the evaporator in those proportions. Students were expected to know how an evaporator works. One needs to realise that an evaporator will remove water only. All the solids will be in the jam and this water being evaporated is coming from the strawberries and not from the sugar. All the sugar together with all the solids in the strawberries will be in the jam but some water will evaporate. Thus the jam is now concentrated with the solid since water has been removed. No solids will go to the water stream. To produce one pound of jam in which 1/3 of this jam is water, it means 2/3 of the 1 pound jam are solids and you know all the solids are coming from the sugar and the strawberries.

To start solving part (a) of this problem i.e. to find the amount of strawberries that makes one pound of jam there is need to choose a basis. "A basis is a reference chosen by a student for the calculations you plan to make in any particular problem, and a proper choice of basis frequently makes the problem much easier to solve" (Himmelblau 1992). In this problem there are four possible bases. The easiest choice of basis would be to take one pound jam, which is the product required out of the process. A second choice could be for example 100 pounds strawberries; a third 100 pounds sugar and a fourth could be 100 pounds of both sugar and strawberries.

A basis of one pound jam is easy and straightforward because one does not need to scale up or down after the calculations are done to get the final answer since the specified one pound jam is produced. With the other three bases, one is not producing one pound of jam. Therefore whatever quantity one produces the strawberries needed would have to be obtained by adjusting the quantities.

Part (b) of task 1 is a conceptual question. If a person understood the problem they were supposed to realise that the water being evaporated is coming from the strawberries since they are made up of solids and water. So if you evaporate water, the mass of sugar plus strawberries added cannot make up the mass of the jam because water has evaporated. The answer to this problem is 'false'. Strawberries have lost some of their water through evaporation therefore the amount of water in strawberries is no longer equal because of evaporation.

In part (c), the student has to show flexibility and understanding of the problem and be able to analyse the situation at hand with an open mind. The type of fruit used to make the jam has now changed. The students were supposed to realise that in order to keep the same specification jam, that is 1/3 water and 2/3 solids from peaches plus sugar, the amount of sugar must remain the same. To keep the same amounts of solids from the peaches in the jam, not forgetting that the peaches have more solids than the previously used strawberries, one has to reduce the amount of peaches added. Therefore the ratio of fruit to sugar will decrease i.e. less fruit is required to produce the same solids.

The jam task is a bit ambiguous as far as the jam specification is concerned. Another person may understand "the same specification" as 1/3 water, 2/3 solids such that he/she might think in the lines of keeping 2/3 solids by decreasing the amount of sugar added to the increased amount of solids in the peaches. In this case the ratio will increase. The option of decreasing the amount of sugar may decrease the sweetness of the jam and results in other consequences. Due to the ambiguity of the problem both answers that is decreasing the ratio or increasing the fruit to sugar ratio are correct if they are well explained as required by the question.

The basis of calculations chosen determines the approach followed in solving a problem. A number of model solutions were produced using different bases. It would thus be important to identify how many students used a particular basis and whether their approach is the same or different.

Task 2: Juice Production

Fresh juice contains 12 weight percent solids and the balance is water, and concentrated juice contains 42% solids. Initially a single evaporation process was used for the concentration, but volatile constituents of the juice escaped with the water, leaving the concentrate with a flat taste. The present process overcomes this problem by bypassing the evaporator with a fraction of the fresh juice; the juice that enters the evaporator is concentrated to 58% solids and the product is mixed with the bypassed fresh juice to achieve the desired final concentration of solids.

a. Calculate the amount of concentrated juice produced per 100kg fresh juice fed to the process, and the fraction of the feed that bypasses the evaporator.

b. The volatile ingredients that provide the taste are contained in the fresh juice that bypasses the reactor. You could get more of these ingredients in the final product by evaporating to (say) 90% solids instead of 58%; you could then bypass a greater fraction of the fresh juice, and you would thereby obtain an even better tasting product. Suggest possible drawbacks to this proposal.

The first thing expected in this problem is to visualise the process involved and to draw a diagram, which shows all the information given in the problem. The proposed diagram for the problem is given in Figure 4-2.

Fresh juice is added to the evaporator where some of the water in it is evaporated. Not all the fresh juice to the process goes to the evaporator. The fresh juice stream passes through a splitter, which divides the feed into two streams specified by the operator of the process. Some of the feed in this process is fed into the evaporator while the other goes round the evaporator to a mixer. In the mixer the bypassed fresh juice combines with the concentrated juice coming out of the evaporator, i.e. the juice which has some of its water removed by heating and evaporation. The product of this mixer is the one that has the final required juice of the process. This bypass was introduced to the process to retain some flavour of the juice that evaporates with the water in the evaporator as the concentrated juice being produced had a poor taste.

Here a student was expected to have knowledge of bypass operations in processes. When students were given this problem they seemed unfamiliar with a bypass process. Students were asked if they were familiar with the recycle process. Fortunately they understood how the recycle works in a system. The recycle process is simply the opposite of a bypass process thus with the aid of the diagrams in Figure 4-3 and Figure 4-4, I illustrated to the students how bypass differs from recycle. It was made clear to the students that this diagram was only an example and not the proposed diagram for the given problem.

To solve this problem, students had to realise that the evaporator removes water from the fresh juice and that no solids of the juice will be evaporated with the water. It was also important for students to note that the vapours of flavour that leave the evaporator with water do not contain any solids. This means that all the solids in the fresh juice end up in the concentrated product.

As far as the bypass is concerned, the students were supposed to realise that when the fresh feed is split to the bypass stream and the feed to the evaporator, the proportion of solids and water in each of the streams remain the same. That is the composition of the bypass, and the feed to the evaporator remains equal to that of the fresh juice entering the process.

In this problem the amount of fresh juice fed to the process is known. To be able to find the amount of fresh juice produced by this amount it would be easy to choose the 100kg fresh juice as the basis for calculations. However several other bases may be chosen in this problem. One could also choose to put a basis at the end of the process such as 100kg concentrated juice produced. However in this case one has to calculate the amount of fresh juice that makes that 100kg concentrated juice. This amount of fresh juice will then be used to adjust the calculation to obtain the amount of concentrated juice produced by 100kg of feed. With such a basis the calculations go backwards, from the concentrated juice to the fresh juice then back to the concentrated juice. In the process of scaling the calculations, it is possible to produce errors or even to forget to adjust amounts. Other bases could be chosen either at the concentrated juice coming out of the evaporator or the fresh juice that enters the evaporator. Similarly more calculations are required here to get the solution to the problem thus the methods could reduce the accuracy of calculations.

In part (b) of the problem, the amount of solids to be left in the juice after evaporation has increased from the 58% of part (a) to 90%. This means that more fresh juice would have to be bypassed to produce a juice mixture of the required concentration, 42% solids. Here a student was expected to analyse the effects of altering the juice process in that way. This required the student to put him or herself in the position of the "juice producer" so as to discover the changes that would result from implementing this proposal.

In order to evaporate the juice to 90% solids, the evaporation process itself would need more energy but less would go through the evaporator. A process with a very high-energy input is very expensive to operate and then this would be the major drawback in that sense. But if one draws a black box on both systems (the original and the proposed), and does a mass balance across the systems, one would find that the same amount of water is being evaporated out of both systems. This implies that the same amount of energy has been used by both systems. Based on this argument one can safely say, there are no drawbacks related to energy consumption. In other words, in task 2 (b) one is only solving the flavour problem. To answer this problem safely one should do a detailed energy balance across the evaporator and students were not expected to do that. Therefore any arguments along theses lines are deemed correct.

APPENDIX 3. MODEL SOLUTIONS

Table A-1 Jam production model solution (Basis=100 pounds strawberries)

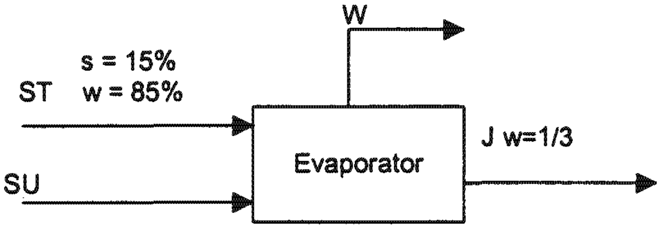
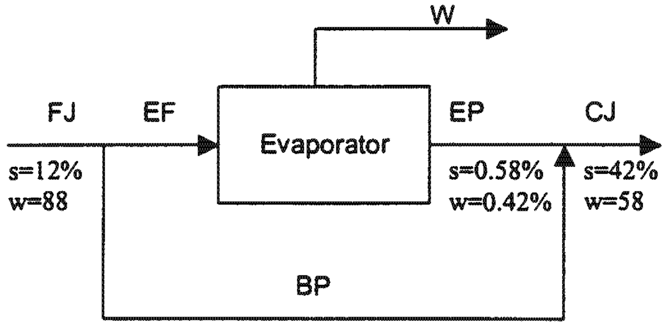
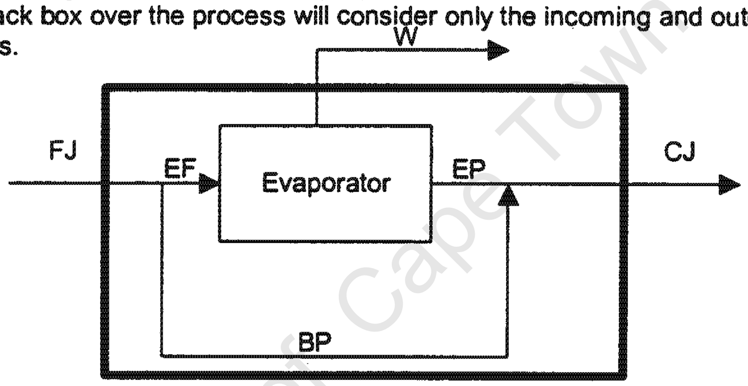
DEFINE	From the problem statement the diagrams in Figure 4-1 may represent the process described. I will call the strawberry stream ST, the sugar stream SU, water stream W and the jam stream, J; s = solids and w = water. 
ANALYSE	Basis: 100 lb. Strawberries Overall balance: $ST + SU = W + J$ Species balance: In strawberries there are 15lb. solids and 85lbs water. From the ratio, ST/SU= 45/55 ∴SU =ST(55/45) Solids balance: $sST + sSU = sW + sJ \Rightarrow 0.15*100+100\left(\frac{55}{45}\right)=\frac{2}{3}J$
PLAN	Well here since I have the amount of strawberries used, I can simply use the ratio 45:55, fruit to sugar to calculate the amount of sugar needed. After that I can use an overall balance to find the amount of jam formed by 100lb. strawberries. Thereafter I will have to scale up/down to find the strawberries needed to produce 1 lb. jam.
IMPLEMENT	$0.15*100+100\left(\frac{55}{45}\right)=\frac{2}{3}J \therefore \left(\frac{2\left(15+100*\frac{55}{45}\right)}{3}\right)=205.833\,pounds$ So that's 205.833 pounds of Jam produced by 100 pounds strawberries. Thus the amount of strawberries needed to make one pound of jam is : $\frac{100}{1}*\frac{1}{205.833}=0.486\,pounds$
EVALUATE	Is 205.833 the right answer here? Yes the calculation is all right.

Table A-2 Juice production model solution (Basis=100kg Evaporator product)

DEFINE	So the process of interest is the one with a bypass. Symbols for the streams are: Fresh Juice, FJ; Evaporator Feed, EF; Bypass, BP; Evaporator product, EP; Water, W; Concentrated Juice, CJ; s=solids; w=water.  I need to find concentrated juice produced by 100kg fresh juice and the fraction of feed that is bypassed.
ANALYSE	Basis: 100 kg Evaporator product (EP) The black box over the process will consider only the incoming and outgoing streams.  Evaporator balance: $EF = W + EP$ ... (1) Solids out of evaporator are 58kg; water out of evaporator is 42 kg. Mixer Balance: $EP + BP = CJ$ ... (2) Solids balance: $58 + 0.12(BP) = 0.42(CJ)$...(3) Water balance: $42 + 0.88(BP) = 0.58(CJ)$...(4)
PLAN	I will first find what C is. Then do an overall balance.
IMPLEMENT	Using equations (3) and (4) (3)*(0.58/0.42): $80.095 + 0.1657(BP) = 0.58(CJ)$...(5) (5)-(4): $38.095 - 0.7143(BP) \therefore BP = 53.33kg$ Substituting values in (3): $\frac{58 + 0.12(53.33)}{0.42} = CJ \therefore CJ = 153.33kg$ By overall balance of solids: Solids in FJ = solids in CJ $0.12(FJ) = 0.42(153.33) \Rightarrow FJ = 536.655$ Thus 536.655kg FJ produces 153.33kg CJ, thus CJ produced by 100kg FJ is $CJ = \frac{100 * 153.33}{536.655} = 28.57kg$; (2), $BP + EP = CJ \Rightarrow BP = 53.33kg$ The fraction bypassed is $\frac{53.33}{536.655} = 0.0994$
EVALUATE	There are so many equations in this part. Let me just see if they are all right. To check the bypass stream let me use the balance at the splitter: $FJ = EF + BP \Rightarrow 536.655 = EF + 53.33 \therefore EF = 483.325$. Solids on EF are equal to solids in EP, Thus $0.12(483.325) = 0.58(100)$ .Bypass OK

APPENDIX 4. EXAMPLE OF A HOW KUDZI'S TRANSCRIPT WAS CODED

Kudzi's Transcript

Kudzi's Transcript	Code (as in Table 4-4)	Sequencing
Strawberries contain 15% by mass solids, 85% water and strawberry jam, crushed strawberries and sugar, 45 to 55 mass ratio and the mixture is heated to evaporate water.... Amount of strawberries to produce one pound of jam.		
Okay, umm, Strawberries contain 15% solid, and 85 % water. Crushed strawberries and sugar are mixed in that ratio. Of this, of this 15% solid and 85% water this is gonna make up 45 parts and then sugar, crushed strawberries and sugar... So the sugar is gonna make up 55 parts sugar, sugar mass ratio mass, so umm the mixture is heated to evaporate water until residue contains 1/3 water by mass.	1.1	1
So pick a basis.	2.1	2
Okay so of 100lbs of, we are making jam strawberry jam, okay I want with the water as well. So 100lb of sugar plus solids plus water. 100lbs solid, water, and sugar together. But... so of my 45, I guess out of the 45lbs of this... So my mass of solid is 0.15*45 which is 6.75 and then water is 0.85*45....15% and 85% strawberries....	2.2	3
Evaporate water until the residue remains with one third.... So to obtain 1/3 water it would have to be 2 parts solid 1 part water so 2/3 of the mixture is umm 6.75lbs of the solids and 1/3 would have to be of say water that gets out ... it would be 3/2 times so the total mass of solid,	2.4	4
No the total mass of crushed strawberries, is it the crushed strawberries yah, total mass of crushed strawberries is 3/2 *6.75lbs crushed strawberries plus crushed strawberries and sugar are mixed, or the mixture of the sugar, okay so I can't do that, this is wrong because I left out.	2.5	5
Okay then I take a mass of solid, which is 6.75, plus the mass of sugar, which is 55 lbs., it's a very sweet jam which equal 2/3 of my jam. My total jam is going to be 6.75 + 55 is equal to 92.625.	4.1	6
Yes that's right because we are boiling off water so it should be less. Okay water is reduced to a 1/3 of that	4.2	7
Now how many pounds of strawberries make a pound of jam?	1.6	8
So we would have to work out of this 92.625, solid strawberries make up. Yah you work out the % of solid strawberry of the total. And you work that back to obtain the strawberries.	3.1	9
6.75 divided by 92. 625 times by 100 is 7.28 right so no that cant be right no 7.28 so that's my percent of percent solid strawberries, percent of solid strawberries, and then I have to divide that by 0.15. Yah is to get my %, 48.6% strawberries. Yes how many pounds of strawberries are needed to make one pound of jam. 0.486 strawberries,...	4.1	10
... so yah 0.486 to make one pound of jam. *Okay.*	5.1	11

Kudzi's Written Solution

a) Strawberry's
15 % solid } 45 55 ~~p~~ sugar
85 % water }

BASIS : 100 lb ~~str~~ solid, water & sugar together

45 lb
0·15 (45lb) = 6·75 lb
0·85 (45lb) = 38·25lb

~~$\frac{2}{3}$ of 6.75 lb~~
~~$\frac{1}{3}$ of x lb~~
~~Total C.S. = $\frac{3}{2}$ × 6·75lb~~
~~= 10·125lb~~

6·75lb + 55lb = $\frac{2}{3}$ jam
∴ total jam = 92·625lb

$\frac{6 \cdot 75\text{lb}}{92 \cdot 625\text{lb}} \times 100 = 7{\cdot}287$ % solid strawberry

$\frac{7 \cdot 287\ \%}{0 \cdot 15} = 48 \cdot 6$ % Strawsberry

0.486lb of strawberrys

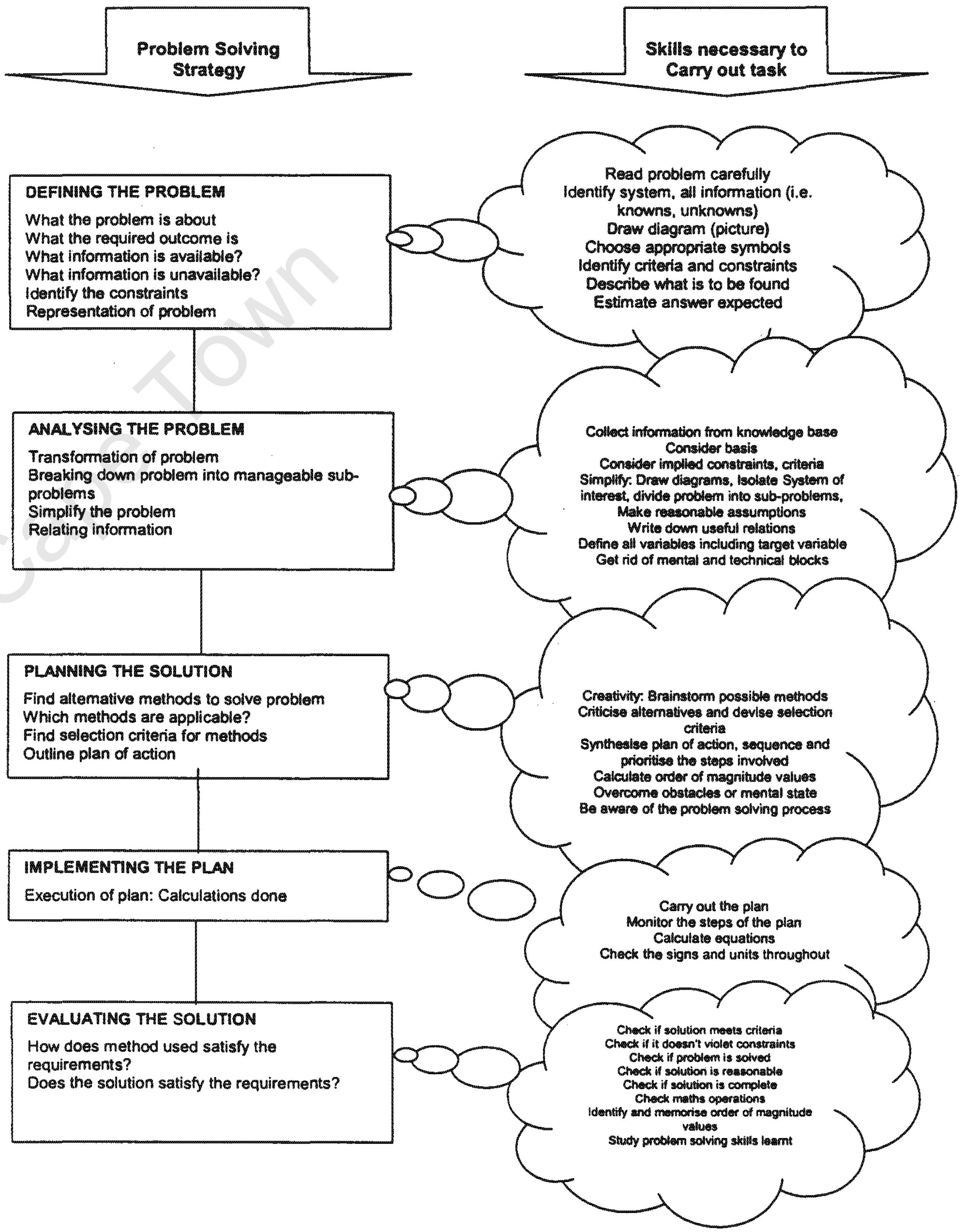
b) No, boil off water

c) Decrease. 20% solid in peaches ~~or~~ means that fewer peaches are required for the same amount of jam. ∴ Ratio decreases

APPENDIX 5. TABLE 2-1, PROBLEM SOLVING STRATEGIES SUGGESTED IN THE LITERATURE

SOURCE	STRATEGY
Polya (1957)	Understand the problem – Devise a plan – Carry out the plan – Look back *Developed for mathematical problem solving.*
Woods et al. (1975)	Define the problem – Think about it – Plan – Carry out the plan – Look back *Modified version of Polya's strategy. Used in a McMaster University project to improve students' problem solving skills.*
Reif et al. (1976)	Description – Planning – Implementation – Checking *Strategy taught to encourage students to examine a problem before blindly calculating and to check their answers afterwards.*
Mettes et al. (1980)	Analysis of the problem – Transformation of the problem – The execution of routine operations – Checking the answer and interpretation of the results *Developed for a thermodynamics course, problems requiring the specification of the solution.*
Bransford and Stein (1984)	Identify the problem – Define and represent the problem – Explore possible alternatives – Act on the alternatives – Look back – Evaluate the effects of your activities *Strategy for improving problem solving and decision-making.*
Schoenfeld (1985)	Analysis – Design – Exploration – Implementation – Verification *Strategy served as a foundation for mathematics and liberal arts majors.*
Conwell et al. (1993)	Acceptance – Analysis – Definition – Ideation or Brainstorming – Selection – Implementation – Evaluation *Koberg and Bagnal strategy introduced to design students.*
Conwell et al. (1993)	Definition of Problem – Information Retrieval – Seeking Alternatives – Development Synthesis – Analysis – Cost/ Benefit Analysis – Reporting to clients *Harrisberger strategy introduced to design students.*
Fogler and LeBlanc (1995)	Define the problem – Generate solutions – Decide on the course of action – Implement the solution – Evaluate the solution *Designed for anyone who would like to improve their problem solving skills.*
Rubinstein and Firstenberg (1995)	Preparation – Incubation – Inspiration – Verification *Problem solving strategy known by psychologists.*
Huffman (1997)	Focus the problem – Describe the physics – Plan the solution – Execute the plan – Evaluate the solution *Strategy given to students to investigate its effect on problem solving performance and conceptual understanding.*

APPENDIX 6. FIGURE 2-1, THEORETICAL FRAMEWORK FOR THE STUDY



APPENDIX 7. CODING SCHEME

1. Defining the problem

1.1. Where all problem conditions noted?

1.2. Were the conditions described correctly?

1.3. Did the student draw a diagram?

1.4. Does the diagram correctly describe the process?

1.5. Were symbols used for representation of variables?

1.6. Was the required outcome noted?

2. Analysing the problem

2.1. Did the student choose a basis?

2.2. Was the basis used correctly with the problem conditions?

2.3. Were problem conditions linked to the required outcome correctly?

2.4. Were relations between knowns and unknowns correct?

2.5. Were these relations checked for their validity?

2.6. Were all relations translated into the correct equations?

2.7. Did student describe any basic concept related to the problem?

3. Planning the solution

3.1. Is there evidence of planning?

3.2. Did student assess the plan?

3.3. Is the plan well structured?

3.4. Is the plan relevant to the problem solution?

4. Implementing the plan

4.1. Does implementation follow the plan exactly?

4.2. Is the implementation checked for errors?

4.3. Was the student able to produce a solution at all?

4.4. Was the solution complete?

5. Evaluating the solution

5.1. Was the solution checked?

5.2. Were the intermediate calculations checked?

6. Characterisation of the solution

6.1. Was the problem solved?

6.2. Were answers to other questions correct?

6.3. The solution was Good (G), Partial (P), and Bad (B)