THE STRATEGIC VALUE OF TARGETED KNOWLEDGE MANAGEMENT – CASE STUDY OF AN AUSTRALIAN REFRIGERATION COMPANY

A thesis submitted in fulfillment of the requirements for the degree of Doctor of Philosophy

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Declaration

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; and any editorial work paid or unpaid carried out by a third party is acknowledged; and ethics procedures and guidelines have been followed.

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Abstract

This thesis is a study of design and implementation of an engineering knowledge management system to facilitate knowledge capture, sharing and reuse to both ensure business continuity and resolve a make-span problem in an Australian refrigeration company. The company had encountered problems with a number of engineering staff in the small product development team leaving the company and taking their expertise with them. This situation has impacted the business continuity of the company, because the knowledge and expertise used in the refrigerated display cabinet development process is a combination of explicit and tacit knowledge as the engineers conduct the product development process intuitively. Records of previous design and testing processes were either non-existent or stored in ways that were not accessible. The other business problem in the company resulted from product development taking too long, in effect from 6 weeks up to the worst case of one year. The company needed research solutions to both of these problems to strategically maintain the competitiveness of the company business.

This research applied a single case study research method with a problem-solving paradigm, Design Science methodology, to develop and then test solutions. Design Science as a research methodology has two components, first design development and second, design evaluation. The researcher developed an engineering knowledge based system as an artefact to solve the problem of enabling company business continuity. Using ontology as a structural base, the KBS contains both knowledge elements captured from the engineers during the data collection process and existing knowledge artefacts in the company. The research used a set of multilayered research techniques, including semi-formal and formal interviews, serendipitous interviews, group meetings, observation and shadowing, to capture and then structure both the tacit and explicit knowledge. The resultant ontology was used to build the KBS to store both tacit and explicit knowledge and answer the engineers' questions about their existing and previous product development processes. The KBS developed in this research is a knowledge repository to maintain records of the products design and testing

processes in a searchable form. Use and then an evaluation of the system by the engineers and the executive staff of the company confirmed that the intention of the system to address the business continuity problem by knowledge capture, classification and storage was achieved and met the company's business needs.

The KBS is a tool that any company can develop. Besides its value as a repository of company and expert knowledge, it is also a source of knowledge that can be used to resolve other business problems through application of analytical methods. This research applied Heuristic Process Mining to the knowledge stored in the KBS to address the second problem identified initially by the company, that of lengthy make span in new product design and development. HPM is a technique using mathematical models to find relationships between tasks in the process. HMP measures dependency and frequency values between tasks and tasks with low D/F value can be eliminated from the process. The engineers then don't need to spend time executing unnecessary tasks. This then can lead to the shorter product testing process. The research showed that the application of HPM to the stored process knowledge in the KMS was able to significantly reduce the product design and testing process in the company.

Both the KBS and the outcomes of the application of HPM were evaluated in the Design Science context for functionality, efficacy, performance, reliability, consistency, effectiveness, completeness, quality feasibility and ease of use. Because the size of the company product development team is small, a qualitative evaluation method with group consensus technique was used. The evaluation showed that ontology as a design method can be applied to represent the company knowledge and the result significantly reflects the company's real engineering processes. The research also confirmed that the structure of the KBS facilitates product development knowledge capture, sharing and reuse. The evaluation of the HPM result in this research has shown that the company's product testing process can be reduced from one that was long and complicated to a shorter and simpler process.

This thesis has made significant contributions to our understanding of the use and impact of knowledge management. These are:

- Tacit knowledge can be captured and codified by using multiple knowledge capture techniques.
- Knowledge stored in a KBS can be used strategically to resolve business problems by mathematical analysis.
- One of the factors to gain KBS implementation success is the system should not change the way experts work in their practice.
- Knowledge capture process can be more successful if researchers have domain knowledge. This is because domain knowledge can facilitate researcher to identify knowledge that needed that needed to be captured.
- Knowledge management system implementation can be done cost effectively across an organization.
- Iteratively evaluating the artefact will increase the quality of that artefact.
- This research applied HPM to the process where the tasks embedded in the process and its sequences are dynamic. In other words, each task can be executed at any stage in the process. Unlike traditional HPM applications where static business process were applied.

Knowledge management is a useful and effective tool in enabling companies to develop and then resolve strategic business issues.

Chapter 1 Introduction

1.1 The Scope of the Research

This thesis is a study of the design and implementation of an engineering knowledge management system to facilitate knowledge capture and re-use, and sharing to both ensure business continuity and to resolve a make-span problem in an Australia refrigeration company.

The research focuses on the strategic role that knowledge management can play in resolving business problems. Porter (1985; 1987; 1991; 1993) argues that the fundamental purposes of strategic management are to maintain competitiveness through cost efficiencies and to maintain position in the market. Product development is one means of strategically gaining business advantage. Customisation in product development is used strategically to differentiate core products to suit different requirements. This can help business gain competitive advantage in the market (Nicholls & Eady 2008). For an organization to perform well in the product development process, it requires particular expertise from specific groups of people inside and outside the organization, that particular expertise often involving tacit knowledge.

Effective manufacturing of customised products is not simply a knowledge problem but rather is one of knowledge management (Nicholls & Eady 2008). Knowledge management requires a number of processes such as knowledge identification, capture, storage and sharing (Booth 2010). Effective information (explicit knowledge) management and tacit knowledge sharing have become an essential part of professional tasks in the product development process (Catalano et al. 2008). 'The management of knowledge is promoted as an important and necessary factor for organizational survival and maintenance of competitive strength. To remain at the forefront organizations need a good capacity to retain, develop, organize, and utilize their employees' capabilities. Knowledge and the management of knowledge appear to be regarded as increasingly important features for organizational survival' (Mårtensson 2000, p. 204). A study of Toyota showed that production development can be improved through use of one resource, knowledge creation (Ichijo & Kohlbacher 2008). One of the key ways to use knowledge creation is to locate the expert in the field area whether in the company or in the technical community (Spangler & Kreulen 2008, p.112). More and more knowledge from design and production processes are continuously accumulating at the personal level as well as in organizational artefacts. This knowledge needs to be captured and re-used to prevent organizations re-inventing the wheel. Using this collected knowledge and expertise has become a critical factor in reducing make-spans and improving the product design time frame. To be able to use the knowledge strategically requires effective knowledge management.

1.2 The Research Problem and Context

In 2008, an Australian refrigeration manufacturing company (the Company) contacted RMIT University about research that was needed to deal with a number of strategic issues that they had identified. The Company is fully Australian owned and operated. There are over 600 employees located in 13 locations across the country. The company provides various refrigeration services and products to the markets which can be divided into three divisions. These include manufacturing which is one of the largest refrigerated display cabinets manufacturer in Australia. The second division is refrigeration which provides full service of design and installation of refrigeration systems in supermarkets such as refrigeration pipe line systems and cool rooms. The last division is air conditioning where the company provides air conditioning design, installation and maintenance services to supermarkets, retailers and house-hold customers. The research in this thesis focuses only on the manufacturing division. The Company manufactures customized refrigerators in various forms such as food product display units in supermarkets, wine cellars, fresh produce displays, dairy cabinets etc. These customized refrigerators are built with specific differences between units as each customer has particular requirements. For example one section of any supermarket has to store dairy products which requires one temperature set point while in another section of the same supermarket there is a need to store meat or seafood frozen products which require another temperature set point. This is an important issue as some of the products require an accurate temperature set point as the products may lose their quality if the temperature set point cannot be maintained. Furthermore, their clients' (which are mainly the big supermarket operators such as, Coles and Woolworth) requirements are very specific. For instance, some supermarket locations have more consumers than others leading to the product turnover rate of their commodities in display cabinets being higher. This means new products at ambient temperature or products just arrived from a delivery have to be added to the cabinet more frequently. Such differences in the Company products then are a direct effect of the needs for different cabinets' cooling capacities.

In addition, supermarkets know that customer behaviour is constantly changing and that the need for their products to be sold in different ways is increasing. This is a key factor in the deployment of refrigerators as most of the products in supermarkets can be, and often are, displayed in open cabinets. This is necessary since products now must have good appearance to the customer without visual obstruction making it easy for customers to choose products. Typical product layouts are shown in Figure 1.1

Figure 1.1 The Company's products

The Company's products must also comply with the national standard for refrigerated display cabinets (AS:1731 2003). These standards are changed frequently and between 2008 and 2010 were modified to meet new carbon emission requirements. The Company had to encompass these needs and changes into the design and development to their new refrigeration products. Essentially, they had to use their expertise in engineering knowledge to design and manufacture refrigerated display cabinets to meet the requirements. These include the needs of supermarket clients, their customers and both new and old manufacturing and environmental standards.

The Company indicated that it needed assistance to ensure that the expertise of their engineers was not lost through resignations, so as to develop better, more effective processes for product improvement and to reduce the time taken from concept to manufacture to meet the changing demands and individual requirements of their clients. Currently the make-span of a new product at the Company can be as long as 1 year. It is critical for this make-span to be reduced to survive in the marketplace. This research aims to demonstrate that by using (i.e., 'tapping into') the expert tacit knowledge of the engineers, costs can be reduced and that the Company's ability to be internationally more competitive and innovative will be enhanced. It will also facilitate retention of this knowledge within the Company in case of an expert leaving the organization. This tacit knowledge problem also similarly exists in the glass and aluminium smelting industries (Nicholls 1993; Nicholls & Cargill 2006). The need for Australian industry to innovate and become more competitive is a key area of strategic and national importance for the Australian Government (Cutler 2008)*.* This research will use the domain of engineering knowledge as a means to resolve the make-span problem.

The Company's problems can be summarized as follows: the team of engineers took too long to get new products to market; the expertise and knowledge of the design engineers was never captured; consequently the Company was vulnerable to employee recruitment by competitors. As a result the Company's competitive position was at risk. Additionally, their costs were too high as design and development took too long. This research uses a specific case to show that, with detailed application of ontology and analysis of the ontological system (using heuristic knowledge mining), that knowledge management (KM) can be a useful strategic tool. This research addresses two key questions:

- How can knowledge management be used to resolve strategic issues in business?
- How do we know these solutions are effective?

1.3 Knowledge Management as a Strategic Tool

Knowledge management is defined as the management of knowledge to improve the organizational efficiency, effectiveness and competitiveness. Knowledge management (KM) helps experts in organizations to pass their knowledge to new employees to be able to work in the organization (Alavi & Leidner 2001; Bartholomew 2008; Hackett 2000; Schwartz 2006). Knowledge management research has shown that KM is a useful strategic tool and has been used to focus on organizational improvement (Davenport & Prusak 1998). Business today operates in a knowledge-based business framework. New technologies and methods have been studied to facilitate knowledge management in organizations, not just for day-to-day uses but also about strategically using knowledge to improve business (Davenport & Prusak 1998; Ichijo & Kohlbacher 2008; Nonaka & Takeuchi 1995). This research has focused on knowledge that employees in companies already have but which has not been used to its full potential (Quintas, Lefrere & Jones 1997). Capturing this knowledge, it is argued, can improve quality of products and services reduce costs and improve organizational use of time. Kamara et al. (2002) argue that KM is the way that organizations make value out of their intellectual assets via methods, tools and techniques to improve the business.

From an engineering perspective, knowledge management includes the way to use knowledge to extract information from an information overloaded environment and to re-use that engineering and manufacturing knowledge to achieve design requirements and reduce overtime delivery of products by better time utilization (Quintas, Lefrere & Jones 1997). Information Technology (IT) based knowledge management systems are not new. They have been used since the early eighties (Kamara, Anumba & Carrillo 2002). Implementing knowledge management systems (KMS) alone though is not the key to success. Organizations that have implemented KMS have still struggled in achieving business improvement. There are other problems related to people and organizations that need to be addressed. People hold some elements of knowledge as tacit knowledge. In engineering this can be professional knowledge and experience and can relate to specific design processes built up over long periods of design and manufacture. IT systems can certainly store explicit knowledge as artefacts and documents and developed properly can store captured knowledge. However, there are problems with knowledge capture which often means that attempts at the use of KM for strategic purpose fail (Kanjanabootra, Corbitt & Nicholls 2010). Strategically used, knowledge can be referred to as two ‘knows’: firstly, know what the organization already knows and secondly know what the organization needs to know (Silvi & Cuganesan 2009). By following this approach it can be argued that the strategic benefits of the use of KM can be realised.

1.4 The Research Strategy

The design of refrigeration systems is not deterministic; it can at best be ‘simulated’ using gas diffusion and cooling space simulation modelling approaches. The engineers at the Company already have access to simulation programs (CFD Software) but in their opinion there are too many assumptions associated with the input parameters and, as a consequence, the output results are not sufficiently accurate for their purpose. Previous research of the aluminium smelting industry (Nicholls & Cargill 2006) suggests that operations research modelling can be used but that there is also a knowledge problem. In this research, the proposition is that the real expertise is in the tacit and embedded knowledge of these engineers.

The story of the research for this thesis represents an example of application of Design Science using a variety of research methods. The research began with the design and building of ontology as a basis for a knowledge-based system to resolve the business continuity problem identified by the Company. The second stage used a Heuristic Process Mining technique extracting production knowledge from the knowledge-based system to resolve the strategic problem of a make-span that is too long.

1.5 Structure of the Thesis

Chapter 2 presents a critical review of existing research. This chapter reviews previous research about knowledge, knowledge management, knowledge management system and tools. It reviews how researchers in research communities used knowledge management as a strategy to improve the organizational effectiveness. Most researchers have categorised knowledge into two types, explicit and tacit knowledge. However, there still are other contexts of knowledge that need to be considered. This need occurs since, to be able to strategically use and re-use this knowledge, specific acquisition techniques are required. This is to ensure that only relevant knowledge is captured. To be able to capture the right knowledge requires multiple knowledge capture techniques. This is because tacit knowledge is often difficult for users to codify and explain. After knowledge has been captured, the engineers then have to select appropriate tools to store it. The researcher used this review to identify the gaps that exist in the application of strategy to knowledge management research and to establish the limitations in existing research on the strategic value of the adoption of knowledge management systems in engineering design and production contexts. The Chapter identifies that knowledge management can be used as a strategic tool for maintaining competitive advantage of an organization.

Chapter 3 describes the research methods used in this study. The first step in the research involved the iterative building of a knowledge management system using Design Science principles (Gregor 2002, 2006; Gregor & Jones 2007; Hevner et al. 2004; Venable 2006) incorporating elements of action research (Baskerville & Wood-Harper 1996). The data was collected using a set of research techniques including structured interviews, serendipitous interviews, shadowing, observation of meetings, observation of laboratory testing and embedding the researcher into the work of the engineers over a five month period (Kanjanabootra, Corbitt & Nicholls 2010). The engineers involved were integral to the design and development process used in building, changing, adopting, using and re-changing the knowledge management system. In this initial part of the research, the researcher and the host-organization were working together intentionally to solve particular problems (Baskerville & Wood-Harper 1996; Hart & Bond 1995). In Design Science a number of cycles of research design and evaluation are intertwined until the problem is solved. In this study the end product was a knowledge management system built on an ontology derived from expert knowledge of the researcher – a mechanical engineer. The researcher used cycles of versions of the ontology and the developing KMS through feedback between the engineers and the researcher to gain the most complete understanding possible of the actual changing process. Following Baskerville and Wood-Harper (1999) the research went through typical action research stages: problem identification, collaboration, action taking and evaluation of the outcomes of the action. Within the principles of Design Science an artefact within this research was designed, built and tested.

In the second part of the research the system built on Design Science principles was then adapted and a heuristic process mining method was applied to extract key facets of knowledge from the KMS that related to the design and development process. This research applies the key principles of building theory and artefacts before, during and as a result of research using iterations of problem diagnosis, technology invention/design and technology evaluation using field studies, and action research. The initial stages of the design were in creating the ontology and then building the KMS. The knowledge classified and then stored in the KMS was then mined.

Chapter 4 describes the knowledge structure and processes used to frame the ontology used in the research. This Chapter also demonstrated the iterative nature of the design and evaluation steps that formed the research method used in the study as part of application of the Design Science Research methodology.

Chapter 5 is a detailed description of the development of a knowledge management system using an ontology grounded in the application of expert knowledge and the design experience of the Company engineers. The normal practice of the product development team did not utilise knowledge management. During their product development process, significant amounts of knowledge, information and data were generated every day. The engineers recorded information in various places, but there was no link to connect this information together. For example, data collected form various measuring instruments stored in the computer in the testing office were not linked to specification details from previous products stored on the Company’s local network and in each engineer’s computer. Meanwhile the engineers' notes of modifications made to the refrigerated display cabinets had been hand-written on paper then stored in drawers, material which the engineers noted they hardly looked at. This is no surprise because information recorded on paper was untraceable. The data derived from the instruments were numerical data, and could not be used in the way they were recorded. To make use of data and information requires links between them. For example, when the engineers modified the suction pressure they needed to see how the cabinet responded in terms of the cabinet temperature. The existing data records were unable to do that. The engineers needed a tool that could store multiple data types and formats and link them together for their knowledge retrieval. Chapter 4 then shows how the application of knowledge management can be used to resolve organizational business continuity. The system can be used to capture expert knowledge. In this case "Knowing what we know" is reflected in the process of capturing both explicit and tacit knowledge from the design engineers and storing that in a knowledge management system for the engineers to re-use in the design process.

Chapter 6 represents a detailed analysis of the make-span problem in the Company with the use of strategic knowledge management by applying a heuristic process mining technique to the captured knowledge in the KMS. The Chapter shows that when structuring a knowledge-based system using a particular method and then a relevant ontology, that knowledge can then be used for other purposes, not just process logging. The structure of the knowledge-based system facilitated the input the modification tasks engineers had made to the cabinets. Then the sequence of each modification was able to be mined. The analysis used in this Chapter reveals the organizational design and development processes, and enables their mapping and interpretation. This means that irrelevant steps in the design and development processes can be identified and eliminated; resulting in a shorter make-span period, improved efficiency in design and development leading to cost reduction. These enable improved competitiveness through getting product to market in a more time-effective manner.

Chapter 7 presents an analysis of an evaluation of both the KBS and the application of heuristic mining using an evaluation framework based in previous research. Various evaluation criteria have been adopted to suit both aspects of this research.

Chapter 8 presents a discussion of the outcomes of the research in relation to demonstrating how strategic use of knowledge management can enable improved design processes as a means to ensure business effectiveness and, through knowledge capture, enable business continuity. This Chapter highlights the key contributions of this research to our understanding of strategic knowledge management and its application for resolving business issues. This Chapter also addresses the limitations of the research undertaken and offers an understanding of what future research should be done.

The structure of the thesis that will be used throughout is shown in Figure 1.2. In the next Chapter the literature relevant to the researcher problems is discussed.

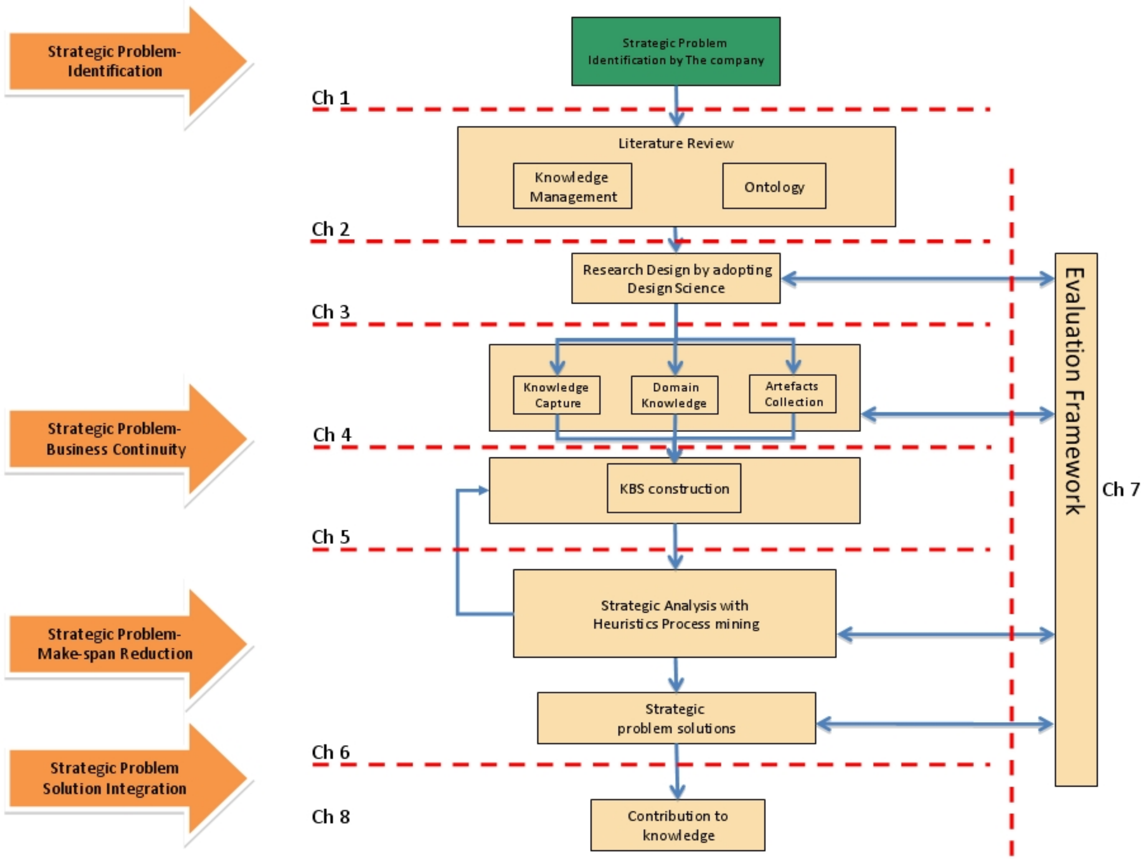
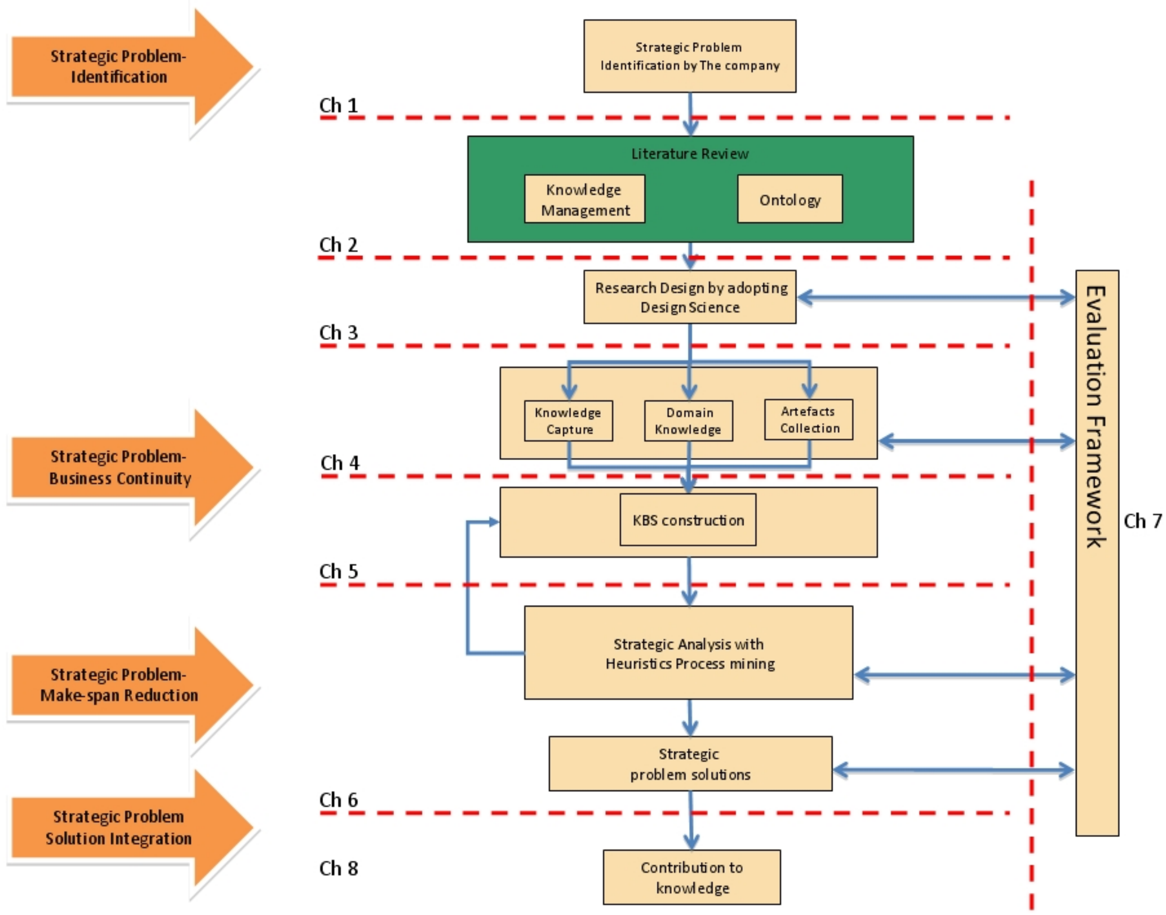


Figure 1.2 Structure of the thesis

Chapter 2 Literature Review



2.1 Introduction

This chapter reviews previous research on Knowledge Management and the ways in which it has been used in business and research. The problem faced by the Company in this case study was more than just a management problem; rather it was a knowledge problem. The knowledge problem in manufacturing organizations often affects both the cost of the product and business competition. The aim of this review is to develop some understanding of how business perceives that KM can be used as a strategic tool to solve business problems. To begin it is important to understand what knowledge is. This is reviewed in section 2.2. Global market businesses are aware of how important information and knowledge is in term of business strengthening. They began to ask themselves 'What do we know, who knows it, what do we not know that we should know?' (Prusak 2001, p. 1002). Section 2.3 then reviews the nature of knowledge and management and what are the problems encountered by researchers. Section 2.4 then reviews the knowledge management tools available to facilitate knowledge management, leading to a discussion in Section 2.5 of knowledge-based systems, what they are and how they work. As part of that process there is a need to understand both knowledge capture (Section 2.6) and knowledge sharing process and problems (Section 2.7). Researchers have emphasised how KM is important for business. However, knowledge management systems can be designed to serve organizations more than just operationally in day-to-day knowledge capture and sharing. The final section 2.8 reviews how KM can be used to further business strategy.

2.2 What is knowledge?

Davenport and Prusak (1998) have described the differences between data, information and knowledge. Knowledge has specific characteristics and has often been compared with data and information; unlike data, which is a set of numerical records that cannot express meaning by itself. To make use of data, users have to add meaning in it. The example used by Davenport and Prusak (1998) is that when customers fill their cars with petrol at the station, the amount of petrol, how much it costs and the customers' payment method, are the data. This data cannot tell why the customer used that station, what the service was like and whether the customers will return (Davenport & Prusak 1998). Organizations often record this into a database. Data can explain only what happens. It cannot tell you how it happened or what to do to improve the business.

Information is the message that changes the receiver's behaviour when the message is perceived. Data with added meaning then becomes information. According to (Davenport & Prusak 1998), information moves around the organization and it has purpose. It provides meaning to organisational data and therefore has added value.

Knowledge has an individual intuitive sense. It has a deeper and richer sense than data and information. Nonaka (1994) mentioned that knowledge and information often have been used interchangeably. However, there is clear distinction between knowledge and information. According to Nonaka (1994, p. 15), ‘Information is a flow of messages, while knowledge is created and organized by a flow of information, anchored on the commitment and belief of its holder’. Goodson (2005, p. 148) refers to knowledge as an ‘insight, experience, and creativity that exist within people expressed through explicit and tacit communication events’. Davenport and Prusak (1998) have defined knowledge as ‘a fluid mix of framed experience, values, contextual information, and expert insight that provides a framework for evaluating and incorporating new experiences and information’ (Davenport & Prusak 1998, p. 5). Knowledge is difficult to evaluate, and knowledge evaluation has to be done via decision and actions.

Nonaka (1994) mentions that the definition of the word knowledge can be viewed in various ways. The meaning of knowledge can be traced back to the history of philosophy. Nonaka (1994) has defined knowledge in his knowledge creation theory as ‘personal belief and emphasizes the importance of the justification’ (Nonaka 1994, p. 15). In organizational Knowledge Creation Theory, knowledge can be defined in three parts. First, knowledge is ‘justified true belief’ (Nonaka & von Krogh 2009, p. 636). Individuals rationalize what they believe based on how they interact with the world. Second, knowledge is an ‘actuality of skilful action’ as we believe that if someone can execute the specific tasks to solve the problem through their action, this means they have knowledge’ (Nonaka & von Krogh 2009, p. 636). Third, knowledge is ‘explicit and tacit along a continuum’ (Nonaka & von Krogh 2009, p. 636).

Alavi and Leidner (2001, p.6) state ‘Knowledge is the state that information possess in the mind of an individual’. Alavi and Leidner (1999) also defined knowledge as a state where data transforms to information and information transforms to knowledge. Alavi and Leidner (1999) also mention that from a process perspective, knowledge is a process of applying the expertise into the situation.

De Long & Fahey (2000) have defined knowledge as ‘a product of human reflection and experience. It depends on context; knowledge is a resource that is always located in an individual or a collective of data in routine process’ (De Long, D, W. & Fahey, L 2000, p. 114). Knowledge, they argue, results in individual capacity for decision-making and actions to achieve some purpose.

Knowledge is a resource that is important to any organization. This knowledge can promote competitive advantage to the organization. Therefore, like other organizational resources, knowledge needs to be managed efficiently to facilitate business goals (Van den Hooff & Huysman 2009). Hara (2009) argues that knowledge is the process by which individuals or groups acquire a situation to understand a specific social context, e.g. a business context. Once knowledge has been distinguished from data and information, managing that knowledge will become a defined task.

Mountney et al. (2007) have categorised knowledge into three types: structured, semi-structured and unstructured knowledge. Structured knowledge is quantitative, and can be expressed in numerical form such as product parameters and dimensions. Second, semi-structured knowledge can be both qualitative and quantitative and can be used to support the design process. However, this semi-structured knowledge is not integrated within it. The final type is unstructured knowledge, which can occur in social interactions such as discussions or meetings (Mountney, Gao & Wiseall 2007). However, this categorization is contradicted by Davenport and Prusak (1998) who argue that the bottom layer, which is data, has the same characteristics as Mountney's 'structured knowledge'. However, the researcher argues that the numerical context can only be data, not knowledge. This is because numbers are attached to other things and cannot be used out of that context. At the same time, knowledge, in the view of Davenport and Prusak (1998) has more meaning than just numerical data. This separation of meaning leads researchers to differentiate knowledge.

2.3 Types of knowledge

To be able to manage knowledge, knowledge itself has to be clarified. The most common knowledge categorization that many researchers have defined is that there are two types of knowledge. These included tacit and explicit knowledge

(Polanyi 1966). Based on Polanyi (1966) many researchers have proposed further definitions of tacit and explicit knowledge as follows;

- Tacit knowledge
  - Polanyi (1962; 1966) state that tacit knowledge is known by only one person and is highly personal, therefore it is difficult to transfer. The tacit knowledge holder cannot make tacit knowledge available for inspection. The phase often cited in empirical research is 'we can know more than we can tell' (Polanyi 1966, p. 4). However Sun and Chen mention that to enable tacit knowledge sharing in organizations requires other techniques such as social networking (Sun & Chen 2008).
  - Nonaka (1994) states that tacit knowledge evolves from human interaction and experience that requires different levels of skills and practice.
  - Nonaka and Konno (1998) define tacit knowledge, through the Japanese way of thinking, as personal knowledge that is difficult to express and formalise. Tacit knowledge, they argue is embedded deeply in roots of action, commitment, ideals, values and emotions (von Krogh, Ichijo & Nonaka 2000). This then makes tacit knowledge difficult to share with others.
  - Torraco (2000) argues that tacit knowledge is not observable and is difficult to express when knowledge is in use. This is because tacit knowledge resides in its owner at an unconscious level.
  - McInerney (2002) claims that tacit knowledge is an expertise of individual development over the years. However, it has never been recorded or documented.
  - Chilton and Bloodgood (2007) mention that tacit knowledge has specific elements. The first element is lack of conscious awareness. This means users use this knowledge without being consciously aware. Tacit knowledge also accumulates over time and exists in an individual and which is difficult to explain. The other element is tastiness or level of expressiveness. In some cases tacit knowledge

is not expressible. In other words users cannot codify and explain it to other people.

  - Greiner et al. (2007) define tacit knowledge in terms of how well people receive information and use it to turn decisions into actions. (Greiner, Bohmann & Krcmar 2007).
  - Nonaka and von Krogh (2009, p. 635) explain that tacit knowledge is 'unarticulated and tied to the sense, movement skills, physical experience, intuition or implicit rules of thumb'. Tacit knowledge is a crucial element, they argue, in organizational knowledge creation theory. In knowledge creation individuals personalise knowledge to connect to organizational knowledge systems for making tacit knowledge available.
  - Tan et al. (2010) define tacit knowledge as a knowledge per se, which is experience that facilitates new knowledge creation (Tan, HC et al. 2010).

- Explicit knowledge
  - Nonaka & Konno (1998, p. 42) describe explicit knowledge as knowledge that 'can be expressed in words and numbers and shared in form of data scientific formulae, specifications, manuals and the like'. Therefore, it is ready to transmit between individuals.
  - To Torraco (2000, p. 45) explicit knowledge expresses individual expertise through specific tools. Explicit knowledge can be observed and articulated when knowledge is in use.
  - McInerney (2002) states that explicit knowledge is knowledge that has been explained and recorded.
  - Hari et al. (2005) explain that explicit knowledge is objective and rational, formalised and coded in communicable languages therefore, it can be transmitted.
  - Chilton and Bloodgood (2007) mention that explicit knowledge is 'completely transmissible'. As users are aware of the context and the usage and its creation. This leads to one of the disadvantages, in the business context, of explicit knowledge, which is that it can be transferred to competitors.

- Sun and Chen (2008) define explicit knowledge as knowledge that is related or compared to data and information. This means knowledge can make sense out of it through processes or systematised ways (Sun & Chen 2008) such as categorising, calculating and contextualising processes. In this context the clear definition between knowledge, data and information depends on how users interpret it (Sun & Chen 2008).
- To Nonaka & von Krogh (2009, p. 1182) explicit knowledge is different from tacit knowledge as 'uttered, formulated in sentence, captured in drawings and writings'. To be able to make knowledge explicit it requires a knowledge conversion process, which is interacting between tacit and explicit knowledge. Knowledge conversion involves how tacit and explicit knowledge interact within four different types of interactions. These include socialization i.e., that the process of converting individual tacit knowledge to others through interpersonal interaction. Combination is the process of reconceptualising explicit knowledge, the outcome of the process of new explicit knowledge. Externalisation is the process of converting tacit to explicit knowledge and internalisation is the process of converting explicit to tacit knowledge (Nonaka 1994).

Nonaka and Kono (1998) mention that tacit knowledge has two dimensions. First, the technical dimension includes informal skills such as 'internal personal skills' or 'know-how'. 'The second dimension is the cognitive dimension which includes beliefs, ideas, values, schemata and mental models which are deeply ingrained in us and which we often take for granted' and 'this cognitive dimension of tacit knowledge is embedded in our brain and it determines how we perceive the world' (Nonaka & Konno 1998, p. 42).

De Long and Fahey (2000) categorize knowledge from its source into three types. First, human knowledge, which constitutes individual knowhow or knowledge of how to do things. Human knowledge is embedded in skills or expertise usually combining explicit and tacit knowledge. Second, social knowledge is a combination of individuals or groups of experts who work together. Social knowledge is largely explicit knowledge. The collection of social knowledge is often more that a sum of individual knowledge. Third, structured knowledge is embedded in organizational systems, processes or routines. This is often explicit knowledge that resides in organizational resources.

Shadbolt and Milton (1999) have mentioned that the other way of categorising types of knowledge is through application of a knowledge engineering principle, which is 'declarative and procedural'. The first type, 'declarative' knowledge, is 'knowledge about facts'. Declarative knowledge also has been called 'static' knowledge. The second type is 'procedural' knowledge, which is knowledge about how to do things. Procedural knowledge also has been called 'dynamic' knowledge (Shadbolt & Milton 1999, p. 310). Shadbolt and Milton (1999) also mention that in this knowledge engineering principle, there are three important problems related to knowledge management in organizations. First, there are vast amounts of knowledge in organizations and to capture and store all of it is impossible. Second, organizational tacit knowledge is difficult to capture and store. Third, domain knowledge is so complex, it is difficult to communicate it through the ordinary language that we use.

To deal with this problem Nonaka (1994) has proposed a knowledge creation paradigm. The paradigm looks at how organizations deal with information and decisions in uncertain environments by conceptualising the organization as a system. Knowledge creation process involves how individuals (not organizations) in the organization interact with each other and develop new knowledge. Knowledge in an organization can be formed only through an individual and they can recreate new knowledge only from their own perspectives. Organizational knowledge creation requires commitment from an individual. There are three factors that bring about individual commitment: intention, autonomy and fluctuation. Intention is how individuals try to make sense of the world in their environment. This can be called an 'action-oriented concept' (Nonaka 1994, p. 17). Next, autonomy is a freedom of how individuals absorb the knowledge. It increases the possibility that motivates individuals to form new knowledge. Last, fluctuation is the state where an individual's perception of meaning is disconnected. This situation will force an individual to try to make sense from what they have in a different pattern. As a consequence, the knowledge as an outcome will be different too. In organizations new knowledge is constantly generated by reconstructing the existing knowledge (Nonaka 1994) and the drive to find answers to the new problem. Knowledge creation is an ongoing process, which comprises a cycle of five steps:

1. The enlargement of an individual's knowledge: Knowledge in organizations accumulates in individuals through tacit knowledge in the form of experience. The quality of tacit knowledge depends on individual experience and types of work. Routine operations can limit the experience of the individual. This is because operational routines do not require knowledge outside the scope of the tasks (Nonaka 1994). However, a vast amount of experience, which is not related to the job, he argues, challenges quality. So, what is the quality of tacit knowledge or experience and how can the quality be enhanced? The quality of individual experience can be raised by balancing tacit and explicit knowledge and crystallising it into new unique and original forms for the individual to use.
2. Sharing tacit knowledge and conceptualisation: As stated above, work experience is embedded in an individual. To share the experience requires some sort of mechanism to articulate that experience. This mechanism can refer to activities that can facilitate interaction between individuals in organizations. This can also be called socialization, as the organizational interaction can trigger the individual behaviour to use their experience.
3. Crystallization is the process where an individual creates new knowledge from the shared experiences of socialization.
4. The justification and quality of knowledge: In this stage the quality of the knowledge will be evaluated. This includes the application of qualitative and/or quantitative standards. This is to assure the quality of the created knowledge.
5. Networking knowledge is the process of distributing new and existing knowledge to an organizational network for others to use.

Understanding the types of knowledge is only a preliminary stage in the usefulness of knowledge to business. What is essentially more important is that the user understands knowledge management itself.

2.4 The Nature of Knowledge Management

Business today operates in a knowledge-based business framework (Davis & Botkin 1994). Knowledge management research has shown that KM is a useful strategic tool and useful to focus on organizational improvement (Davenport & Prusak 1998). Knowledge management has become an important topic in organizational management. The nature of industrial based business has changed to knowledge based business where knowledge, innovation, information is more important (Drucker 1998). When technology is available for everyone it becomes a significant competitive advantage. Thus, competitive advantage is now derived from knowledge, knowledge creation, innovation and organizational learning (Quintas 2001). Organizations also need to provide the necessary tools to support their knowledge workers. ‘On the one hand, knowledge workers are independent. They, not the Company, own the means of production - their knowledge and they can take it out the door at any time’ (Webber 1993, p. 27). This problem is important and is what was happening at the case study Company in this research. Using technologies and methods to facilitate knowledge management in organizations, not just for day-to-day use, but also strategically using knowledge to improve business, have been studied previously (Davenport & Prusak 1998; Ichijo & Kohlbacher 2008; Nonaka & Takeuchi 1995). Organizations see that knowledge is the key to competitive advantage. Job positions in organizations, such as chief knowledge officer (CKO) and knowledge manager, have appeared (De Long, D, W. & Fahey, L 2000). However, not every organization has succeeded in implementing knowledge management programs. To be able to succeed in knowledge management, organizations need to understand what the nature of knowledge management is and what are techniques and tools available to undertake it. There is also a need to understand what the barriers that contribute to KM failure are.

From a process perspective, knowledge management is ‘a process of applying a systematic approach to capture, structure, manage and disseminate knowledge through out the organization in order to work faster, re-use best practice, and reduce costly rework from project to project’ (Dalkir 2005, p. 3)

From an analytical perspective, knowledge management is a goal-driven and useful activity which aims to improve business processes. Knowledge management includes the formalising and codifying knowledge in its context of organizational structure (Bots & de Bruijn 2002).

From an organizational participant’s perspective, knowledge both implicit and explicit is attached to domain experts. The knowledge will have value only when it is attached to the professional in the domain. Therefore, knowledge management is defined as a process of managing domain experts. Knowledge management is a mixture of ‘goal seeking’ and ‘playful’ activities. This means when experts work together unexpected outcomes, or innovations, can occur through their interaction (Bots & de Bruijn 2002).

Another perception of knowledge management is where organizational practice facilitates organizational knowledge sharing and learning. The purpose is to strengthen knowledge that the organization has and to seek knowledge that they lack in order to develop organizational benefits (Ferguson, Huysman & Soekijad 2010; Hislop 2009).

Knowledge management then is a process of design and implementation processes, tools, structures, systems and culture to facilitate knowledge capture, sharing and re-use to enhance organizational performance (Gottschalk 2005). Knowledge management processes involve people and tools. KM has subsequently become a critical discipline for risk management (Kenyon 2009; Perrott 2007), increasing productivity (Cooper 2003), knowledge retention and innovation management (Kannan, Aulbur & Haas 2005; Rao 2005).

Researchers have also argued that knowledge management is one of the key factors for organizations to derive competitive advantage (Bots & de Bruijn 2002;

Drucker 1998; Smedlund 2008; Wu, J et al. 2010; Wu, Y, Senoo & Magnier-Watanabe 2010; Zack 1999). Wu et al. (2010) mention that the most significant reason for organizational failure is that organizations fail to manage critical organizational knowledge (Wu, Y, Senoo & Magnier-Watanabe 2010). However, it is still difficult to demonstrate that if knowledge management is effective, how well they will gain competitive advantage. Competitive advantage includes an increased rate of innovation, decreased time to competency and increased productivity (Bots & de Bruijn 2002; Falk 2005, p. 81).

Wu et al. (2010) have proposed an organizational knowledge creation diagnosis model can be used to assess competitive advantage from using knowledge management. The model is used to indicate the knowledge creation activities in organizations. Organizational knowledge creation has been a focus because managing, capturing, sharing and distributing existing knowledge is not enough, to gain long term competitive advantage organizations need to create new 'know-how' (Alavi & Leidner 2001; Wu, Y, Senoo & Magnier-Watanabe 2010). Nonaka and von Krogh (2009) argue then that knowledge creation is one of the outcomes from knowledge management as a competitive strategy.

Booth (2010) argues strategically that knowledge management is 'the identification, capture, structuring, and sharing of knowledge and experience in order to provide personnel with access to experience and supporting resources for the purposes of decision support' (Booth 2010, p. 100). Technology is just a tool to facilitate a knowledge management process and is not the solution. Kamara et al. (2002) argue, again strategically, that KM is the way that organizations create value from their intellectual assets via methods, tools and techniques to improve the business. From a strategic engineering perspective, KM is extracting information from an information-overloaded environment and re-using that engineering and manufacturing knowledge to achieve design requirements and better utilise time to reduce overtime delivery of products (Quintas, Lefrere & Jones 1997).

Knowledge in experts is not just stored in their brains, it is also within creating new knowledge based on what they know at the time. For example, when experts encounter a problem and are able to solve it, the next time when they encounter the same problem they will take less time to solve it. This knowledge needs to be shared among employees in the organization. The organization needs not to just create new knowledge, they also have to use what they already know well to be able to compete in the market (Bartholomew 2008). Knowledge creation and re-use then is a strategic tool for organizations.

Other researchers and research collections (Lehaney et al. 2004; Wickramasinghe et al. 2009) have recognised the strategic value in knowledge management. Bartholomew mentions that knowledge management provides a strategic framework, techniques and tools to help experts pass their expertise to new graduates to work faster, better and to generate intellectual capital (Bartholomew 2008, p. 22). This expertise is often embedded in tacit knowledge form, which is difficult to transfer. Knowledge management can facilitate organizations to identify tacit knowledge and its' owners and enable the owner of tacit knowledge to be reachable by other employees (Schwartz 2006, p. 13).

Knowledge management is the management of the knowledge of all type and form to improve working efficiency, effectiveness and competitiveness of the organization (Alavi & Leidner 2001; Hackett 2000). Knowledge management also focuses on using technologies to make knowledge learned from previous projects easy to access and to enable knowledge sharing (Bartholomew 2008).

Verburg & Andriessen (2011) note that knowledge management activities can be used strategically to improve the performance of organizations. The purpose of identifying, acquiring, storing, distributing, sharing and applying knowledge is to utilise that organizational knowledge to achieve organizational goals and stay competitive (Greiner, Bohmann & Krcmar 2007).

At a more micro level, other researchers (Davenport, Jarvenpaa & Beers 1996; Demarest 1997) have identified that the application of knowledge management in organizations impacts strategically on success and failure. Experience, or organizational leaning, requires knowledge management to include knowledge derived from both successes and failures. This is because success-based knowledge can be re-used to prevent re-inventing the wheel and failure-based knowledge can be a lesson to not repeat the same mistakes again. Knowledge management should provide task-related knowledge that workers need to make decisions to perform those tasks (Obeid & Moubaiddin 2010). Understanding success and failure through knowledge enables more efficiency at the worker level.

To improve such issues, the organization has to identify the knowledge and its role in organizations. Employees need to know what knowledge that they need to acquire to be able to get their job done. Building up a knowledge sharing culture in an organization and building a knowledge infrastructure for knowledge sharing to fit the culture of the organization is vital strategically (Davenport & Prusak 1998; Toufic et al. 2005).

In summary, one of the strategic purposes of knowledge management is to promote organizational learning to improve overall performance. Knowledge management is a complex process. It contains a vast amount of tasks. Alavi and Leidner (2001) mention that knowledge management contains four basic processes, which are: creating, storing/retrieving, transferring and applying knowledge at the worker level. Each process contains significant outcomes for organizations (Alavi & Leidner 2001). However, trying to encourage and build up knowledge creation and sharing is a challenge. Knowledge that employees already have, which is not being used to its full potential, offers organizations the opportunity to improve efficiencies and competitiveness (Quintas, Lefrere & Jones 1997). Capturing this knowledge, it is argued, can improve the quality of products and services, reduce costs and improve organizational use of time. However, like all strategies it is important to understand what factors enable success.

There are many factors that contribute to successful knowledge management. These include the effectiveness of knowledge management infrastructure in organizations (Gold, Malhotra & Segars 2001) influenced by technologies, organizational culture and structure (Table 2.1).

Table 2.1 Successful knowledge management factors

Technology in this context includes information technology (IT) that can facilitate organizational knowledge creation, transfer, and retention in organizational knowledge repositories. However, it doesn't mean having IT in place will bring competitive advantage to the firm. Instead IT, together with other organizational resource, can increase organizational performance (Mills & Smith 2011).
Organizational culture in a knowledge management context is complex. This issue relates to behaviour that influences organizational knowledge management (Mills & Smith 2011). For example, in some Japanese firms knowledge management is informally embedded within all of the organizational activities. Therefore, it is sometimes reflected that these Japanese firms are lacking in formal knowledge management. However, this informality of knowledge management embedding in Japanese firms gives them a different perspective on knowledge management. It gives them a way to naturally manage their organizational knowledge (Štrach & Everett 2006). While studying Scandinavian and Singaporean management styles, which affect knowledge management, Cordeiro-Nilsson & Hawamdeh (2010) show that Singaporean firms manage by using vertical hierarchy structures. The decision-making is at the top level and only limited information is disseminated to employees on knowledge management processes. This knowledge management aspect, the authors argue, is discouraging employees to think. In contrast, the Swedish management style uses open consensus and discussion with employees. The discussion encourages knowledge to be shared and generates new knowledge (Cordeiro-Nilsson & Hawamdeh 2010). The Swedish management style can facilitate effective knowledge management, and, while this is not strictly organizational culture, it involves organizational structure as well. The authors argue that knowledge management in Sweden is more successful than in Singapore as a result of this management style. Kannan et al. (2005) have pointed out from their research that effective and successful knowledge management is highly involved with people. Therefore,

during the KM development time, organizations have to consider everyone who is involved, especially users of knowledge who create knowledge sharing activities in organizations, who facilitate cross-department knowledge sharing and who demonstrate that knowledge re-use links to innovative outcomes (Kannan, Aulbur & Haas 2005).
Organizational structure in a knowledge management context includes organizational hierarchy, rules, procedures, and regulations (Mills & Smith 2011). For example, the small organization has a structure that is not too hierarchical, therefore, to get something done is quicker than in large organizations with more complex structures. Researchers (Gold, Malhotra & Segars 2001; Wu, Y, Senoo & Magnier-Watanabe 2010) have mentioned that knowledge sharing cannot be forced. Employees have to be able to share their knowledge freely. However, management's role can facilitate and support and encourage organizational knowledge sharing (Van den Hooff & Huysman 2009) through the adoption of appropriate structures and policies.
Organization learning is also a key factor in knowledge management success (Davies & Brady 2000). Organizations often learn from project activities when they encounter the job for the first time. After certain periods of time, learning activities will become standard practice and employees will start to learn new things. The other technique used in organizations to facilitate success in knowledge management for new comers is on-the-job training (Štrach & Everett 2006).
Leadership has also been shown to be important for successful knowledge management (Jing, Faerman & Cresswell 2006; Parolia et al. 2007). Knowledge management is a complex issue in any organization. The organization needs to have good leaders who can articulate and share a vision looking for better performance. Leaders from progressive organizations are pursuing ways to increase the value of organizational knowledge assets (Wiig 1997). Their clarity of purpose and efforts are significant in the success of knowledge management programs in organizations.

However, like in all business endeavours, there are challenges to success and often these barriers to success need to be addressed with the same attention as those factors that enable success

2.5 Knowledge management barriers

Not every organization is succeeding with their knowledge management implementation. Researchers (De Long, D, W. & Fahey, L 2000; Huang, Chang & Henderson 2008; Lilleoere & Hansen 2011; Lindsey 2006) have studied and listed common barriers that contribute to knowledge management failure.

Long and Fahey (2000) have reviewed the cultural barriers to successful knowledge management. Knowledge management requires an interaction between the employees (Gold, Malhotra & Segars 2001). They have found four ways in which culture influences knowledge creation, sharing and use in organizations and also common practices that often create barriers to successful knowledge management (De Long, D, W. & Fahey, L 2000, pp. 116-23).

- Organizational culture shapes assumptions about what knowledge is important. This happens when there are sub divisions in organizations. For example, the R&D department might perceive that a product's feature is important while the finance department is more concerned about the cost of the products. This different view (knowledge perception) often leads to miscommunication and conflict between the subcultures.
- Organizational culture mediates the relationship between levels of knowledge. Culture is embedded in how knowledge is being distributed in organizations. Culture norms and practices determine who is supposed to control what knowledge and who must share their knowledge.
- Organizational culture creates a context for social interaction. Social interaction can be assessed in three dimensions. These included vertical, horizontal and special behaviour in social interactions. For example in some vertical interactions, formality is a normal practice in an organization (as in the Singapore example above) and sharing their ideas with the executive level seems out of reach to employees. Cross-functional areas might be exclusive and separate, discouraging horizontal sharing of knowledge. Some functional areas in organizations hold specific domain knowledge that can be unintelligible to others in a company and is therefore not shared.

- Organizational culture shapes creation and adoption of new knowledge. Adopting a strategy of accessing and using external new knowledge is important to organizations. Good examples of organizations where success has emerged from adopting external knowledge include Wal-Mart (Malhotra 2005), Motorola (Bhatt 2001) and General Electric (Meso 2000). Where there is a barrier to this external knowledge, new ideas and innovation derived from new knowledge creation can be stifled.

Research has shown that for organizations to be successful in implementing knowledge management, they need to investigate their organizational culture. Dow and Pallaschke (2010) have highlighted the cultural barrier to knowledge sharing in a study at the European Space Operations Centre. Firstly, they showed that lack of time, as in space industry time, is a key pressure. Day to day tasks of employees already occupies all their time. This leads to a lack of time to reflect and share their knowledge. Second, working in an organization with a very high performance environment, staff who make mistakes tend not to share their them. Third, knowledge is power and employees don't generally share their knowledge since they fear losing power and consequently status in the organization. Fourth, a hidden profile phenomenon occurred in this organization; this occurs when some of the staff process specific knowledge, which remains hidden to other colleagues. Lastly, the organizational structure such as its hierarchy structure limits organizational communication (Dow & Pallaschke 2010).

In other research, Huang et al (2008) have studied how knowledge transfer barriers can be reduced during new product development process between departments in organizations. They found that communication is an important factor contributing to reduction of the knowledge transfer barrier. Employees between departments, such as R&D and marketing, often found people from other departments thought differently and were difficult to understand when they tried to explain. This decreased the effectiveness of the communication. The effect was to reduce the effectiveness of the knowledge transfer process (Huang, Chang & Henderson 2008). Accepting these factors that both promote success and act as barriers to it, it is important to understand the knowledge management process itself. This is important because many of the barriers to success arise because of a lack of appreciation of the cyclic, dynamic nature of the knowledge management process itself.

2.6 Knowledge management process

The knowledge management process is cyclic and continual (Booth 2010). Davenport and Prusak (1998) explain that the knowledge management process has three steps: knowledge generation or acquisition, knowledge codification and knowledge transfer (Davenport & Prusak 1998). To Booth, it is an ongoing process which contains four steps: identification, capture, sharing and maintenance (Booth 2010). While Dow and Pallaschke (2010) propose a similar process, they also propose a final step, which is importance awareness creation. Dalkir (2005) has proposed an integrated knowledge management cycle based on literature in three steps: knowledge capture or creation; knowledge sharing or dissemination; and knowledge acquisition and application (Dalkir 2005).

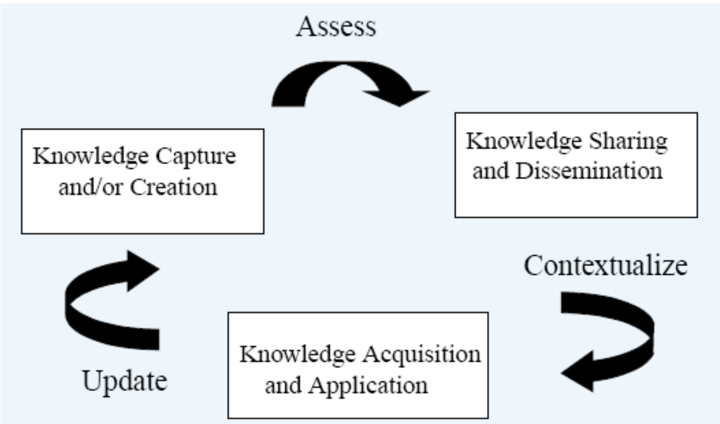


Figure 2.1 An integrated Knowledge Management cycle
Source: (Dalkir 2005, p. 43)

Fig 2.1 shows the knowledge management process, which begins with knowledge capture and includes tasks such as knowledge identification, capture and codification of the existing knowledge. Knowledge creation refers to knowledge that does not currently exist in the organization, therefore, the new knowledge has to be developed to suit the organization needs. Then the identified knowledge is codified and stored in the system for dissemination. After the captured knowledge has been used and reviewed then the contextualisation is carried out.

Contextualisation refers to the sense people in the company make of knowledge relevant to their work tasks, products, or processes. This is done to ensure that the knowledge is embedded in the business process. The next step in the cycle is in the process to update the contents that are dated, or found in need of replacement with better knowledge. Knowledge management then is an iterative process (Dalkir 2005) and to be effective it needs systems in place to promote effectiveness in use, facilitate success and address known barriers.

2.7 Knowledge Management Systems

A knowledge management system is a computer system that has been applied to manage organizational knowledge (Alavi & Leidner 2001; Davenport & Prusak 1998). The system is/has been built to facilitate the knowledge management process and include knowledge capture, storage and sharing. A knowledge management system offers organizational knowledge maps that facilitate cross-functional learning (Lavoué 2011; Torraco 2000, p. 58) to achieve organizational goals. Alavi et al. define a knowledge management system as 'a class of information system applied to manage organizational knowledge' (Alavi & Leidner 2001, p. 114). It refers to an IT based system built to facilitate, utilise and enhance organizational knowledge creation, storage, retrieval and transfer. Wu, J et al. (2010) argue that a knowledge management system is the application of computer-based technologies used in a company to organize their knowledge resources. It involves processing of knowledge codification and repositories into the knowledge-based system. Alavi and Leidner (2001) argue from a review of research that IT plays an important role in organizational knowledge management initiatives. From this research, they argue there are three major KM applications: First, they state, IT is used for coding and sharing best practice. The purpose is to transfer internal knowledge within the organization. The second application is the creation of corporate knowledge directories. In organizations there are vast amounts of knowledge and its holders. Directories offer pathways into these. The third application is the creation of knowledge networks. The networks mentioned can help the organization bring experts together virtually (Alavi & Leidner 2001, p. 114).

People hold some knowledge elements as tacit knowledge. In engineering this can be professional knowledge and experience that relates to specific design processes and can be built up over long periods of design and manufacture. This accumulative design knowledge is an organizational asset. While IT systems can certainly store explicit knowledge (as artefacts and documents) there are problems with knowledge capture. Rather than working properly to store captured knowledge, often attempts at the use of KM for strategic purposes fail because there are no systems in place to deal with the issue of hoarding accumulated tacit knowledge (Kanjanabootra, Corbitt & Nicholls 2010).

Since the 1980's many businesses have shifted from being information-based to knowledge-based. Technologies have been developed so that everyone can gain access to information. An organization requires knowledge that their competitors don't have in order to be able to survive in the market and gain a competitive advantage. Information technology-based knowledge management systems are not new. They have been used since the early eighties (Kamara, Anumba & Carrillo 2002). Their initial intent was to gain competitive advantage. Implementing knowledge management systems alone, though, is not the key to success. Organizations can implement a knowledge-based system and still struggle to achieve business improvement because there are other problems, related to people and organizations, that need to be addressed.

There is no clear literature that discusses how many types of knowledge management systems exist. So far the term KMS still refers to the definition of Alavi and Leidner (2001) which is the computer-based knowledge management system (Alavi & Leidner 2001). Because it is a broad term, it means anything that is computer-based and has a purpose in facilitating knowledge management processes, which include capturing, classifying, storing and reusing. It is all referred to as a KMS, even if it applies to only one process, or one attribute of knowledge management. The following discussion refers to various knowledge-based system applications used by organizations.

- **Discussion forum system**

  A discussion forum system is a simple, single purpose IT-based system where questions or situations are posted then, other users who can suggest solutions will post their answers afterwards. The goal of the discussion forum is to promote a 'who knows what' environment in the organization (Alavi & Leidner 2001; Preece et al. 2001). Escalfoni et al. (2011) have described another similar system which captures innovation knowledge through a story-telling method. The story is then stored in the organization online forum for others to use. The stories have been categorised into identified events together with the discussions related to that particular story (Escalfoni, Braganholo & Borges 2011). In a similar way Japanese organizations emphasize the important of knowledge sharing by using company histories and legendary heroes or organization founders to admire new staff through the whole organization (Štrach & Everett 2006).

- **Online knowledge community**

  An online knowledge community is an Internet-based system that invites peers to share their experience among others in a similar area. Both tacit and explicit knowledge can be shared through the system. For example, an oil company (Kukreja & David 2006) has set up an online community and allows users to ask question regarding the petroleum industry from the community's database. If the questions have not been asked before, the system then will escalate the questions for human experts to answer and store the answers in the database for re-use next time. The system has been used among the 650 employees in the company in different location such as France, USA, Belgium (Kukreja & David 2006). Hosono (2006) has explained that *Fujitsu* implemented the *ProjectWEB* system to facilitate knowledge management concepts in their organization. The system has features such as a bulletin board system, a schedule, a *To Do List Web* mail system and a Library. The system aims to help the members of *Fujitsu* share day to day project tasks, and this includes problems that individuals have encountered during the operations/manufacturing/servicing processes (Hosono 2006). These communities are fundamentally interactive systems designed to enable sharing or knowledge and problem solving. Their focus is essentially on day-to-day activities and their strategic role is to ensure people know ‘what is going on’, rather than improving product design, or decreasing costs per se, even thought there is some evidence these outcomes have emerged.

- **Expert systems and Artificial Intelligence**

  An expert system is a computer system that tries to manipulate specific domain knowledge of experts by organising this knowledge into knowledge-based systems (Nakai & Kanehisa 1991). Expert systems are complex and often involve vast amounts of rules. These characteristics can facilitate a complex conceptualisation of knowledge representation. Expert systems are really rule-driven, IT-based systems designed to offer solutions to problems. They are often specific to a domain and most often offer a solution based on existing knowledge. These systems don’t easily adapt to the inclusion of new knowledge on a continuous basis and are thus often static instruments. Expert systems have been shown capable of solving medical complex problems (Clancey 1983) and business problems (Coakes, Merchant & Lehaney 1997). Artificial Intelligence, in a more expanded form, involves the use of robotic systems to undertake work processes. They rarely generate new knowledge but in some circumstances can be self-learning. However their task is often to replace human systems. Most knowledge management encompasses the generation of knowledge continuously and appropriate systems to manage this often them selves need to be able to capture, store and codify knowledge continuously. These expert systems evolved into knowledge-based systems.

- **Knowledge-based systems**

  A knowledge-based system is a computer system that contains knowledge used by experts in the domain of interest. Knowledge that the experts have used to solve a specific problem and the knowledge stored in the system should be the same knowledge. A knowledge-based system is designed to capture knowledge to help the users solve a problem (Ammar-Khodja, Perry & Bernard 2008). The knowledge-based system is designed to store knowledge. The difficulties are not using the system instead it requires knowledge engineers to structure the system so that it can be used and updated. Tan et al. (2010, p. 3) argue that knowledge-based systems should have the following features:

  1. Make sharing important knowledge easy and persuade the team members to share knowledge.
  2. Enable knowledge stored in a format that is easy to share.
  3. Facilitate "live" knowledge capture. This means the system should enable users to record new knowledge found during the production/design process and then make it available to re-use in later stages in that process.

  These type of systems form the focus of the first part of this study because the problem revolved around experts and their knowledge and their need to capture that knowledge and set it up for re-use.

- **Ontology**

  Grubber (1995) has mentioned that in the early stages, knowledge-based systems were developed using specific computer programming languages which were based on the existing hardware due to the technology constraints at the time. There have been various computer languages used in development of knowledge-based systems. However, to be able to design a knowledge-based system at the knowledge level, requires a standard language which has three conventions (Gruber 1995, p. 908). These include, a representation language format, agent communication protocol and specifically the content of shared knowledge (Gruber 1995, p.

907). Ontology is a form of representation. Ontology is ‘an explicit specification of a conceptualisation’ (Gruber 1995, p. 908). In artificial intelligence anything that exists can be represented. This concept goes back to Aristotle’s idea where he was trying to classify everything in the world (Studer, Benjamins & Fensel 1998). Therefore to represent knowledge in a specific domain to a set of objects and their relationships that are represented is called the universal discourse.

Hiekata et al. (2010) have mentioned that ontology is a consistent and useful and commonly used modelling method. Heikata et al (2010) have used ontology to build a hierarchical structure of the components of knowledge used in the shipyard industry as part of a knowledge-based system. Their system included ontological terminology, which related to shipbuilding and problems arising in the ship building processes. More recently research by Kim, H et al (2007) and Milton, S et al (2010) have both argued for and demonstrated the value of ontology in applications to resolve business problems.

Researchers (Alavi & Leidner 2001; Gunendran & Young 2009; Pan & Rao 2009) have found that, typically, organizations utilize the form of knowledge-based system that best suits their purpose. In car manufacturing the key system chosen has been robots to improve quality and reduce costs (Lilleoere & Hansen 2011); in medicine it is often expert systems that have been used to solve problems, which are multidimensional (Prasnikar & Skerlj 2006). In both cases the knowledge-based system is part of business strategy. There is often a clear business reason for their development and adoption.

The effectiveness of a knowledge management system is strategically significant in term of capturing, storing and reusing organizational knowledge. However, the lesson learnt by many organizations is that a knowledge management system is not everything, otherwise it will replace all of the employees in the organization. One of the effective ways to implement a knowledge-based system and utilise it is not to try to combine everything into the system. The knowledge-based system does not need to answer answers for everyone in the organization. Different parts of the organization require different knowledge. Therefore, developing a knowledge-based system to serve only specific purposes from a particular department (McLaughlin & Paton 2008) is often the most effective.

Building a knowledge-based system, however, is not just reliant on the adoption of technologies and computer languages and representational formats. The quality of any knowledge-based system relies on the quality of the content and then the quality of its use (Girardi & Leite 2008; Howlett & Lee 2010; Sapuan 2001). It is therefore important to understand that the best strategic value of knowledge management can only come from the effectiveness of the content and the effectiveness of the sharing of the knowledge that exists and is captured.

2.8 Knowledge capture

2.8.1 The nature of knowledge capture

Most of the manufacturing companies re-use their design knowledge one way or the other. This includes taking feedback from customers and modifying their existing models to suit new requirements (Bailey et al. 2000) or solve problems from previous products. This mean the existing design knowledge needs to be captured and stored in a system for re-use. This is especially the case for tacit knowledge where the decision-making process from previous product development had not been recorded. Most of the time the information or knowledge that was recorded is the final outcome from those decisions. The key tacit knowledge involved and not captured is most often missing and this 'hole' in the knowledge acts as a barrier to process improvement (Dulaimi 2007; Kivrak et al. 2008; Zielinski et al. 2006).

Knowledge capture is debated to be the most important process in knowledge management practice (Booth 2010). Tacit knowledge capture is the process of 'capturing the experience and expertise of the individual in an organization and making it available to anyone who needs it' (Dalkir 2005, p. 80). The emphasis is for an individual to gather the captured information and create new knowledge. While explicit knowledge capture refers to the systematic method to capture, organize and refine information and make it easy to find exiting forms of knowledge (reports, documents, plans etc) to facilitate specific organizational problem solving and learning (Dalkir 2005). The explicit knowledge can also include facts, procedures, operational manuals, brochures, video, reports and heuristic ways to solve specific problems (Herndon et al. 1991). However, new knowledge creation and capture or existing tacit knowledge capture cannot be done without an organization. This is because the individuals themselves rarely create their own knowledge. They most often create their knowledge through some form of interaction. Taylor & Boraie (2004, p. 23) have identified four dimensions that are important to knowledge capture. These include appreciating of local knowledge, building relationship with freelance consultants, sensitivity of national culture differences and the knowledge capture process itself. Due to the complex nature of knowledge itself, and of the people involved, it requires various different techniques to be used to capture different kinds of knowledge.

2.8.2 Knowledge capture process and methods

Various techniques have been used to capture knowledge in organizations. The different nature of knowledge requires different techniques. Dalkir (2005) has mentioned that the techniques used in tacit knowledge capture process are derived from expert systems design. The purpose is to capture the knowledge that experts use to solve specific problems and make tacit knowledge explicit. The techniques mentioned include talk analysis, observation, questionnaires, surveys and simulation (Dalkir 2005; Matsumoto et al. 2005). Matsumoto et al. have used another technique included in the knowledge capture process which is 'analysis of the public domain knowledge' (Matsumoto et al. 2005, p. 85). Analysis of domain knowledge is the process in which knowledge engineers, as an example of a domain expert, go into an organization in which knowledge needs to be captured to familiarize themselves with the existing experts. This will help the knowledge engineers to better understand domain knowledge.

Dow and Pallaschke (2010) in their research of managing knowledge at European Space Operations Centre, used various knowledge capture techniques which included structured interviews and tasks such as coverage analysis to find the unique knowledge. Mulder and Whiteley (2007) studied capturing tacit knowledge in a single case of a multi-site organization. They found that there are four conditions necessary for successful tacit knowledge capture. These included teleological motive and purpose, a bounded environment, a defined product control vocabulary, and the use of interactive and iterative processes. Under these four conditions, they argue, tacit knowledge can be captured effectively (Mulder & Whiteley 2007). The various techniques used are now discussed in Table 2.2 below.

Table 2.2 Knowledge capture techniques

Interviews Interviews are the most often used technique to capture tacit knowledge and transform it into an explicit form (Dalkir 2005). Interviews can be categorised as either structured or unstructured interviews (Denzin & Lincoln 1994; Lloyd 2011). These two types of interview are used differently in the knowledge capture process. For example, unstructured interviews are used to ask open questions to experts to gain a broader view of the knowledge that needs to be captured, while structured interviews are used to confirm the knowledge that has been captured from the unstructured interviews (Matsumoto et al. 2005). Interview techniques can help the researcher introduce key terminology in the domain knowledge. In reality it is impossible that all knowledge can be captured within one interview. Most researchers have used interview techniques together with other techniques or methods or they conduct interviews multiple times (Shadbolt & Milton 1999).
Observation The technique of observation has been used to capture knowledge related to specific tasks such as machine operating. The observation involves experts doing their tasks whether it is their real life job, or simulation or problem scenarios. The purpose is to gain an understanding of how these experts perform their tasks (Dalkir 2005; Luthans, Rosenkrantz & Hennessey 1985). Researchers (Basil 2011; Matsumoto et al. 2005) have used video recordings of the expert's actions during their operation with the device. However, the limitations of these techniques are that it cannot help the researcher answer the 'why' question and in some case it can make the experts, who have been observed, feel uncomfortable. To solve the second limitation, consent from the

experts is needed (Matsumoto et al. 2005).
Surveys or Questionnaires Surveys or questionnaires have often been used to collect general ideas and specifically to capture tacit knowledge. Luthans et al. (1985) have used questionnaires to ask subjects to categorize the organization's activities and behaviours to capture managerial knowledge. The outcome is to gain an idea of what sorts of skills are require to become managers (Luthans, Rosenkrantz & Hennessey 1985). Questionnaires have also been used to check knowledge management system's requirements (Staab et al. 2001).
Simulation Simulation as a knowledge capture technique is a combination of tools designed to capture explicit and tacit domain knowledge by using real or setup situations. The purpose is to allow phenomena to happen the way it is supposed to without, or with little, external impact. Then, the researchers capture what is happening and then analyse and codify the knowledge captured. For example, Ju et al (2004) have used cameras to capture images via motion detection, computer usage and white boards to capture specific work phenomena. As a result they claim that this tacit knowledge can be used by workspace designers to gain a good understanding of how employees use their workspace (Ju et al. 2004).
Artefacts study This technique has been used primarily with other techniques such as interviews or observation (Fergus et al. 2003; Stake 1995). Artefacts study helps knowledge engineers grasp some idea of the existing domain knowledge that underpins the tacit knowledge to be captured. There are vast amount of artefacts that reside in any organization. These include manuals, reports, procedures, business plans or any generic text-based or image-based artefacts. For example, Kanjanabootra et al. (2010) and Fergus et al. (2003) have studied the artefacts in companies and the key elements involved in the capture process of explicit knowledge have been identified. These include talking with knowledge holders and managers, understanding the types and

forms of explicit knowledge and its locations, and what the structure of the existing systems is which support knowledge retrieval in those companies.

Shadowing

Shadowing is the process where the researcher closely follows persons in their workplace (Bessot et al. 2002). The location is not limited to the internal organization but also can include external locations. During shadowing the researcher uses observation but also asks questions at any time during the shadowing process (McDonald 2005; Quinlan, E 2008). The expectation with this method is that the person who is being shadowed will answer and comment on the activities that they perform. The purpose is to reveal particular contexts behind the operational tasks. During the shadowing process the researcher will record what they observe in detail. The means of recording can vary from normal notes, voice recordings or video recordings.

The advantages of shadowing techniques compared to other methods such as interviews or observations alone are that shadowing can gain more in depth detail and can get to operational details through understanding trivial processes (McDonald 2005), which are part of the tacit knowledge domain and which are rarely disclosed in interviews or surveys. This technique can help researchers answer ‘why’ questions better than other approaches. The shadowing technique is subject-sensitive (Beech & McKeating 1980). Consent from experts who are going to be shadowed is required prior to the shadowing process. This is because this technique is intrusive (Meunier & Vasquez 2008) for the individual being shadowed and in some organizations will expose business confidentiality and elements of knowledge which underpin competitive advantage for the Company. Another constraint of using the shadowing technique to extract tacit knowledge is that the technique can interrupt the normal working process. Persons who are being shadowed have to answer the researcher’s questions or engage in dialogue about what they are doing (McDonald 2005).

Each technique used to capture knowledge has advantages and disadvantages. Researchers have to select the techniques to suit the nature of knowledge and the type of organization. There are researchers who have applied multiple techniques to capture knowledge both tacit and explicit in the one organization. (Kukreja and David (2006) show how the Schlumberger companies in the oil and petroleum industry have created their knowledge hub by using multiple techniques to strategically manage their knowledge. These include implementing an online community to enable their employees from different locations to ask problem-based questions through the system, which contains a database of answers from other employees.

The Schlumberger company also used data mining to find solutions. The company gathers information, procurement data, and operational data and build that into a repository and combines it for further analysis. Through this knowledge the company can gather information, classify and store it for re-use and this can help geo-scientists make decisions faster which can significantly save the company costs. In another study of Capital Motor Inc, a Mercedes Benz distributor in Taiwan, Liew (2008) has described how the Company uses an enterprise information portal to capture and store knowledge about customer relationships. The system was created and is run by using a virtual community of practice through the Internet. The system has features, which can capture and store case-based problems related to customer relationships and how to solve and share this knowledge across Taiwan Island. The company is using a knowledge management strategy to manage what they can do, which is to service their customers and acquire relevant knowledge regarding customer relationships.

Examples of knowledge capture application from empirical research highlight the difficulties that exist in knowledge capture. IBM used a story telling technique to discover and then share knowledge especially tacit knowledge, as ‘tacit knowledge is the most means of sharing knowledge’ (Dalkir 2005, p. 88). Leake and Wilson (2001) have captured knowledge from the aerospace design domain and stored that knowledge in a system for the company experts to re-use. The system developed used concept mapping to capture aerospace design knowledge, which is also complex. The system brings out the previous design knowledge for users to consider together with the new requirements to develop new aero plans (Leake & Wilson 2001). Matsumoto et al. (2005) have used knowledge capture reports (KCR) to capture design knowledge from various disciplines in a series of projects. The KCR's structure has eight sections based on the different categories of the projects. The knowledge captured by the KCR highlight the strength and weaknesses of each project for future use (Matsumoto et al. 2005). One weakness is incompleteness but on the other hand substantive knowledge is also captured by KCR. The other weakness highlighted in the research relates to a lack of uniformity in use of the captured knowledge. Perry et al. (2007) have applied a differentiable knowledge capture and transfer process to capture and share organizational knowledge across a number of divisions in an organization. The purpose of this work was not just to capture and enable sharing of knowledge among current employees but to also include the next generation of the employees (Perry et al. 2007).

Ju et al. (2004) have used IT-based tools to capture workspace design knowledge from designers. The tools for capture included motion detector controlling video cameras. They have captured design knowledge from various knowledge sources. These included the user's motion in workspace, white board usage and computer usage. The workspace design purpose is to design the space that users can use functionally and comfortably (Ju et al. 2004). The process was successful to some degree but didn't deal with reasons for various observed behaviours.

Once captured, tacit knowledge needs to be analysed and codified to some format so that knowledge can be re-used (Boh 2007; Storey & Kahn 2010). This is especially important in strategic situations where re-use forms the basis of competitive advantage through innovation. Tacit knowledge requires specific methods in order to be analysed and codified (Boh 2007; Milton, N et al. 1999). In some cases knowledge engineers might have to analyse the captured knowledge before they codify it. Knowledge codification techniques include cognitive mapping (Zielinski et al. 2006). This is a powerful technique as it can capture both complex concepts of the knowledge and the relationship between concepts. Cognitive mapping can capture both tacit and explicit knowledge and show the interrelationships between them and thus is especially useful. Decision trees are the most used technique to capture explicit knowledge (de Ville 1990; Quinlan, JR 1986). The knowledge is then codified in a form of flowchart or decision path, which suits process knowledge. A technique of knowledge taxonomies (Borst 1997; Ein-Dor 2006; Rubin, Noy & Musen 2007) is also used as a knowledge representation technique where concepts are represented in a block. Each concept block has its own definition and can be linked to other concepts by relationships (Quinlan, JR 1986). Each technique can be used depending on the nature of the knowledge being addressed. However, whilst there are methods for capturing both tacit and explicit knowledge as part of knowledge management in organizations, there is a need for the knowledge captured and codified to actually be used, fundamentally via sharing. Without use and sharing there is no real purpose for the time and cost involved in knowledge capture.

2.9 Knowledge sharing

Knowledge sharing is the process of exchanging knowledge between two or more people (Ford & Staples 2010; Ling, Sandhu & Jain 2008). Knowledge sharing is a process, in which an individual passes on their knowledge. These include both tacit and explicit knowledge (Ford & Staples 2010). This knowledge includes existing knowledge and new knowledge generated between knowledge sharing processes. Most of the time this happens while employees or experts with domain knowledge in organizations are doing something together (Lilleoere & Hansen 2011; Lindsey 2006). Knowledge sharing is important as research has shown that it can be used to create competitive advantage for the organization (Bryant 2005; Grant 1996; Porter 1993).

However, there are factors that impact the efficiency of knowledge sharing. There include an individual's absorptive capacity (Reilly & Sharkey 2010) for knowledge. Individual absorptive capacity is an ability of an individual to interpret received knowledge and utilise it and turn in to action (Lilleoere & Hansen 2011). Nonaka (1994) mentions that to share tacit knowledge in the organization requires social interaction between an individual through human activity. Individuals in the group or in a "self-organizing team" perform this activity. The purpose of these activities is to pursue new problems and solutions. This interaction group can be within the organization or among individual formed inside and outside the organization (Nonaka 1994). Nonaka has listed factors that contribute to the success of knowledge sharing. These are trust among individuals in the group, and the existence of a common perspective that each individual has towards the group and towards dialog or individual communications. Holste and Fields (2010) have studied trust in knowledge sharing in an international organization. The research found that warm relationships and respect are most likely to develop through face-to-face interaction among workers. This relationship among workers or trust has affected willingness to share tacit knowledge. Van den Hooff and Huysman (2009) have found that organizational culture has an effect in organizational knowledge sharing, the more interaction of employees in an organization, the higher the trust (Van den Hooff & Huysman 2009).

Barson et al. (2000) identify the people barrier to effective knowledge sharing. They have studied how knowledge management is used in a new product introduction process from concept to manufacturing. They have found that the people barrier is affected by international differences amongst people, organizational differences, departmental differences, scepticism towards technology, the need for rewards, the accuracy of knowledge, fear of penalty in failure, fear of becoming redundant, fear of losing resources, fear of losing company stability/market position and protection of proprietary knowledge (Barson et al. 2000).

McLaughlin and Paton (2008) have studied how IBM’s integrated supply chain impacts on end-to-end performance. McLaughlin and Paton have found that knowledge is not considered at an organization-wide level. However, knowledge is more used in process at the work group level. Therefore, to be able to share this knowledge the organization has to select the appropriate approach (McLaughlin & Paton 2008). Barriers exist and can be resolved by adopting this approach.

Van den Hooff and Huysman (2009) and Verburg and Andriessen (2011) discuss two approaches used in effectively managing knowledge sharing. First, there is an emergent approach, which focuses on practices, on the social nature of the members in the organization and on the types of knowledge. Knowledge sharing embedding, they argue, is a social issue. Knowledge sharing is not a process of sharing an object between donors and receivers. However, it is the process of generating knowledge by receivers. Knowledge sharing can be considered a success when the receivers understand or make sense out of the context. Knowledge sharing involves a number of factors within that social context. These include the social dynamic of the group or the relationship of the member of the group. These interpersonal relationships of the members determine how well they connect to each other and contribute their knowledge The second approach is an engineering approach which focuses on how management influences knowledge sharing or social capital. Knowledge sharing requires a management of infrastructures, technical aspects and culture to facilitate knowledge sharing and organizational support (Kannan, Aulbur & Haas 2005; Van den Hooff & Huysman 2009).

Van den Hooff and Huysman (2009) used online surveys in six different organizations as a data source. The business included 'a cable provider, a mail service provider, an insurance company, a consultancy and both the Dutch national and the international branches of a heavy lifting and transport company' (Van den Hooff & Huysman 2009, p. 3). They found that social dynamics has as a significant influence on knowledge sharing. They also found that adoption of the engineering approach, 'which influences the creation of conditions by providing infrastructure, technical and management to stimulate knowledge sharing is also significant across all of the example companies (Van den Hooff & Huysman 2009).

Lilleoere and Hansen (2011) have studied knowledge sharing in a research and development team in a pharmaceutical company. The research has shown that knowledge sharing is a source of innovative thinking and knowledge creation in that R&D team. In the pharmaceutical industry time to market of some drugs is long. The average time to market of the new products is 59.2 months (Prasnikar & Skerlj 2006). The consequence of long time-to-market is high risk and cost. Lilleoere and Hansen (2011) found that knowledge enablers have impacts on pharmaceutical time-to-market. These enablers include knowledge sharing that happens when individuals socialize between each other. This, they argue, can potentially reduce product time-to-market. Physical proximity between colleagues is also a knowledge sharing enabler (Lilleoere & Hansen 2011).

Verburg and Andriessen (2011) have studied knowledge sharing in a knowledge network. Knowledge, they showed, can be shared through a variety of networks. These include networks both internal and external to the organization. Verburg and Andriessen's knowledge sharing network concept, in the researcher's view, is quite similar to Nonaka's self-organizing team (Nonaka 1994; Verburg & Andriessen 2011). Verburg and Andriessen has categorised types of knowledge networks into four types. These include:

1. The informal network which is the network in which the members of this network are related to practice such as in the same organization. In this type of network there are substantial commitments between members;
2. The question and answer (Q&A) network has a lower level of commitment. The purpose of the network is to solve specific problems;
3. Strategic networks are comprised of experts from different places and often have limited numbers of member. This type of network is highly interactive; and
4. An online strategic network has similar characteristics to the strategic network. However, their means of communication is in electronic format.

The purpose of the knowledge sharing network is to exchange information and experiences that the members of the network have (Borst 1997; Ling, Sandhu & Jain 2008). Knowledge sharing within the network happens through the interaction between members in the meeting. In a project-based type of group knowledge sharing is an ongoing process from project start until the project is finished. Knowledge sharing also can be considered as a problem solving process (Karlsen, Hagman & Pedersen 2011). In some organizations staff did not successfully adopt knowledge sharing. It often fails because the organizational member intentionally withholds their knowledge. Webster et al. (2008) have reported a number of reasons knowledge workers will not share their knowledge in organizations. The factors are associated with knowledge values including power and politics in organizations, psychological ownership of expertise and territorial behaviours. The factors associated with the nature of social exchange also include interpersonal dynamics, organization culture and norms and individual characteristics (Webster et al. 2008).

Knowledge sharing is a vital activity for successful knowledge management. The process of knowledge management should not be seen as an object transferring between people. It should be seen as a social dynamic between group's members to share the process of knowledge creation and construct meaning out of it (Van den Hooff & Huysman 2009). Managers often find their information and knowledge is derived two-thirds from social interaction, either in meetings or in conversations, while only one-third comes from documents (Davenport & Prusak 1998). This shows that knowledge sharing among people is important strategically for organization growth, for innovation and to maintain or even gain competitive advantage. Knowledge sharing requires interactions between sharers. These included formal activities such as face to face, training and conference or informal activities such as employee's social network (Holste & Fields 2010). Knowledge sharing involves factors such as trust (Štrach & Everett 2006), culture, and receivers absorption capacity. Importantly knowledge sharing is important strategically.

Product development is one of the means of competitive advantage (Ponn, Deubzer & Lindemann 2006; Studer, Benjamins & Fensel 1998). The product development process requires innovative knowledge creation based on existing tacit and explicit knowledge. Knowledge sharing pays an important role in the knowledge creation process (Lilleoere & Hansen 2011). Lilleoere & Hansen (2010) have studied knowledge sharing enabler and barrier factors in a pharmaceutical organization where their current time-to-market is long. Innovative knowledge creation is an important factor to reduce products' time-to-market and is thus strategically important to this company. They have found that one of the enablers in pharmaceutical research and development - professional knowledge sharing or knowledge creation - occurred during individual interaction. As a consequence it has potential to reduce time to market. Another enabler found in Lilleoere & Hansen's research (2011) occurs in the synergic influences such as where open space office facilitated informal meetings both between the members, work involvement and job interest. The barriers to effective knowledge sharing found in Lilleoere & Hansen (2011) are physical distance between members and a lack of available knowledge. Strategically though, the effect of knowledge sharing is important.

Knowledge as an organizational resource is somewhat secure during economic down turns (Hari, Egbu & Kumar 2005). Unlike other physical resources, knowledge is not depleted when used. Instead, it expands, is refined and grows (Stewart 1994). It has a strategic economic value. Therefore, sharing and re-use of organizational knowledge facilitates organizational knowledge strengthening.

Throughout this section on knowledge sharing and the previous discussion on knowledge capture, there has been frequent reference in the research to the role of knowledge management in the strategic direction of organizations.

2.10 Knowledge Management and Strategy

There are various forms of strategy that can be applied to gain business advantage. These include operational strategy, technology strategy, and management strategy. However, knowledge management strategy is also one of these strategies (Grant 1996; Grant & Baden-Fuller 2004; Massingham 2004; Nickerson, Jack A. & Silverman 1997; Wiig 1997; Zack 1999). Knowledge is a crucial organizational asset which is a source of competitive advantage (Alavi & Leidner 2001; Davenport & Prusak 1998; Quintas, Lefrere & Jones 1997; Sun & Chen 2008; Van den Hooff & Huysman 2009). This is especially true in manufacturing businesses (Appleyard 1996; Catalano et al. 2008; Cross & Sivaloganathan 2007; Gunendran & Young 2009; Madhavan & Grover 1998). This is because re-using design knowledge is the most effective way to produce products with required specifications and is cost effective (Cross & Sivaloganathan 2007) as well as not repeating the same mistakes made in the previous product processes. The nature of competitive advantage has shifted from a products-based perspective to be an organizational resource-base which is people (Martin 2008). In the past, businesses often gained business advantage through the manufacturing of the products that competitors did not have. Today in business, when the business releases newly developed products to the market, within just a short time their competitors will be able to come up with the same product that is as good as that released product and can be cheaper or possibly even better products. To be able to survive in this market, the Company in this research needed to be aware of external impacts such as those identified by Porter (1979, 1985, 1987, 1991) that will impact their business strategy in their particular industry.

Porter's theory proposes a five forces model for industry analysis. There are five forces which impact the business. These include, the bargaining power of customers, bargaining power of suppliers, threat of substitute products and threat from new entrants (Porter 1979, 2008).

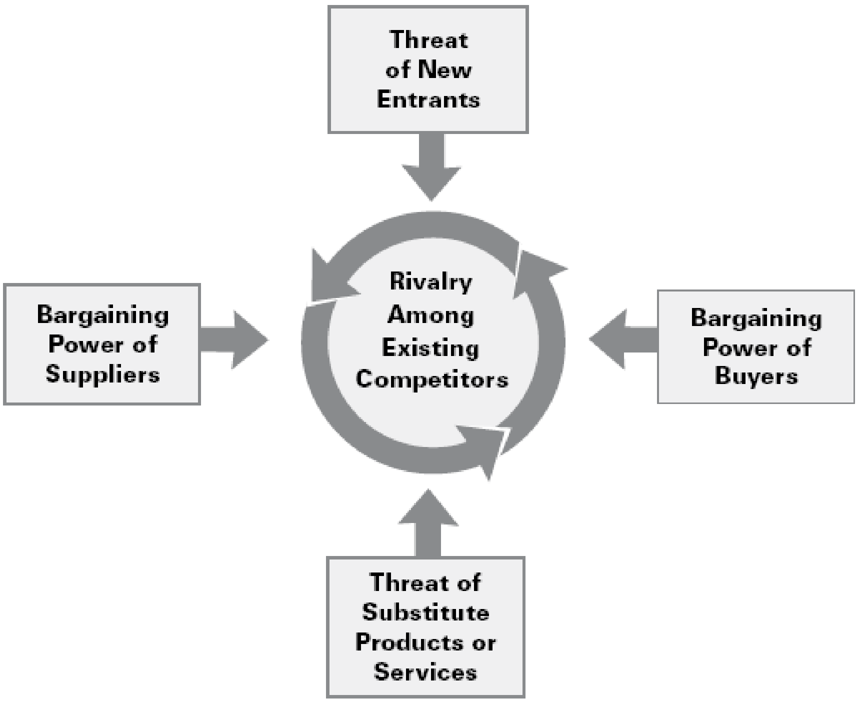


Figure 2.2 The five forces that shape industry competition

Source: (Porter 2008, p. 42).

However, knowledge is not part of that theory as a driver of strategy. Knowledge is unlike other organizational resources. Organizational knowledge combines both tacit and explicit knowledge embedded into organizational routines. It is not ready to use, not easy to buy from the market place and is difficult to imitate (Zack 1999). 'The management of knowledge is promoted as an important and necessary factor for organizational survival and maintenance of competitive strength. To have knowledge management in place can help the business react faster to market change situations. To remain at the forefront organizations need a good capacity to retain, develop, organize, and utilize their employees' capabilities. Knowledge and the management of knowledge appear to be regarded as increasingly important features for organizational survival (Mårtensson 2000). Porter argued that the fundamental purposes of strategic management were to maintain competitiveness through cost efficiencies and to maintain position in the market (Porter 1991, 1993). Strategically used, knowledge management can be referred to as 'two knows': know what the organization already knows and, secondly, know what the organization needs to know (Silvi & Cuganesan 2009). These two 'knows' strategically refer equally to the forces identified by Porter. Using the 'two knows', it can be argued, enables the realization of the strategic benefits of knowledge management. This research will cover both of these two strategic aspects. For example, 'Knowing what we know' is reflected in the process of capturing both explicit and tacit knowledge from the design engineers in the Company studied and storing that in a knowledge management system for the engineers to re-use in the design process.

Implementing a knowledge management strategy also gives an organization the opportunity to improve knowledge quality and (Alavi & Leidner 2001; Sun & Chen 2008). Information technology (IT) now plays an important role in facilitating KM implementation more effectively. However, it requires alignment of KM and IT. The other part of using KM strategically, 'knowing what we need to know', is covered in the second part of the research where we apply a heuristic process mining technique to the captured knowledge in the KMS. This analysis reveals organizational design and development processes and enables their mapping and interpretation. This means that irrelevant steps in the design and development processes can be identified and eliminated, resulting in a shorter make-span period, improved efficiency in design and development and consequent cost reduction. The result is improved competitiveness through enabling product to reach the market in a more time effective manner.

Choi and Lee (2003) have found that organizations achieve better performance resulting from a dynamic style integrating explicit with tacit oriented methods. There is a sense that knowledge becomes the basis for strategic use in product development and in meeting organizational business goals.

Zack (1999) argues that the area between knowledge management and organizational strategy overlaps. If an organization knows ‘their customers, products, technologies and market more, the organization should perform better’ (Zack 1999, p. 126). Knowledge strategy and business strategy is intertwined (Taxén 2010). Zack has proposed a ‘knowledge strategy’ framework to describe and evaluate organizational knowledge strategy. The model facilitates organizations to find the gap of what they need to know and bridge the gap. The emphasis has been put more into knowledge in terms of organizational strategy. This is because it represents a substantial organizational asset, operational creativity that is difficult to reproduce (Whelan, Collings & Donnellan 2010). Knowledge is essential to organizations and can provide long-term sustainability to strategic business. There might be arguments that technology is also important. However, technology cannot provide knowledge strategy to organizations, it can only facilitate it. This is because eventually technology will be available to everyone (Davenport & Prusak 1998; Nonaka 1994). The knowledge-based objective of any organization is to sustain normal business operations by constantly discovering new knowledge, new ways of solving problems and deriving new solutions from existing knowledge (Nelson & Winter 1982). One of the effective ways of being a knowledge-based organization is to apply available technologies to facilitate the process of creating knowledge from existing knowledge. This also synchronises with the objectives of knowledge management proposed by Wiig (1997) which is to make organizations act as intelligently as possible to secure overall business success and to recognise the best value out of their knowledge assets (Wiig 1997, p. 8).

Knowledge management strategies are both formal processes and structures that businesses employ to collect, interpret and internalize knowledge. These include both knowledge codification and personalization strategies (Earl 2001; Storey & Kahn 2010; Wyatt 2001). A codification strategy (Storey & Kahn 2010) is more than just storing documents. Rather, it is the embodiment of tacit knowledge in organizational processes and practices. Personalization strategy is the process of individuals sharing their knowledge with others in the organization (Storey & Kahn 2010; Wyatt 2001).

There are various knowledge management strategies used to facilitate business. Martin (2008) has listed possible KM organizational strategies as follows: building technical infrastructures to support KM, structuring organizational learning, facilitating a knowledge-friendly culture, establishing KM policy and measuring organizational capital (Martin 2008). The purpose of this process is to support knowledge workers to re-use what they know and supporting them to create new knowledge.

Wiig (1997) has mentioned that most organizations pursue one or more knowledge management strategies. These include:

1. Knowledge strategy as business strategy, which focuses on creating, capturing, storing, reusing and renewing the available knowledge for re-use when needed.
2. Intellectual asset management strategy, which focuses on the enterprise level. This includes intellectual assets, patents, operational management, customer management and organizational reengineering.
3. Personal knowledge asset responsibility strategy, which focuses on the personal knowledge level. This includes knowledge related investment, and effective use and innovation in each employees, too make sure that this knowledge will be applied to organization’s work.
4. Knowledge creation strategy, which focus on basic and applied research and development and motivate employees to capture lessons learnt from others to increase productivity.

5. Knowledge transfers strategies, which focus on systematically making knowledge available for employees to perform their tasks.

Zack (1999) has studied organizational strategy to identify knowledge management initiatives in 25 organizations. His view about business strategy and knowledge management is that if the organization knows more about their products, services, customers, technologies and markets, they should perform better. However, it is different from real practice. This is because there is no clear link between organizational competitive strategy and their intellectual capital (Zack 1999). One of the ways for organization to strategically positioning themself in the market through their 'unique, valuable and inimitable resources and capabilities rather than the products and services derived from those capabilities' (Zack 1999, p. 127). Positioning the organization through these resources and capabilities, he argues, is more sustainable than being based on only products. To be able to do this the organization requires a clear link between business strategy and knowledge. Once the business strategy has been identified then, the knowledge that requires performing tasks to achieve the business strategy also needed to be identified (Zack 1999). Zack (1999) has proposed a knowledge strategy framework as shown in the diagram below (Figure 2.3).

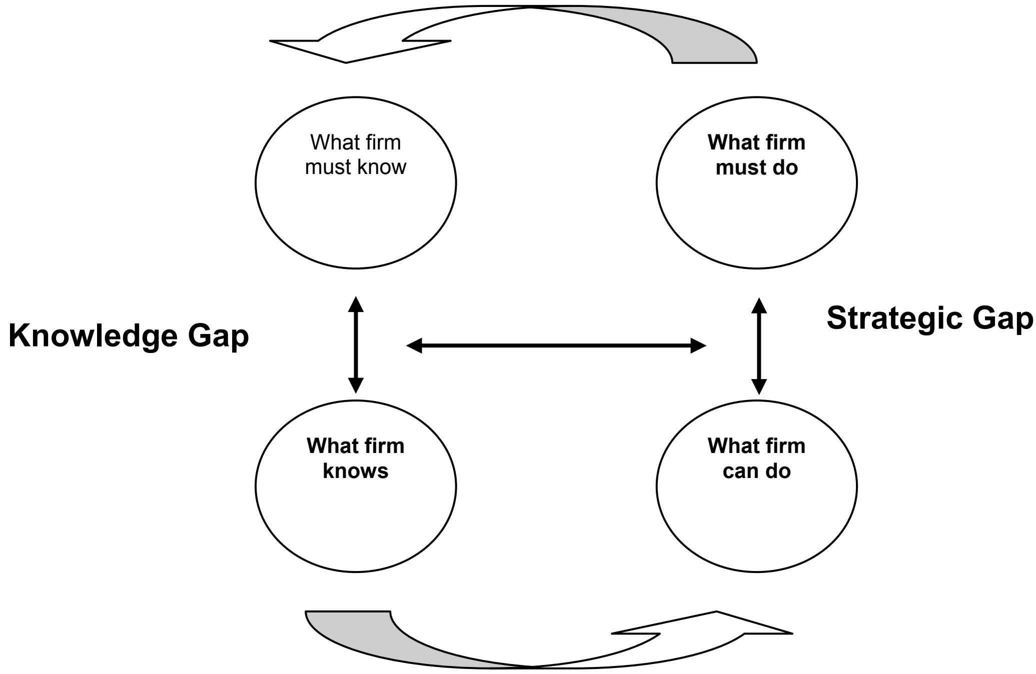


Figure 2.3 Knowledge strategy framework

Source: (Zack 1999, p. 136).

Zack's (1999) knowledge strategy framework suggests that for an organization to be able to be positioned well in the market they need to know what they must know and what they must do to achieve their goals. If the firm knows everything that they need to know and they can do everything that they need to do, there will be no knowledge gap and no strategic gap. This will lead to business success. However, in reality most of the organizations studied by Zack have both a knowledge gap and a strategic gap. This is a useful theory but has only been applied to whole of organization studies. There has been no application of this framework to the intricacies within individual companies in detail enough to explain what causes the gaps and how the gaps may be addressed by design. Both that gap and that detail are the focus of this research.

Traditional strategic management theory focuses essentially on transaction, cost analysis (Liebeskind 1996, Porter 1991). This approach to knowledge argues that investment in innovation creates new knowledge and the risk associated with it is reflected in the return on that investment. However, such theory offers no understanding of what particular strategies needed to be put in place to assure this return. The knowledge-based theory of the firm was an attempt to do this. This theory builds of the Resource-based Theory of the Firm (Conner 1991; Conner & Prahalad 1996; Wernerfelt 1984), which argues that the basis for competitive advantage results from the extent and application of the resources the firm can use. Connor and Prahald (1996) extend that argument to include knowledge as a key resource.

Grant (1996) in his development of the specific Knowledge-Based Theory of the firm viewed organizations as environments where knowledge from individuals have been integrated through employee's interaction in the organization. In the knowledge-based theory of the firm the organization is not just about reference to knowledge application. It also relates to knowledge creation. Grant has reviewed factors such as organizational existence, coordination, structure and boundary, and has analysed how these factors affect competitive advantage and sustainability of the organization. The theory argues that organization have to utilise the individual knowledge of their employees, not just use what they have but also they have to create an organizational environment where individual knowledge can be integrated and create new knowledge. The goal is to utilize individual's knowledge by improving knowledge sharing and creation within these factors to maintain or increase organizational competitive advantage (Grant 1996).

The research described in this thesis will provide a detailed example to show how the knowledge gap and the associated strategic gap for an organization can be addressed through the application of knowledge management. The framework adopted for this research uses the Zack (1999) model, Nonaka's (1994) Dynamic Theory of Organizational Knowledge Creation and the knowledge-based theory of the firm (Grant 1996) to examine what happens when addressing knowledge and strategy gaps. This research will evaluate the impact of a knowledge management system, developed and then implemented collaboratively within an engineering company (Fig 2.4).

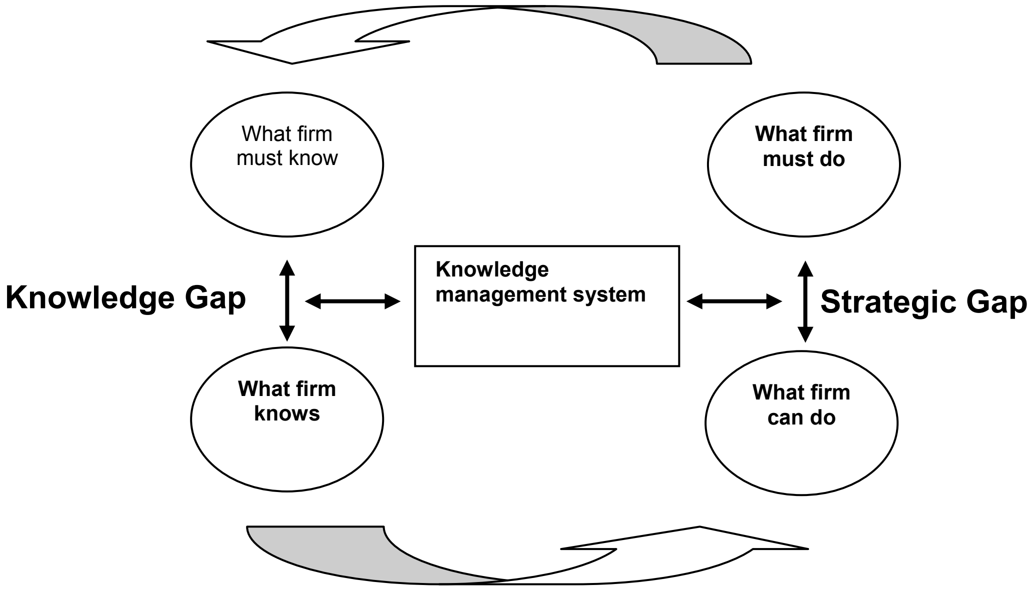


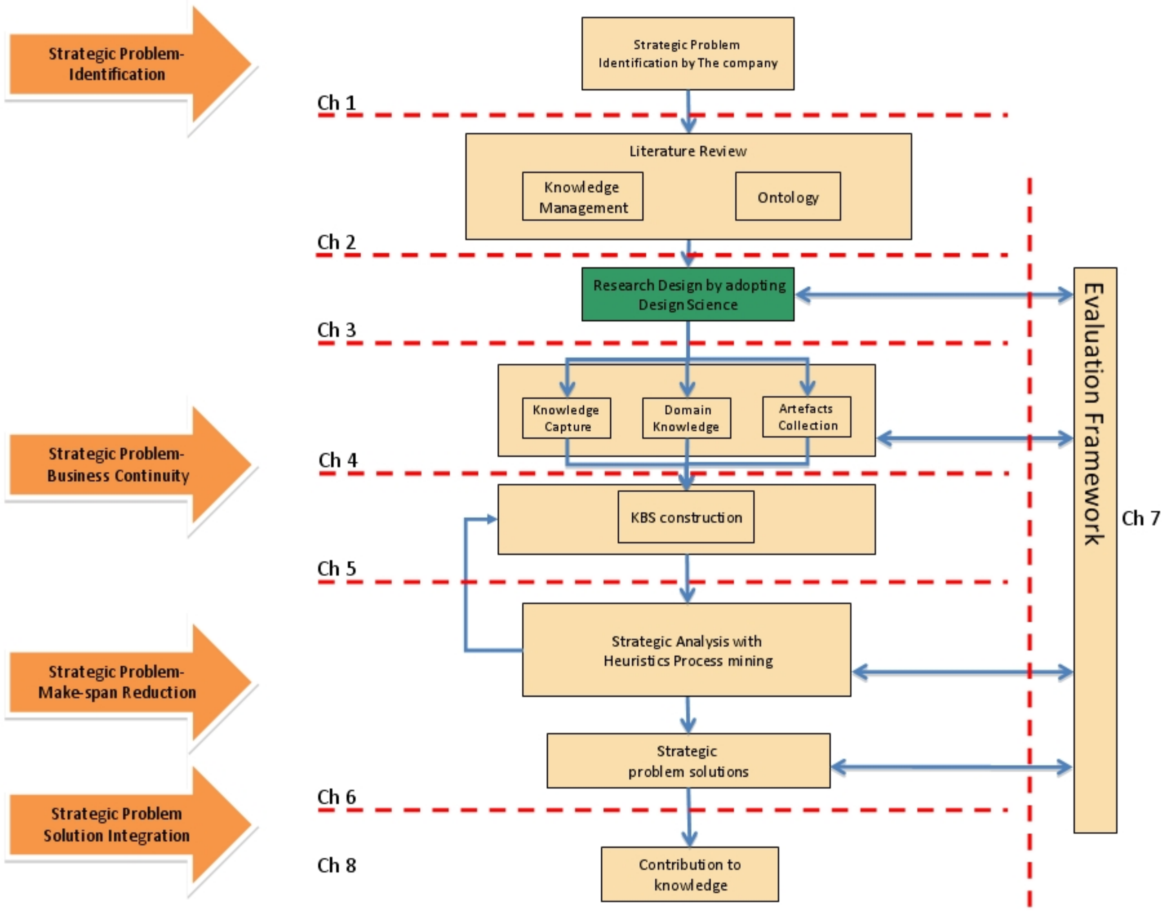
Figure 2.4 Research framework

Source: Modified from (Zack 1999, p. 136).

2.11 Conclusion

Research in knowledge management has been shown to be useful when used as a strategic tool to solve business problems. The most often cited solution is to capture knowledge and store it in a knowledge management system. However, there is general acceptance that tacit knowledge is difficult to capture and codify but the use of multiple techniques can help the researcher to overcome these problems. While using ontology as a tool for knowledge representation can overcome the knowledge codification problem, this research will utilize these combinations of tools to resolve the two identified business problems of the Company, namely lack of business continuity and a problem of lengthy make-spans in the product design and build process. The process will be to use the conceptualisations in the Zack framework in a detailed study of designing solutions for two key identified business strategy problems in an engineering company (the Company). In the following chapter, the methodology used to create a knowledge-based system through adoption of a Design Science approach with an application of ontology, and the techniques proposed to solve the make-span problem are discussed.

Chapter 3: Research Methodology



3.1 Introduction

This chapter will present details of the research methodology used in this research. It will detail the research process and justify the research methods chosen. To begin, section 3.2 will describe the research processes and their justification based on an analysis of two strategic business problems with the collaboration of the Company being researched. The Company had two distinct problems which required two different solutions. Section 3.3 provides details of case study research which forms the framework for the use of Design Science as the principal research methodology for the first part of the research. Section 3.4 provides details of Design Science as a research methodology, and how Design Science is used in this engineering-business related research problem. Section 3.5 presents the evaluation framework used throughout the research as an integral part of Design Science. To ensure that the Knowledge Management System developed in the first part of the research is going to work, an iterative evaluation is required. Section 3.6 presents details of the heuristic process mining techniques used in the second part of the research which is aimed at resolving the second issue, reducing the make-span. Section 3.7 draws conclusions about the research methodology used, and why they have been used.

3.2 The research process

Qualitative researchers study things in their natural settings, attempting to make sense of, or interpret, phenomena in terms of the meanings people bring to them (Creswell 1997; Denzin 1994). Morgan and Smircich (1980) argued that the choice of research methods had to evolve out of the context of the research, not out of abstract reasoning (Morgan & Smircich 1980). The context of this research is embedded in the intricate interplay of numerous ways the engineers involved interacted with each other, with executives, with clients and with the design/build and testing process they were using on a daily basis. These interactions created a very complex environment where the adoption of simple tools of research would have produced little of any value. There was a need to address all of the processes in multiple ways to ensure that all of the detail in and nuances of, the data, information and knowledge were captured accurately. In this way, the researcher becomes much more experienced with the context of their research. The researcher was able to justify their understandings based on the detail of their observations, discussions and interviews. In this research, that complexity was addressed by the use of multiple qualitative research methods and techniques.

Despite the increase in mixed method approaches (Mingers 2001), it is unusual for qualitative methods to be used in combination with each other (Frost et al. 2010). This is often a problem because of the multiple ideologies often embraced by qualitative researchers. Qualitative research covers a range of philosophies (Pope, Mays & Popay 2007), research designs and specific techniques including: in-depth qualitative interviews, participant and non-participant observation, focus groups, document analyses, and a number of other methods of data collection. There are also diverse methodological and theoretical approaches to research design and to data analysis. These can include action research, case studies, ethnography, grounded theory, phenomenology and a number of others (Miles & Huberman

1994). The researcher’s perspective, in essence his own domain knowledge, can also play a key role in qualitative data analysis and the extent to which generalizations can be made. However, they are rarely undertaken as part of the one research project. Certainly, comparisons are being attempted within, (Frost et al. 2010) but those comparisons assume that each method is informed by different ideologies. In this research, the same interpretive structure (Walsham 1995) – based on the researcher’s domain knowledge and technical expertise – forms the unifying framework through using a single interpretive case study, as a means of understanding the design story and history of the Company, and action research.

The research began in 2008 as a result of the Company approaching RMIT University, seeking research to resolve some strategic problems they were encountering. On agreement with the University it was decided that the project needed research and that a PhD research project was appropriate.

An initial meeting with the Company and its members involved in the product development process showed that the one group of engineers in the Company spend many months developing products to meet their customer requirements and that the management of the Company believed that this process was too long. These engineers have been developing refrigeration cabinets for more than 15 years. However, the engineers often encountered problems during the product testing process which delayed the time-to-delivery target. It should be remembered that refrigeration design cannot be deterministically arrived at and that successful design is the product of an iterative heuristic process based on (at best) a simulation arrived at base. The engineers often manipulated multiple factors simultaneously to reach the cabinet’s efficiency goal faster. However, the existing information recording system used by the engineers and executives did not enable knowledge and information capture, storage, retrieval and re-use. The engineers recorded all of the data and knowledge from their design, build and testing processes in various places. These reports included hand written log sheets, which were not readily searchable or retrievable. At the beginning of the research project the engineers mentioned that they hardly ever looked at previous reports. As a result they and the executives noted that the engineers had to spend time repeating tasks and repeating experiments previously conducted on the cabinets. Thus, knowledge about the testing process from previous products was re-used ineffectively or not used at all, resulting in time delays in new product customization. The initial interviews in the research process showed that the engineers performed their cabinet design, build and testing processes based on their memories.

The initial research also showed that, most importantly, there was significant knowledge generated during the daily cabinet design, build and testing meetings. However, this knowledge had never been captured. Hence, as the engineers noted, it had rarely been re-used. This new knowledge directly impacted the new product development timeframe and, as the executives commented, affected the Company's competitiveness in the marketplace. The situation was considered to be critical to the Company, with one consequential problem that the staff turnover rate was worrying the CEO. The number of engineering staff who left the Company had been increasing and expert corporate product knowledge was being lost.

The initial phase of the research proposal was addressed in discussions with the executives, engineers and supervisors, informed with extensive reading. The researcher concluded and then proposed to the Company that they needed an organizational knowledge repository to capture existing and new tacit knowledge, existing explicit knowledge, to enable knowledge and information storage, classification and re-use to retain their competitive advantage within the marketplace. The Company agreed this needed to be researched, designed, implemented and evaluated as the first part of the research project.

Another problem related to the Company product development process was that their product development process was iterative with no set procedures. Decisions were made based on observations and expertise derived from group meetings in an arbitrary fashion, rather than on any planned process or systematic framework. Among these modifications sometimes there were uncommon modifications which happened only once.

The Company was aware of both problems. However, it did not have a solution and the engineers did not have time to solve the problem themselves. The Company indicated that they needed a tool to store their organisational knowledge. This tool had to contain features such as knowledge and information integration and the system had to be able to link together knowledge from testing log sheets and information from various other storage sites of expert knowledge and product completion reports locations without reconstruct the Company's computer systems and network. The other feature required was that the system should not demand a great deal of computational knowledge to capture and re-use the stored, data, information and knowledge. The system, they specified, also needed to store captured tacit knowledge so that it could be strategically analysed and used by the existing and any new engineers. The knowledge management system was intended to frame a solution to the two strategic company issues. A knowledge management system was needed as an outcome of the first stage of the research. That need, together with the problem orientation being design, led the researcher to investigate the use of Design Science as a relevant research method for the single case study of the Company.

3.3 Case Study research

Yin (1994) has defined case study research as one which 'investigates a contemporary phenomena within its real-life context, especially when the boundaries between phenomena and context are not clearly evident' (Yin 1994, p. 13). Both Yin (1994) and Eisenhardt (1989) also suggested that a case study is a good technique to use to study social phenomena in a single setting. It can help researchers answer 'how' and 'why' questions in the situation that involves social behaviour through exploratory, descriptive or explanatory research (Barkley 2006; Blaxter, Hughes & Tight 2006; Eisenhardt 1989; Rowley 2002; Stake 1978, 1985, 1995; Yin 1994).

3.3.1 Case study characteristics

Previous researchers have suggested that the following are characteristics of case study research:

- A case study cannot be used in every type of research. It is suitable only for some types of research questions such as ‘why’ and ‘how” where the question is more related to finding explanation (Eisenhardt 1989; Stake 1978, 1995; Yin 1994). This research focuses on both the ‘why’ and the ‘how’.
- Case study research does not require control over the behaviour of the event or subject of the study (Rowley 2002; Yin 1994, 2002). This research is not concerned with behaviour but rather with action.
- Case study research focuses on contemporary events in a real life context (Yin 1994). The research involves intensive study of a single unit such as an individual, or group or institution (Kazdin 1982; Rowley 2002). This research focuses on a detailed, intensive study of design, build and testing of products in real time in the context of a single company.
- The information collected is very detailed, comprehensive, and often reported in a narrative form (Kazdin 1982). The information collected may be retrospective (Kazdin 1982). In the first part of the research, the focus is not only on what was happening currently, but also on collecting what has happened, what is stored, what artefacts are available and the past history of products in the Company.
- A single case study is similar to an experimental study. It is suitable where the case is specific for some reason. As it is a single ‘Unit’ in the study, critical evaluation might be required when the theory is needed to be established (Blaxter, Hughes & Tight 2006; Flyvbjerg 2006; Rowley 2002). The second part of the study uses the knowledge collected and codified to provide the basis for a detailed analytical solution using modelling, experimenting to provide a range of solutions to a make-span problem.
- Multiple case studies are basically a multiple number of ‘Units’ of experimental. There is no clear answer that how many ‘Units’ should be included in the study. Therefore, specific consideration when select the number of ‘Unit’ is required (Blaxter, Hughes & Tight 2006; Rowley 2002).
- Case study research can be used to achieve various aims such as providing description or testing theory (Eisenhardt 1989). This research both provides description of what has and is happening in the Company

product development process and tests solutions against strategic management theory.

Based on the above then, a case study context for both parts of the research can be said to be appropriate. However, there are some limitations of case study research. First, the size of the interested group is small, which makes the researcher unable to generalise findings to cover the whole population. Second, similar to other types of experimental research, case study research can help the researcher describe what occurred, or is occurring, but cannot always tell why it occurred. Third, the method is not immune to individual bias (Flyvbjerg 2006; Marczyk, DeMatteo & Festinger 2005; Rowley 2002).

Even though case study research has some restrictions, the method can contribute high value to the knowledge of individuals, organizations and society (Yin 1994). Yin (1994) mentioned that a case study does not require control over behavioural events and focuses on only temporary events. The technique aims to answer 'why' questions where the researcher deals with 'operational links' needing to be traced overtime, rather than mere frequencies or incidence' of the subject of study (Yin 1994, p. 6). Before proposing solutions to the Company's business strategic problems in this research, the cause of the problems needed to be explored and explained first. A typical case study technique uses various kind of evidence from difference sources to do that (Rowley 2002). For example in this research, the Company's catalogues, past testing reports, testing log sheets, data logs, meeting notes, interviews, and observations were collected and combined to gain an understanding of the actual phenomena. This is because each source has different strengths and weaknesses in their detail. Case study research then helps the researcher gain real understanding about how effective the Company's management and engineers have been in managing their business knowledge. Then suitable solutions can be proposed to suit the practices of the Company. Case study research provides a suitable framework for the research. However, the detailed methodology framework within that case study relates to design and so a Design Science methodology was adopted.

3.4 Design Science

To explain Design Science methodology the word ‘Design’ needs to be described. Design, in this context, refers to the process of ‘creating something new that does not exist in nature’ (Vaishnavi & Kuechler 2008, p. 8). Hevner and Chatterjee (2010) have described design as ‘the instructions based on knowledge that turns things into value that people used. It embodies the instruction of making things. However, design is not the thing’ (Hevner & Chatterjee 2010a, p. 1). The design paradigm is used in various domains such as engineering, architecture, production and software development. However, they share the same goal in which the design should be suitable for purpose, should not have any bugs and should be a pleasure to use (Hevner & Chatterjee 2010a). What then is science? March and Smith (1995) have mentioned that natural science is ‘concerned with explaining how and why things are’ (March & Smith 1995, p. 253). This is similar to Hevner and Chatterjee’s (2010) view, which stated that goals of good science should ‘develop a theory, paradigm or model that provides a basis for research to understand the phenomenon being studied’ (Hevner & Chatterjee 2010a, p. 4)

Therefore, Design Science is the technology-oriented process of ‘creating things that serve human purposes’ (March & Smith 1995, p. 253). ‘It is fundamentally a problem solving paradigm’ (Hevner et al. 2004, p. 76) through engineering and science, or in other words, ‘improvement research’ (Vaishnavi & Kuechler 2008, p. 11). Design Science methodology has to have problems as a driving force to conduct the answer-finding process. March and Smith (1995) have identified that there are two basic activities in Design Science process. These include both building and artefact and evaluation. In Design Science research building activity is the process of building artefacts to solve practice problems (Stacie, Deepak & John 2010). Design Science method tends to be used to create innovative and valuable solutions. To summarise, ‘the fundamental principal of Design Science research is that knowledge and understanding of a design problem and its solution are acquired in the building and application of an artefact’ (Hevner & Chatterjee 2010a, p. 5).

Iivari and Venables (2009) have summarised the similarities and differences between Action Research (AR) and Design Science Research (DSR) from previous literature (Iivari & Venable 2009). One of the definitions Livari and Veneble (2009) mentioned is from Rappoport (1970) who said that Action Research facilitates finding a good understanding in both ‘the practical affairs of man and the intellectual interest of the social science community’ (Rapoport 1970, p. 510). Based on this definition the Design Science paradigm is developed by various researchers. For example, Baskerville et al. (2009) mentioned that Design Science has been used to develop ‘new technologies to solve problems’. These problems and solutions often relate to socio-technical elements in nature. The process aims to gain a good understanding about problems, systematically suggesting appropriate solutions and evaluating innovative solutions (Baskerville, Pries-Heje & Venable 2009, p. 1; Iivari & Venable 2009). Design Science research is similar to Action Research where both methods generate new scientific knowledge by modifying the real settings, such as in organizations, (Baskerville & Wood-Harper 1996) and by evaluating the outcomes of solutions (Baskerville, Pries-Heje & Venable 2009). The emphasis is that, if there is no new knowledge created during the process of developing the artefact as an outcome, at best it can only be applying best practice or conducting and improving routine processes and therefore is not Design Science research (Vaishnavi & Kuechler 2008), rather it is often Action Research. Baskerville et al (2009) have made the comparison between Design Science Research and Action Research as shown in Table 3.1

Table 3.1 Comparison between Design Science Research and Action Research from (Baskerville, Pries-Heje & Venable 2009, p. 4)

Characteristics	Design Science Research	Action Research
Orientation/ Method for	Research	Practice and Research
Goal	Problem solving	Problem solving and / or behavioural understanding
Specificity	Generalised	Situation specific and generalised

Design role	Invention/ Generative	Application or (invention and application)
Outcome	Design theory or artefact shown to have utility	Situated organizational improvement and (behavioural theory or design theory)

While (Iivari & Venable 2009) have compared DSR and AR from different aspects, shown in Table 3.2, their focus is on developing a real outcome. They argue that Action Research can be considered as a special case of Design Science Research. However, Design Science aims to build an artefact while this is not necessarily the case in Action Research. Furthermore, paradigmatically, Design Science Research and Action Research can be used together or can be used separately by using Design Science to build the artefact and using Action Research to evaluate it. That research process is the approach adopted in this study.

Table 3.2 Paradigmatic comparison between Design Science Research and Action Research by (Iivari & Venable 2009).

Paradigmatic dimension	Design Science Research	Action research
Ontology	Realism or anti-realism	Anti-realism
Epistemology	Mainly positivism, but also anti-positivism especially in evaluation	Mainly anti-positivism
Methodology	Constructive (building) Nomothetic (evaluation) Idiographic (evaluation)	Idiographic
Ethics	Means-end Possibly interpretive Possibly critical	Means-end Possibly interpretive Unlikely critical

Design Science research is not new and it has been conducted in various domains for decades especially in Information Systems.

In Design Science new kinds of artefacts and methods are developed during the process in a way similar to the process of developing emerging knowledge processes (Markus, Majchrzak & Gasser 2002). Emerging knowledge processes (EKPs) are the organizational activity patterns in which organizational knowledge is accumulated and then re-used under different circumstances in the process. These include, for example, new product development, organizational design and strategy-making. Markus et al. (2002) have suggested that there are three main factors involved in the EKP's development process: process, users and user's information requirements. These three factors are the key components that contribute to how the EKPs will look, how they works and how we know that they work. The EKP is complex and development therefore requires new design theory (Markus, Majchrzak & Gasser 2002). Wall et al (1992) argue that this new EKP design theory is an intertwining of a selection of system features and the development process principles. Markus et al (2002) have proposed design theory as design principles. These design principles, according to (Markus, Majchrzak & Gasser 2002) are more user focused:

- Principle1: *Design for Customer Engagement by Seeking Out Naive Users.* This principle ensures that users are catered for during the design process, as user's knowledge is also growing along with the process development. Users are then able to understand the benefits and know how to use the system. When new users come into the organization they have to catch up with what everybody who already knows about the system. Principle 1 is encouraging system designers to be aware of this problem.
- Principle 2: *Design for knowledge translation through radical iteration with functional prototyping*. This means the system prototype as an outcome from the design process should be able to demonstrate a real life situation in terms of system functions. It should also be easy for users to evaluate the system as well if the system prototype can demonstrate how it can be used in the real working process situation.

- Principle 3: *Design for offline action*. The system should be designed to reflect its usefulness to the users, not simply for demonstration or for a testing process.
- Principle 4: *Integrate expert knowledge with local knowledge sharing*. The designed system should be able to help people in the same department share their knowledge. For example in a production line, the system should enable both engineers and workers on the factory floor to share their knowledge through the system. This is because combining relevant knowledge and enable sharing is a good way to support emergent knowledge processes.
- Principle 5: *Design for implicit guidance through a dialectical development process.* The system design should be able to help the users understand the process through implicit guidance. The guidance should include steps about how to use the system and extend the understanding of technical terms to encourage discussion among users.
- Principle 6: *Componentised everything including the knowledge base*. The system design should be flexible and compatible for future infrastructure changes (Markus, Majchrzak & Gasser 2002).

This type of research was re-iterated in Hevner et al (2004) as one of the foundations in Design Science research. Both Markus et al (2002) and Hevner (2004) propose that these artefacts are built in a five step process:

1. Construct a conceptual framework: In this stage the research question is identified and justified. The problem has to be significantly new and has not been solved before in the current industrial context. This can cover previous problems that have not been proven or it can be a new way of doing things. The conceptual framework design leads to theory building. This is to ensure that the efforts of studying existing theories have been put in to form new concrete theory for the particular problem.
2. Develop a systems architecture: This is the process of setting up building a process through requirements gathering. This includes system structure, functionality, components, objectives and measureable evaluation.

3. Analyse and design the system: After the requirements have been gathered, if there are external implication involved, it has to be looked after. These included external domain knowledge, alternative solutions, and evaluation for alternative solutions.
4. Build the system: In this stage a system prototype is built based on the gathered requirements. The building process is one way of learning which included a problem insight and deals with the complexity of the system.
5. Experiment, observe and evaluate the system: In this stage the system that is built is evaluated against all of the requirements. This stage includes the system testing process through experimentation or observation. Experimentation can help system developers gain new knowledge through system experiments.

Hevner et al. (2004) have also argued that Design Science is inextricably related to Behavioural Science, especially in Information Systems where the IS application directly impacts on people, organizations and technology (Hevner et al. 2004). Therefore, the research process has to also include evaluation of the artefact. This is to ensure that the artefact built can solve the identified problem. Hevner et al (2004) have described that the Design Science research paradigm as a process which contains sequences of activities performed by experts to produce an innovative artefact. Then an evaluation process takes place to provide feedback to the artefact building process. These design and evaluation processes both improve the quality of the artefact and the design process. Design Science research then builds and evaluates as an iterative process. It might take a number of iterations until the artefact reaches a final outcome.

Hevner et al. (2004) have suggested seven Design Science principles which act as guidelines to assist researchers gain a better understanding of the requirements of Design Science (Hevner et al. 2004):

1. *Design as an artefact:* The outcome of Design Science research has to be an artefact. It can be any of one of the four forms suggested in (March & Smith 1995): constructs, models, methods and/or implementations.

2. *Problem relevance:* The goal of Design Science research is to acquire knowledge to produce an artefact to solve the previously unsolved important business problem, increasing the effectiveness of the business process through that design.

3. *Design evaluation:* An evaluation process is crucial in Design Science research and it has to be done through demonstrated rigour. There are various techniques and aspects used in the evaluation process. In this dissertation artefact evaluation has been developed based on previous research.

4. *Research contribution:* The Design Science process has to provide a clear contribution to the design relevant area. These contributions include:

    a) The artefact itself has to contribute a solution to the unsolved problem by helping people to do things in innovative ways in a real world implementable way. Other than that, the artefact has to provide new value to the information system community in term of methodologies, design tools and/or prototype system.

    b) Foundation: the artefact development process should extend or improve the existing foundation of the business process.

    c) Methodologies: the creation and evaluation development in the research should contribute to the existing methodology.

5. *Research rigour:* The process of building and evaluating the artefact has to be rigorous. The rigour can be found through good selection of appropriate existing evaluation techniques, through a knowledge base, through theoretical foundations and the application of various research methodologies in the creating and evaluating process. In particular the theory of design and action is where justified method or theories of how to do things have been used during the artefact development process (Gregor 2006).

6. *Design as a search process:* The nature of Design Science is an iterative cycle used until an optimal solution is found. It is a realistic problem solving

method in which the available means, laws and heuristics have been viewed and utilised for the best possible solution to satisfy the specific problem.

7. *Communication of research:* Design Science research must be presented at a level of detail for the technical-oriented people to understand. At the same time it also should be able to give a general overall view for management-oriented people to understand.

It is against these principles that the efficacy of the research process and outcomes will be evaluated (Chapters 7 and 8).

3.4.1 Outcome of the Design Science Process

If the Design Science has been viewed as a problem solving method, it has to have outcomes. March and Smith (1995) have listed the four outcomes of Design Science: constructs, models, methods and/or implementations that can help humans perform goal-directed activities (March & Smith 1995):

- First, 'construct' (vocabulary and symbols in (Hevner et al. 2004)) which is the conceptualisation, which has been used to express problems in the domain of interest and offers specific solutions to the problem.
- Second, 'model' (abstractions and representations in (Hevner et al. 2004) is a statement expressing relationships between constructs. It has been used to describe research activities. Model represents how things are, and can also be used as models to describe theory.
- Third, 'method' (algorithms and practices in Hevner et al. 2004) is a set of steps, guidelines or algorithms used to perform a task. Method is the combination of both constructs and models.
- Fourth, 'outcome' is an instantiation (implemented and prototype systems in Hevner et al. 2004) which is the consideration of design artefacts within the environment. This aspect looks at how the artefacts, which impact the business environment will be considered. This will demonstrate the feasibility and effectiveness of the model and/or method (March & Smith 1995).

3.4.2 Design Science process as research

March and Smith (1995) have suggested that there are two activities in Design Science research: build and evaluate. However, build and evaluate is parallel in process between discovery and justification. Building activity aims to get the artefact to perform specific tasks. Artefact feasibility becomes the object of study. To ensure that the artefact built is working, scientific evaluation becomes a crucial part (March & Smith 1995).

The Design Science research paradigm aims to find solutions for specific problems. Design Science research is iterative and has an evaluated artefact as an outcome (Hevner & Chatterjee 2010a). Hevner and Chatterjee (2010) list eight characteristics of Design Science research which confirm its research focus, saying the research:

1. Originates with question or problem;
2. Requires a clear articulation of a goal;
3. Follows a specific plan or procedure;
4. Usually divides the principal problem into more manageable sub problems;
5. Is guided by the specific research problem, questions or hypotheses;
6. Accepts certain critical assumptions;
7. Requires collection and interpretation of data or creation of artefacts; and
8. Is by its nature cyclical, iterative or more exactly helical (Hevner & Chatterjee 2010a, p. 3)

The nature of the iterative process is a cycle of tasks that have been repeatedly and systematically done during the artefact development process. This is to ensure that the artefact developed is working and serve its purpose. This cycle of findings for a valid solution to an identified problem creates new knowledge to help researchers to understand design principles (Vaishnavi & Kuechler 2008) and improve business outcomes.

This research then adopts the Design Science guidelines of Hevner et al. (2004) as the framework for both the research process. These guidelines are shown in Table 3.3.

Table 3.3 Design Science Research Guidelines.

Guideline	Description
Guideline1: Design as an artefact	Design-science research must produce a viable artifact in the form of a construct, a model, a method, or an instantiation.
Guideline 2: Problem Relevance	The objective of design-science research is to develop technology-based solutions to important and relevant business problems.
Guideline 3: Design Evaluation	The utility, quality, and efficacy of a design artifact must be rigorously demonstrated via well-executed evaluation methods.
Guideline 4: Research Contributions	Effective design-science research must provide clear and verifiable contributions in the areas of the design artifact, design foundations, and/or design methodologies.
Guideline 5: Research Rigor	Design-science research relies upon the application of rigorous methods in both the construction and evaluation of the design artifact.
Guideline 6: Design as a Search Process	The search for an effective artifact requires utilizing available means to reach desired ends while satisfying laws in the problem environment.
Guideline 7: Communication of Research	Design-science research must be presented effectively both to technology-oriented as well as management-oriented audiences.

Source: Hevner et al (2004), p.83

This research then uses the above principles and framework of Design Science research as the basis for developing solutions to the identified problems in the Company. How these principles were adopted and used as part of the research process follows in the next sections of this chapter.

3.5 Research Part 1 - Designing a Knowledge-Based System Artefact

The purpose of the first part of the research for the Company was to produce an outcome that could help the Company capture their employee's knowledge for re-use. In this research the artefact developed was a knowledge-based management system. The system construction started with initial meetings with the engineers. The engineers' requirements were gathered from the meetings. The focus here was to capture what they wanted to know 'we did this, this happened; we did that, that happened'. At this stage the researchers were studying information about the products that the Company manufactured to gain an understanding of what are the engineers were doing. The research was in essence incorporating a Design Science approach to a knowledge engineering problem (Studer, Benjamins & Fensel 1998).

The literature suggested that there are a number of tools that are often used in knowledge capture research (Ashley et al. 2003; Bailey 2010; Bryson, Cox & Carson 2009; David et al. 1990; Doo Soon, Ken & Bruce 2009; Eva, Aldo & Valentina 2009; Hari, Egbu & Kumar 2005; Iria 2009; Jihie, Jia & Taehwan 2009; Kenneth & Jeffrey 2002; Lockwood & Forbus 2009; Sharif & Kayis 2007; Torres et al. 2010; Yasmin & John 2001). One of them is to develop a knowledge-based system as the tool that collects all knowledge captured, both explicit and tacit. In this research a knowledge-based system will be the research outcome, or artefact, to resolve the identified business problem. The first research process involved capturing the knowledge and to ensure as much completeness as possible a multiple methods approach was chosen.

The data was collected in two parts: 1. the collection of existing explicit knowledge and then part 2, collection of tacit knowledge. The explicit knowledge of the Company was included in the Company products catalogues, testing log sheets, product plans and images, design drawings, and testing reports. The recorded knowledge was significant in the design process of the knowledge-base system because it was a physical reflection of the tacit knowledge/expert knowledge that the engineers had previously and were still using on a daily basis in their design and build of each refrigeration cabinet. This knowledge was then classified using an ontology and designed into the process of building the knowledge-based system. Details of this process are explained in the next chapter.

To deal with the capture of the tacit knowledge a multi-layered methods process was used (Kanjanabootra, Corbitt & Nicholls 2010). These methods were used to capture company domain specific engineering knowledge in this refrigeration company. This enabled the researcher to overcome the previously reported inconsistencies, incompleteness and weaknesses in previous attempts at tacit knowledge capture in other companies and in previous research.

Previous research has argued that capturing knowledge in organisations is often fraught with problems. The most common problems identified include:

> 1) Knowledge capture often fails because its implementation consumes huge amounts of time and is not incorporated in the business process. Too often, organizations require staff to use knowledge capture systems using IT (Bryson, Cox & Carson 2009; Kamara, Anumba & Carrillo 2002) or to keep diaries as they work. Both techniques are problematic. Staff complain that they do not have the time needed to fill them in properly. They are also concerned that such a system 'takes' their personal knowledge at no cost to the Company and consequently, they may fail to provide complete information.
>
> 2) It is often the case that unusable knowledge is captured. Staff will often provide too much knowledge, much of which is not newly created knowledge. Often, staff do not understand the strategic nature of what they 'know' and fail to discriminate between what they have created and what is generally known (Alavi & Leidner 2001; Gupta, Lakshmi & Aronson 2000). This leads to knowledge management systems that are incomplete, over-burdened and unable to be differentiated to provide a basis for discrimination of strategic and focused knowledge.

3) Knowledge has not been horizontally transferred among the employees, nor has it been vertically transferred through generations of employees (Ardichvili et al. 2006; Parolia et al. 2007). Often knowledge remains in the possession of individuals who forget to disclose, or deliberately do not disclose, newly created knowledge. In addition, they often do not make any attempt to transfer their knowledge either across to their colleagues and peers in the organization or to the organization itself. Often people leave organizations without sharing, and take crucial information with them.

4) Tacit knowledge itself is difficult to transform or codify during the knowledge storing process. Knowledge is often difficult to interpret because of a lack of domain knowledge held in central repositories. Because interpretation is poor, those who are operating the knowledge management systems often do not have the capacity to accurately record, discriminate between or classify knowledge. Ontologies are rarely, if ever, created or used in business to classify and store created tacit knowledge, and have seldom played that important role (Boh 2007; Milton, S, Keen & Kurnia 2010). Nonaka (1994) noted that the interplay between tacit and explicit knowledge was the key driver of growth in a knowledge-based firm (Nonaka 1994). Ontology offers a means to classify that interaction, and collaboration the elements of both tacit and explicit knowledge in a codified format.

5) There are often problems with the usability of captured knowledge. Nonaka (1994) argued that capturing knowledge was sometimes fraught, as staff in organisations often did not recognise the knowledge they were creating. Without a clear appreciation or perception of what people have created, and coupled with a lack of strategic focus, knowledge that *is* reported is often misunderstood and of little value (Aykin & Douglas 2007; Geisler 2007).

6) Problems persist in the implementation and use of systems that store captured knowledge. Knowledge management systems often result in their non-adoption by employees. They can be too difficult to use, too slow,

disorganized, not applicable to the specific user group, or could simply be too confusing to use as they lack clear classification due to a low level of understanding by the developers (Han 2010; Lin & Tseng 2005; Wargitsch, Wewers & Theisinger 1998).

7) There is evidence that a lack of knowledge capture and organizational culture prevents completeness (De Long, D & Fahey, L 2000; Gold, Malhotra & Segars 2001; Quaddus & Xu 2007). Nonaka (1994) and Nonaka and Takeuchi (1995) realized the importance of having an embedded knowledge culture as part of the organization's raison d'être (Nonaka 1994; Nonaka & Takeuchi 1995). They argued that accepting the role and value of capturing and sharing knowledge as part of a knowledge creation process was the prime motivation of organizational development. Without that culture, knowledge capture will be less than complete and often inaccurate (Mason & Pauleen 2003). A knowledge-oriented culture challenges people to share knowledge throughout an organization (Davenport & Prusak 1998; Gold, Malhotra & Segars 2001).

The multi-layered methodologies used (Fig 3.1) to capture the Company domain-specific engineering knowledge in this refrigeration company enabled the researcher to overcome the previously reported inconsistencies, incompleteness and weaknesses in knowledge capture in organisations. In fact, the researcher acted as a 'coach'. By using a systems perspective, modelling knowledge, understanding business processes and extracting knowledge at all levels in the Company, the researcher was able to identify incompleteness where parts of the system did not match, and ensured knowledge completeness by iterative checking with the engineers and observing multiple instances of the Company's product development systems. Working in the teams of engineers and embedding observation and shadowing techniques for data collection ensured that the researcher was himself aware of all that was happening. 'Coaches' are used in sport to bring teams together, identify weaknesses and train sportspeople to address performance issues. As the KMS was being built, the researcher was able to identify omissions and record them, feeding the information back to the engineers within the KMS itself. Thus, weaknesses within the ‘culture’ (often an issue in ineffective knowledge capture) were addressed as well.

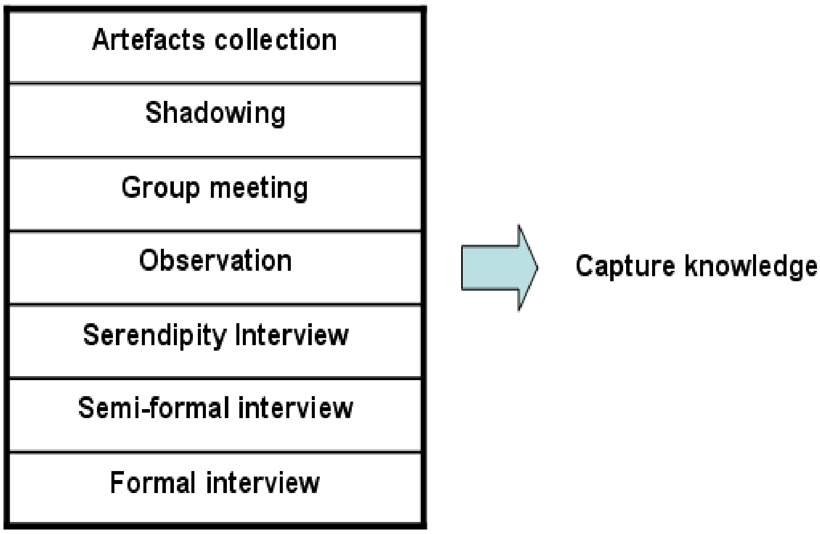


Figure 3.1 Multi-layered research approaches

Using a multi-layered qualitative research method has enabled the researcher to uncover all elements of the research context, from the formal to the informal, from the structured to the serendipitous, and from the constructed to the ephemeral. All these elements are necessary to build the rich pictures needed in effective knowledge capture. Tacit knowledge is embedded deeply in thought and action in all organisations, and to extract it has required the building of a whole body of knowledge, based on iterations using multiple and complementary research methods.

This multi-layered research approach was adopted simultaneously in various components of the research. All formed part of the case study. The various sets of information collected were used to interpret what was happening as a basis of the development of ontology to form the foundation of a useable knowledge management system. Interviews and artefacts searching framed in ethnographic work derived the story of design, testing and building of commercial refrigerators in the Company. The ontology design was enhanced through knowledge and information collected and interpreted in the group meetings, in both forms of interviews and through application of domain knowledge in making sense of observations. All of these processes were iterative, and used the principles embodied in action research and Design Science. The common element was interpretation based in the domain knowledge of the context of the research, in the method proposed by Morgan and Smircich (1980).

The result was a highly complex knowledge-based management system that reflected the real complexity of the Company's workplace, but simplified those processes based on the ontological structures created. The system's structures enabled the stored forms of knowledge to be interrogated, and provided the answers needed by the engineers to be exposed time and again, consistently and quickly. These answers were derived either from the knowledge creation processes emerging daily in their meetings or work, or from the artefacts stored in the Company over a long period of time. In the second part of the research the methods used were different as the business problem involved required a different approach to the building of possible solutions. However, it relied entirely on the knowledge-based system developed in the first stage.

3.6 Research Part 2 – Mining the knowledge-based system to find solutions to shorten the make-span.

The second part of the research aimed to develop a solution to enable the engineers to shorten their cabinet prototype development time. The initial research derived from interviews showed that the cabinet testing process contained a random series of tasks from start to finish. This unsystematic order of tasks made the cabinet testing process long and unpredictable. The process is shown in Figure 3.2. A Design Science research framework (Gregor 2002, 2006; Hevner et al. 2004; Nunamaker, Minder & Titus 1990; Venable 2006, 2010) was again adopted to find the solution to shorten the cabinet testing process. In the second part of the research, the process again involved an iterative type process like action research, but in this phase, instead of using an ontology to construct a knowledge classification system, the researcher adopted an algorithmic form of analysis using Heuristic Process Mining. The HPM was used to apply to the knowledge that was stored in knowledge-based system (the outcome from first part of the research).

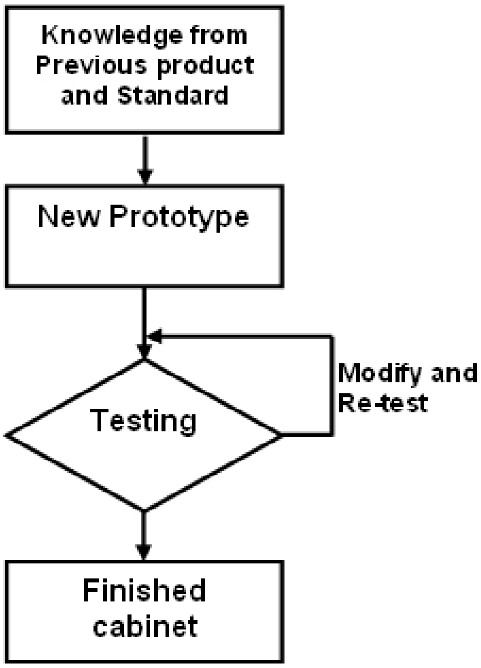


Figure 3.2 Cabinet prototype development process

Heuristic process mining uses an α-algorithm applied to the workflow process. The application helps the researcher answer 'how' questions about the studied process, in this research a commercial refrigerated display cabinet design and development process. This α-algorithm has been shown in previous research to be able to reveal what is hidden in workflows (Rozinat et al. 2009; Rozinat et al. 2007; van der Aalst, Ton & Laura 2004; van der Aalst, Weijters & Maruster 2004; Weijters & Van der Aalst 2003).

This research examined the heuristic order of tasks in the workflow nets derived and mapped from the processes used in the Company, stored as knowledge in the knowledge-based system. Workflow nets are a subset of Petri Nets and is a low level form of a Petri net which models a workflow process definition (van der Aalst 1998). Workflow nets consist of (T) responses to tasks that have been executed and (P) conditions which correspond to any given stage in the workflow net. Workflow nets also can specify routing of the process. The workflow net structure is simple. In this research the knowledge base system was mined to extract 13 cases of complex work processes. These 13 testing processes were mapped into workflow nets and HPM analysis was applied. The details of the mathematics of the application of the algorithm to the data mined are described in detail in Chapter 6.

In summary, the researcher adopted an initial research strategy of formal and informal discussion. Formal meetings were initially held with the CEO and COO. This was followed by a formal meeting with all of the engineers. In parallel, the researcher had informal discussions with each of the engineers while they were working, and attended the normal morning meetings of the engineers where they discussed their projects, the outcomes of the previous day's testing and any new designs. Information and knowledge collected was recorded and an on-going analysis was undertaken. The purpose of this process was to build an understanding of all the elements involved in the design/build/test processes used by the engineers in the Company. This researcher was using his domain knowledge as an engineer to both understand and classify the knowledge being collected. Once an initial framework had been established through observation and shadowing, the researcher began an iterative process of continued observation, questioning, observation, participation and shadowing to build an ontology of engineering knowledge. This ontology was then tested against each subsequent series of observations.

Simultaneously, explicit knowledge was collected and included in the developing ontology. This knowledge was based in Company artefacts such as plans, drawings, CAD drawings, brochures, and client specifications and included the detailed knowledge specified in National Standards. Each set of documents provided substantially more detail to enable the classification to become more and more a real representation of their work processes. Without the contextual/domain knowledge, this process could have represented only part of what was happening. As argued above, multiple methods used in this way aggregate the captured knowledge and improve its validity and accuracy. Multiple iterations of this process occurred over a 12 month period. Each iteration was progressively incorporated into a knowledge management system built on the ontology created from the research and the expert and domain knowledge of the researchers. Ultimately, each iteration of that system was tested with the engineers and eventually adopted. An evaluation of the system after two years of research by the engineers and the executives confirmed that its fundamental purpose - to capture knowledge to ensure business continuity of the Company - was attained.

The final part of the research methodology used in this research relates to the evaluation of both parts of the research. To undertake this evaluation formally within the principles of Design Science, the researcher developed an evaluation framework to apply to the process and outcomes in both parts.

3.7 Evaluation Framework

Hevner et al (2004) argue that the evaluation process is important for Design Science research. This is to ensure that the artefact as an outcome of the research has adequate quality and can solve the organizational problem as it was supposed to do.

(Stacie, Deepak & John 2010) have listed the benefits of the evaluation process in Design Science as follows:

1. To confirm that the artefact that has been designed offers a better solution to the current practice. (Nunamaker et al. 1990; Vaishnavi and Kuechler 2008);
2. To give feedback to the researcher about the quality of the artefact and any refinement required (Hevner 2004); and
3. To enable use of a social science research approach to theorise the evaluated artefact (March and Smith 1995).

The evaluation process in Design Science research refers to the development of criteria to assess the artefact performance. March and Smith (1995) view the evaluation process by looking at how well the artefact performs. There are various kinds of artefacts produced from Design Science research. Each type of artefact has specific characteristics. Therefore, evaluation criteria are different. The evaluation of artefacts evaluation requires a purpose (Stacie, Deepak & John 2010, p. 11). The purpose is to answer question such as ‘Does the artefact or theory work?’ and ‘How useful is the artefact?’ In this research both outcomes are artefacts, albeit in different formats with one an ontology-based knowledge-based system and the other a heuristic analysis based on the application of an algorithm.

March and Smith (1995) mentioned that there are four outcomes from the Design Science process. Therefore, the evaluation criteria can be different (March & Smith 1995). These criteria include:

- Criteria use to evaluate constructs involves completeness, simplicity, elegance, understandability, and ease of use. However, Venable (2010) in his research found that the effort and elegance of the system has less importance compared with other issues such as novelty of the new design, simplicity or clear understanding of the system (Venable 2010).
- The criteria used to evaluate models by looking to see how the model matches the real world phenomena, completeness, detail, robustness and internal consistency.
- The criteria used to evaluate methods are operationality, efficiency, generality, and ease of use.
- The criteria used to evaluate instantiation consider efficiency, effectiveness and how the artefact impacts both the environment and users (March & Smith 1995, p. 261).

Hevner et al. (2004) and (Hevner & Chatterjee 2010b) have summarised the normal design evaluation methods used in artefact evaluation (Table 3.4). They have identified that different types of artefacts require different kinds of evaluation. This is because the artefacts have different specific characteristics. However, the framework to evaluate still needs to address common elements of the designed artefacts for example efficacy, useability, efficiency, effectiveness etc.

Table 3.4 Evaluation methods of artefacts in Design Science

1 Observation	Case Study: Study artefact in depth in business environment
	Field Study: Monitor use of artefact in multiple projects
2 Analytical	Static Analysis: Examine structure of artefact for static qualities (e.g., complexity)

	Architecture Analysis: Study fit of artefact into technical IS architecture
	Optimization: Demonstrate inherent optimal properties of artefact or provide optimality bounds on artefact behaviour
	Dynamic Analysis: Study artefact in use for dynamic qualities (e.g., performance)
3 Experimental	Controlled Experiment: Study artefact in controlled environment for qualities (e.g., usability)
	Simulation. Execute artefact with artificial data
4 Testing	Functional (Black Box) Testing: Execute artefact interfaces to discover failures and identify defects
	Structural (White Box) Testing: Perform coverage testing of some metric (e.g., execution paths) in the artefact implementation
5 Descriptive	Informed Argument: Use information from the knowledge base (e.g., relevant research) to build a convincing argument for the artefacts utility
	Scenarios: Construct detailed scenarios around the artefact to demonstrate its utility

Source: Hevner et al (2004) (Hevner & Chatterjee 2010b)

In a similar and confirmatory way (Stacie, Deepak & John 2010, p. 15) have proposed evaluation criteria for artefact evaluation as follows:

- Plausible: used to evaluate how sensible the artefact is, considering the current understanding of the domain. The plausible evaluation can be done by domain experts (Alexander 1979), as they have ability to view and comment on the solution (Stacie, Deepak & John 2010).
- Effectiveness: used to evaluate how the artefact is used to address the problems and to recommend solutions to the problem.
- Feasible: used to evaluate the operationality or implementabity of the artefact, in other words to ensure that the artefact works and if there is any articulating condition, it has to be identified (Stacie, Deepak & John 2010).

- Predictive: used to evaluate if the artefact gives the result as it is expected to. Even if the artefact using conditions are varied, the artefact should generally give the same result (Stacie, Deepak & John 2010).
- Reliable: in various environments, does the artefact still give the same result.

Goodhue (1995) has mentioned that one of the ways to evaluate a system is to let users evaluate the system. However, researchers have criticised this in that this method is lacking in theoretical support. Goodhue (1995) has found that to evaluate the new system by users involves other factors. This includes tasks that are associated with the system. Users look at how the systems as tools are going to help them perform their tasks. (Goodhue 1995). He has proposed 'task-technology fit' (TTF) for a user evaluation scheme with 12 dimensions of TTF. These are:

1. Lack of confusion
2. Level of detail
3. Meaning
4. Locatability
5. Accessibility
6. Assistance
7. Ease of use
8. System reliability
9. Accuracy
10. Compatibility
11. Currency
12. Presentation

In essence they fit into the same categories of Hevner et al. (2004) and Stacie et al, (2010) described above.

Venable (2010) has studied the on-going debate about the quality of Design Science research by surveying scholars who have published, reviewed and edited Design Science research papers. The participants were asked to rate the importance of the stated issues from most important (10) to not important (1). The questions related to artefact evaluation found that application of methods varied in importance:

- Evaluating the utility of the designed artefact for solving the problem to be addressed had a mean = 8.35
- Evaluating the efficiency of the design artefact had a mean = 6.35
- Evaluating the efficacy of the designed artefact in a realistic setting had a mean = 7.11
- Quantitatively measuring the utility, efficiency, or efficacy of the designed artefact had a mean = 5.74
- Evaluating the designed artefact in comparison to other extant solutions to the problem had a mean = 7.37
- Evaluating the designed artefact for side effects (undesirable or desirable) had a mean = 6.12

The participants rated some aspects as less important that others, but all appear significant for evaluation. For example, evaluating the efficiency of the design artefact is less important than evaluating the efficacy of the designed artefact in a realistic setting (Venable 2010). Furthermore, Venable's research showed that the common call for measured evaluation was not universally supported. The researcher's surveys emphasised the value of quantitative evaluation. This can also mean the effectiveness and efficacy of the design artefacts can be evaluated qualitatively.

Nunamaker et al. (1990, p. 101) have proposed five criteria that are essential to proper evaluation:

1. The purpose is of actual phenomena and is clear.
2. The results make a significant contribution to domain knowledge.
3. The result can be tested against objectives and requirements.
4. The result offers a better solution compared to existing practice.
5. Knowledge gained can be generalized for future use.

Others broaden the perspective and a requirement of evaluation in Design Science Dalkir (2005) has needs to be assessed when used to avoid the 'garbage in garbage out' problem. These qualities needing assessment include accuracy, readability/understandibility, accessibility, currency, importance, reusability and credibility (Dalkir 2005; Tan, HC et al. 2010). Markus et al. (2002) argue that there are eight verification requirements. These include competency, completeness, consistency, correctness, testability, relevance, usability and reliability. If the quality of the knowledge that is going to be stored in the system has been assessed, we can believe that the quality of the knowledge when users retrieve will have quality also.

Stabb et al. (2001) argue that feasibility is essential in order to determine success or failure of the system being developed. A feasibility study helps developers identify problems and opportunities in potential solutions. However, feasibility should be carried out before starting the building process (Staab et al. 2001).

All of the criteria discussed above have been collated and refined into an evaluation framework for the artefacts developed in this research. Table 3.5 lists the evaluation criteria to be used and their source and the forms of evaluation to be adopted as part of the research process.

Table 3.5 Evaluation Framework

Evaluation Criteria	Source of the criteria	Forms of Evaluation - Artefact 1 – the Knowledge-Based System	Forms of Evaluation Artefact 2 – the Heuristic modeling solutions
Functionality	(Dalkir 2005 Hevner, et al. 2010; Hevner, et al. 2004; Nunamaker, Minder & Titus 1990; Venable 2010)	Observation: Case study Description: using Scenarios, and Testing using demonstrations, and interviews,	Analysis using algorithms and optimization
Solve the problem by offering better solution	(Dalkir 2005 Hevner, et al. 2010; Hevner, et al. 2004; Nunamaker, Minder & Titus 1990; Venable 2010)	Observation: Case study Description: using Scenarios, and Functional Testing using demonstrations, and interviews,	Analysis using algorithms and optimization
Quality	(Dalkir 2005 Hevner, et al. 2010; Hevner, et al. 2004; Nunamaker, Minder & Titus 1990; Venable 2010)	Observation: Case study Testing: using evaluative interviews	Testing: using evaluative interviews
Efficacy	(Venable 2010, Hevner, et al. 2004)	Observation: Case study Informed argument	Testing: iterations using evaluative interviews
Performance	(Venable 2010, Hevner, et al. 2004)	Observation: Case study Description: using Scenarios, and Functional Testing using demonstrations, and interviews,	Description using informed argument and Analysis using algorithms and optimization
Reliability	(Goodhue 1995; Hevner, et al. 2010; Hevner, et al. 2004; March & Smith 1995; Stacie, Deepak & John 2010)	Observation: Case study Description: using Scenarios, and Testing using demonstrations, and interviews,	Analysis using algorithms and optimization
Consistency	(Goodhue 1995; Hevner, et al. 2010; Hevner, et al. 2004; March & Smith 1995; Stacie, Deepak & John 2010)	Observation: Case study Experiments and testing	Analysis using algorithms and optimization and dynamic analysis
Effectiveness	(Goodhue 1995; Hevner, et al. 2010; Hevner, et al. 2004; March & Smith	Observation: Case study Informed argument	Analysis using algorithms and optimization

	1995; Stacie, Deepak & John 2010)	Description: using Scenarios, and Testing using demonstrations, and interviews	
Accuracy	(Goodhue 1995; Hevner, et al. 2010; Hevner, et al. 2004; March & Smith 1995; Stacie, Deepak & John 2010)	Observation: Case study Functional Testing Informed argument	Analysis using algorithms and optimization Testing: iterations using evaluative interviews
Predictive (Always give the same solution when use)	(Goodhue 1995; Hevner, et al. 2010; Hevner, et al. 2004; March & Smith 1995; Stacie, Deepak & John 2010)	Observation: Case study Structural testing	Analysis using algorithms and optimization Informed argument
Feasible	(March & Smith 1995)	Observation: Case study Interview, questionnaire	Testing: iterations using evaluative interviews Informed argument
Ease of use	(Dalkir 2005; Goodhue 1995; March & Smith 1995)	Observation: Case study Interview, questionnaire	Testing: iterations using evaluative interviews
Presentable	(Dalkir 2005; Goodhue 1995; March & Smith 1995)	Observation: Case study	Testing: iterations using evaluative interviews
Usability	(Dalkir 2005; Goodhue 1995; March & Smith 1995)	Observation: Case study	Testing: iterations using evaluative interviews
Understandability	(Dalkir 2005; Goodhue 1995; March & Smith 1995)	Observation: Case study	Testing: iterations using evaluative interviews
Simplicity	(Dalkir 2005; Goodhue 1995; March & Smith 1995)	Observation: Case study	Testing: iterations using evaluative interviews
Level of completeness	(Goodhue 1995; Hevner, et al. 2004; March & Smith 1995)	Observation: Case study Testing using demonstrations, and interviews	Testing: iterations using evaluative interviews Informed argument
Quantitatively measurable	(Hevner, et al. 2010; Nunamaker, Minder & Titus 1990; Venable 2010)	N/A	Analysis using algorithms and optimization Informed argument
Testable against all requirements	(Hevner, et al. 2010; Nunamaker, Minder & Titus 1990; Venable 2010)	Observation: Case study Testing using demonstrations, and interviews Description: using Scenarios, and	Analysis using algorithms and optimization Informed argument

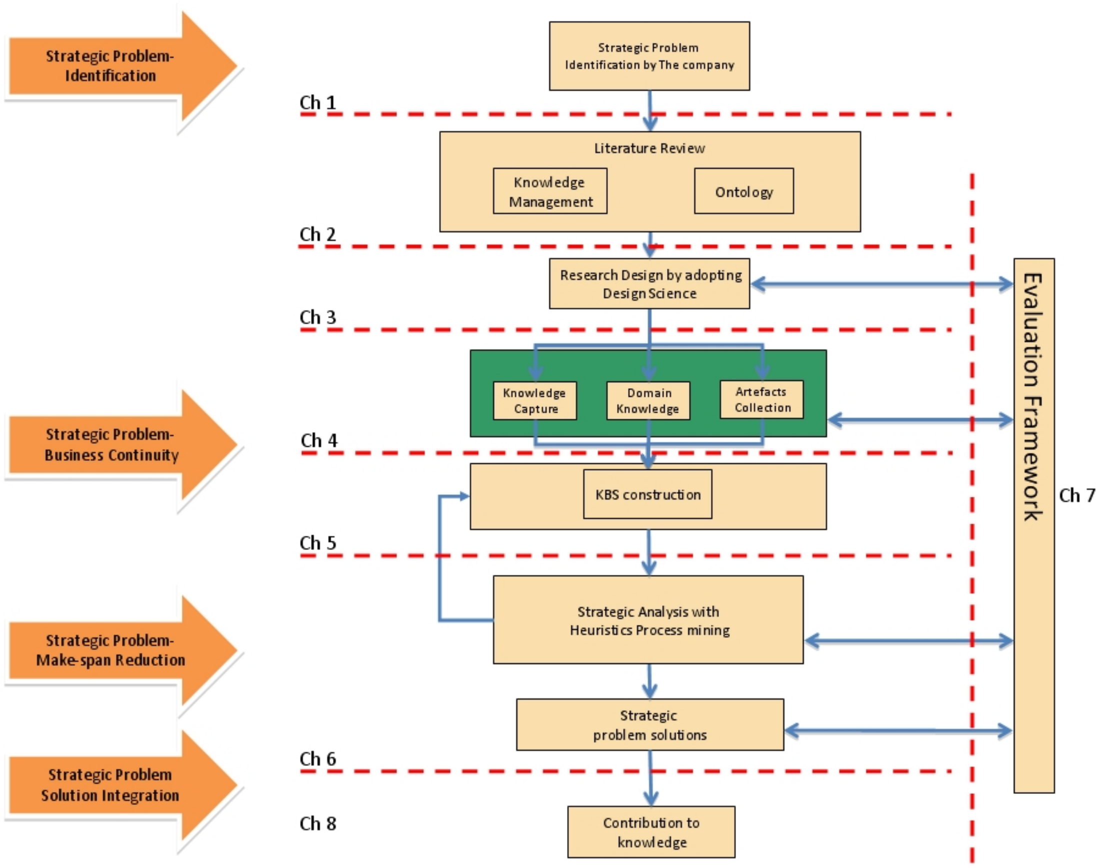
		Testing using demonstrations, and interviews	
Plausible (sensible)	(Stacie, Deepak & John 2010)	Observation: Case study Testing using demonstrations, and interviews	Analysis using algorithms and optimization Informed argument
Side effects	(Venable 2010)	Observation: Case study	Observation: Case Study
The process is contributing to knowledge	(Nunamaker, Minder & Titus 1990)	Observation: Case study	Observation; Case Study

The evaluation framework is used then to evaluate the outcome from both the first part of Design Science research, which is the product development knowledge-based system, and the outcome from the second part which is the solution form Heuristic Process Mining.

3.7 Conclusion

This research uses the principles of Design Science to develop and evaluate a knowledge-based system as an artefact to capture and codify both tacit and explicit knowledge that exists in the Company files and in the expert knowledge of the engineers and executives of the Company. This artefact is evaluated against the Company's stated requirement to maintain business continuity by capturing and reusing the engineers' practical knowledge within a determined evaluation framework. The second part of the research uses a heuristic process mining technique to mine that knowledge and apply an algorithm to eliminate unnecessary tasks in the design, build, testing process of products in the Company. This too is evaluated using an evaluation framework. The next chapter (Chapter 4) describes the development of the principles underpinning development of the knowledge-based system.

Chapter 4: Development of the engineering knowledge management system - designing and building the artefact



4.1 Introduction

This chapter demonstrates the research behind, and therefore how, the engineering knowledge management system for the Company was developed. This chapter describes the research processes used to collect the artefacts and other explicit knowledge in the Company; and then those used to collect tacit knowledge from the engineers. The chapter then describes how the researcher used a collaborative process with the engineers and the researcher's domain knowledge as a practising mechanical engineer to create an ontology on which to build a knowledge-based system. The Chapter deals with the context in which the system was built, and the methodological underpinnings of the methodology used to both frame and build the ontology for the knowledge-based system.

4.2 Knowledge creation and work processes in the Company

The engineering team consists of five engineers responsible for the cabinet design/build/test process. Two engineers (S1 and S2) are responsible for refrigeration calculation. Another engineer (S3) is responsible for cabinet production, and engineers (S4) and (S5) are responsible for testing procedures. All are involved as a team in design and redesign after testing. Their product design task is to develop refrigerated cabinets, which cool stored products down to specific temperatures all over the cabinet and where overall power consumption does not exceed specific levels stated in the National Standard (AS: 1731, 2003). Cabinet development in this Company is a time consuming task. The design/build/testing periods can vary from four weeks up to one year. The design, build, modification and testing processes are done based on the personal experiences of each engineer and the testing process is based on trial and error.

The first task of the researcher was to understand what happened during the Company's cabinet design and development process and through a series of site visits, interviews and daily observation, develop and then test an understanding of how the Company's processes worked. Cabinets were designed based on a small number of prototypes. When an order for a new cabinet came in one of these was chosen as the base for that order. On some occasions a completely new design was needed. That design, based on the existing prototypes, was constructed by Engineers S3, S4 and S5. Then the new or existing design was tested and modified continuously in a test laboratory.

Every morning the engineers conducted a product development meeting in the laboratory office. The engineers reviewed the cabinet testing results from the previous day. Most of the time there were 4-5 prototype cabinets being tested in the laboratory. They then brainstormed decisions to modify the prototype cabinets. The purpose of cabinet modification was to improve cabinet efficiency to approach the required levels in the National Standard. The decisions made were a collective of the domain expertise of each engineer. Engineer S1 was responsible for the application of refrigeration theory and calculations. Engineers S3, S4 and S5 then evaluated whether the idea could be implemented from both a production and testing point of view. Often, the design ideas were limited in terms of the production process or from a testing procedure perspective. The engineers then “constructively argue” (S3) for an optimum solution to emerge in the modifications for that day. These modification ideas are also derived from the group’s experiences from previous designs, builds and testing processes. For example, the engineers knew that if they covered the holes on the left hand side of the rear duct panel cooled air will be supplied more onto the right side of the cabinet. This will also lower the temperature of the M-package (test unit) on the right side of the cabinet. This particular knowledge did not come from theory. The knowledge derived from the results of their previous testing.

In another example, from the production aspect, previous experience of design limitations told the engineers that changing the rear duct panel was a time consuming task. This is because it is located at the back of the cabinet and all of the cabinet assembly had to be taken out to gain access to this rear duct. Therefore, the engineers tried not to change the rear duct panel. Instead the engineers often tried to modify the rear duct panel structure or modify other parts for the required result. If the result appeared not as they expected then they would consider changing the rear duct panel, but it was costly and took significant time. This was their created tacit knowledge, one example of tacit knowledge constantly being generated in these meetings everyday. This group generated the very specific engineering knowledge for the products and, therefore, the engineering team’s know-how. These important forms of tacit knowledge were generated during the product development meetings but had not been recorded at all. It is crucial to capture and re-use this knowledge as part of meeting the Company’s strategies.

The testing laboratory consisted of a testing office where computers were installed and where the engineers had their product development meetings. On both sides were 13 testing bays, each bay was a temperature control room where, after initial design and build, the testing cabinet was installed. Each cabinet was attached with a number of measuring devices including thermometer probes connected to M-packages in the cabinet, refrigerant pressure gauges, refrigerant flow meters, refrigerant temperature gauges, and electrical power measuring gauges. These parameters were continuously measured and recorded in specific software in the computers in the testing office.

Every morning two of the engineers noted the results parameters from the computer and wrote them manually onto A3 sheets of paper, one for each cabinet case and posted them on a white board in the testing office for review in the morning meeting. The results included the temperature of the M-package on every shelf, the cut-out and cut-in temperatures, refrigerant pressure and electrical energy consumption. Once more modifications emerged from the engineers discussions, modifications were then made and the cabinets run for another 48 hours. The process was repeated iteratively until the expected M-package temperature and the energy consumption of the cabinet met the National Standard. The Company's product development process is shown in Figure 4.1.

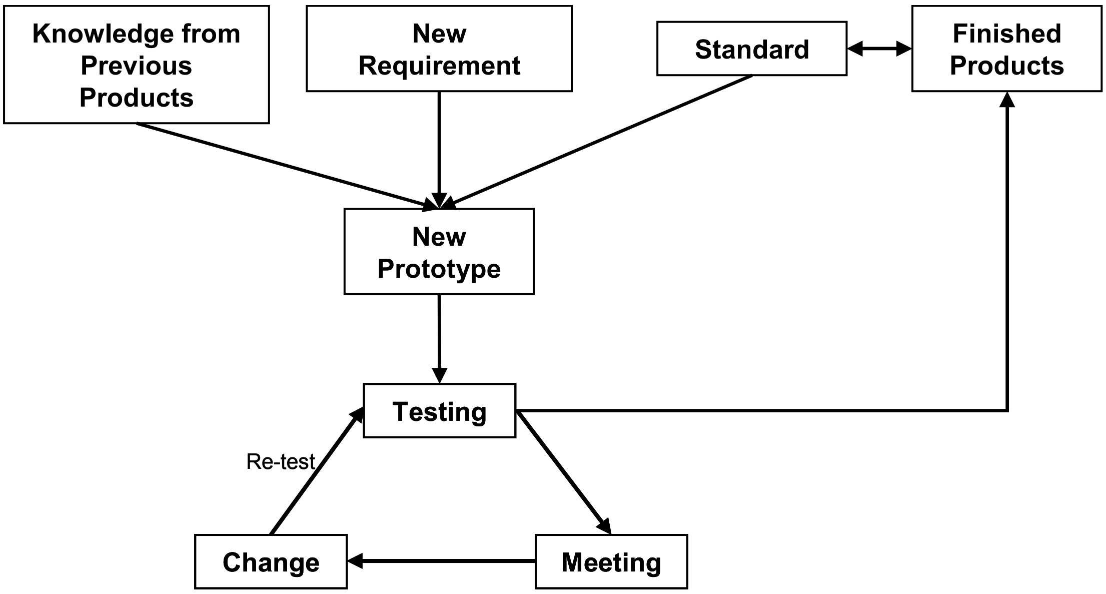


Figure 4.1 The Company product development process

There were four places in the Company where the engineer's product development knowledge and information was stored. The testing measurement parameters were stored in the computer in the testing office. This part was mainly data associated with application of their domain knowledge. The testing log sheets were stored with the testing reports in drawer cabinets in the main office. Knowledge embedded in these documents represented cumulative knowledge now documented in various formats. The third storage set was the design plans and product documentation stored in the COOs office and made up of sketches, CAD drawings, specific measurements and production schedules. The final knowledge storage identified by the researcher was in the cabinets themselves, the result of the specific practice of the engineer's knowledge. However, there was no link in the Company to connect these four sources of knowledge together, which could lead to knowledge reuse and sharing. The engineers admitted that each new product started afresh. The previous designs and data collected and the knowledge stored were rarely, if ever, referred to.

Another dimension to the knowledge creation processes in the Company related to their ongoing knowledge creation in the meetings reported above. The engineers rarely re-used the information and knowledge in the stored reports because the data was kept in different places and in formats that were difficult to access. The testing log sheets contained crucial knowledge about cabinet testing, recorded in hand writing and on their admission, nearly impossible to re-use. The time pressure on the engineers was also a factor that discouraged them from properly capturing their knowledge and making it accessible. The significant missing element was the tacit knowledge that had not been recorded at all during the cabinet testing process, either from individual or from the team meetings. The engineers just remembered everything they had done and the results that came from those actions. Every morning in the product development meeting, the engineers recorded only the finalised outcome of the modification task from their brain storming process. However, the researcher observed many times in these meetings, that the outcomes derived from the group discussions and were not recorded. The researcher observed many meetings over a six-month period and noted that new knowledge was constantly being generated from each engineer's store of experience and tacit knowledge and was not captured. This could pose a significant risk to the Company should any engineer leave the organization. Their knowledge would be lost with them, as would the capacity to train new engineers in that knowledge. For business continuity the Company CEO recognised the need to start capturing their engineering knowledge, both everyday experience knowledge or tacit knowledge and make existing explicit knowledge accessible.

Technical tacit knowledge, however, is difficult to capture (Chapter 3, Section 3.5). Tacit knowledge often happens here and there during a process. To codify this knowledge and write it down as a note is often impracticable. However, engineers reading bits and pieces from various notes from all over the place might not give the knowledge that they want. Tacit knowledge, like explicit knowledge in documents, plans etc, needs to be kept in a specific structured form, in essence an ontology. Structural knowledge stored will help the users find the answers needed when needed. This is 'just in time' type of knowledge (Bartholomew 2008). Instead of the engineers recording whole reports or articles, structured knowledge can be retrieved for the topic they need in a rapid access form. The Company needed a system that would store explicit knowledge, capture and store tacit knowledge, and link them together to enable "just in case" type knowledge "for new engineers to browse for broad topics about the cabinet testing procedure such as the standards, assembly parts drawing and testing reports (COO)".

In the world of high business competition the Company needed to deliver their products to the market faster and with a competitive price. For the Company to gain competitive advantage in the refrigeration industry in Australia they had to be able to develop their products in a shorter time period. This shorter product development process should, the CEO believed, result in cheaper production costs. Explicit knowledge then needed to be identified and tacit knowledge needed to be captured and linked for the engineers to share and reuse their knowledge in their product development process. The remainder of this chapter demonstrates how knowledge was captured and how the knowledge management system was constructed.

4.3 Conceptual underpinning of knowledge systems

4.3.1 Knowledge Management Systems

Effective knowledge management can determine corporate productivity, maximize market share, promote customer loyalty, improve product sales, service quality etc (Wu, J et al. 2010). To carry out effective knowledge management requires a knowledge management system as a tool. Alavi and Leidner have determined that a knowledge management system is ‘a class of information system applied to managing organizational knowledge’ (Alavi & Leidner 2001, p. 114). A knowledge management system uses IT or computer-based software as a tool to facilitate a knowledge repository, knowledge sharing, knowledge retrieval, knowledge transfer and leverage their knowledge resource in the organization (Alavi & Leidner 2001; Taxén 2010; Wu, J et al. 2010). IT-based systems include; organizational database(s), web-based ontology, knowledge-based system, and software available in the market such as Business Intelligence (BI) from IBM, Lotus Notes, SharePoint, and Groupware. The system assimilates knowledge identifying, managing, creating and sharing organizational knowledge to help workers find ‘just in time’ answers to business problems. The organization’s knowledge includes business policies, procedures, documents, databases and the experiences of employees (Leung 2005; Rah, Gul & Wani 2010). Knowledge management systems have also been viewed as a means for communication (Alavi & Leidner 2001; Goodson 2005; Gruber 1995). Apart from providing a repository of knowledge in an organization, knowledge management systems have also been used as a training system for new employees (Štrach & Everett 2006).

An example of an IT-based knowledge management system is Aurora Health Care, who implemented a knowledge management system to facilitate health care service to a community in Wisconsin (Ginter & Root 2010). The knowledge categories relevant to each community health service were initially identified. Knowledge in each category was captured and used in a knowledge-based system to store and share organizational knowledge in electronic form. The Aurora employees mentioned that it was crucial to have a knowledge management system to leverage knowledge from inside and outside organization to facilitate their process (Ginter & Root 2010). The system was supported by the parallel application of quality management principles such as Six Sigma, statistical process control, Baldrige Criteria and LEAN principles. In another example Rolls-Royce, the world’s leader in jet engine manufacturing, has implemented a knowledge management system called SPEDE. The system provided effective access to manufacturing process information and captured lessons learned during the process (Milton, N et al. 1999).

One of the common tools used in knowledge management system is a knowledge-based system. The system should be able to facilitate identified organizational knowledge capture and store the knowledge in each specific category. This will be detailed in next section.

4.3.2 Knowledge-based systems

Whereas knowledge management systems are often general and focus on collecting, storing and using knowledge organisation-wide, a 'Knowledge-based system is computerized system that uses knowledge about some domain in order to deliver a solution concerning a problem' (Ammar-Khodja, Perry & Bernard 2008, p. 90). A knowledge-based solution that is derived from the system should be the same as when an expert in the domain knowledge uses when they encounter the problem themselves. The knowledge-based system is used to capture domain knowledge and help users solve specific problems (Kim, M, Kim & Suh 2009). A knowledge-based system is an IT system which has been designed to store expert's knowledge to help the expert re-use their knowledge to solve specific problems (Ammar-Khodja, Perry & Bernard 2008; Gennari et al. 2003). Knowledge-based systems constructed by knowledge engineering model the domain knowledge and other attributes into the knowledge-based system (Ammar-Khodja, Perry & Bernard 2008). The domain knowledge mentioned in this research is about the product and the engineering process. Researchers have defined knowledge-based engineering differently (Ammar-Khodja, Perry & Bernard 2008; Chapman & Pinfold 1999; Fan & Bermell-Garcia 2008). For example, Fan and Bermell-Garcia stated that a knowledge-based engineering system is a special tool used in the engineering design process. Ammar-Khodja et al. (2008) viewed knowledge-based engineering as 'being an engineering methodology in which knowledge about the products, techniques used to design, analysed and manufacturing a product, is stored in a special product model' (Ammar-Khodja, Perry & Bernard 2008, p. 91). However, all of the definitions mentioned are about the processing of product engineering processes. The purposes of the knowledge-based system in this research are to also store domain knowledge to help the domain engineer solve product design problems and to retain the organization's knowledge for business continuity. A knowledge-based system consists of an ontology and it constituent parts. However, in reality the terms knowledge-based and ontology are very similar and difficult to distinguish (Noy & McGuinness 2000).

4.3.3 Ontology

Ontology use has been particular successful in various businesses. These include the biomedical, medicine, building industry and food industries (Milton, S, Keen & Kurnia 2010).. In the philosophical sense ontology refers to 'the nature and structure of reality'. Aristotle had studied ontology centuries ago (Guarino, Oberle & Stabb 2009). The other definition derives from computer science. This is the most cited definition of the ontology which is 'an explicit specification of a conceptualization.' (Gruber 1993; Guarino, Oberle & Stabb 2009). Ontology is knowledge representation of an interest domain use for sharing conceptual terms of explicit knowledge in organizations (Baker 2009; Kuntz 2006). In ontology the conceptualization is a defined term of the domain knowledge and the relationships. Conceptualization refers to 'an abstract model of how people think about things in the world, usually restricted to a particular subject area' (Uschold & Gruninger 2004, p. 59). The reflective capacity of ontology is high because it models reality. Ontology development is a process of breaking down concepts in the domain into smaller objects. Then defined objects are used to form a hierarchy of relationships with other objects in the domain (Gero & Kannengiesser 2006; Zhanjun, Maria & Karthik 2009). The ontology then is a practical concept, defined as a well-structured organization of concepts that covers the processes, objects and attributes of the interest domain. (Zhanjun, Maria & Karthik 2009). Interlinking of the knowledge items changes the concept from a knowledge-oriented to a content-oriented view. This contented-oriented view helps the user to access knowledge needed more easily (Steffen et al. 2001).

In Engineering, ontology has been used to model unstructured engineering documents, and facilitate information retrieval (Zhanjun, Maria & Karthik 2009). Ontologies are used to specify terms, the meaning of terms (semantics) and the relationships with other terms for a specific slice of reality or domain (Guarino, Oberle & Stabb 2009; Milton, S, Keen & Kurnia 2010; Smith 2004)

There was a significant amount of textual and numerical information generated during the Company's product development process. This information had been stored in different forms and in different places. The engineer's group meeting effectively acted to create tacit knowledge through collaboration between members of the team. This collaboration enabled sharing of the existing knowledge and generation of new combined knowledge. As in previous research (Taxe'n 2010), product development meetings were complex and contained a large amount of knowledge fragments. Based on previous applications and the arguments of (Milton, S, Keen & Kurnia 2010), ontology was considered advantageous in application to business in that it could be structured to store knowledge from various sources. In this research the ontology has been applied to store captured tacit knowledge from the engineers, together with the explicit knowledge from the Company artefacts. This use of ontology was considered the best way to help the Company retain their engineering expertise and help the engineers share and re-use their knowledge.

Both types of organizational knowledge, tacit and explicit, have been identified in the Company during the data collection process. This process, described in Chapter 3, Section 3.5, used multiple methods to capture the knowledge and provide the basis to build the knowledge–based system.

4.3.4 Methods for building a knowledge-based system

Knowledge-based systems facilitate knowledge sharing, and re-use in organization. The tool used in this research is ontology. There are a number of software packages (Ontology Editors) available for ontology construction in the research community. Each ontology editor uses its own language. However, some ontology editors have translators to enable translation from one to another language that can be read with other software. Most ontology editors have been developed by universities: for example, the University of South California developed *Ontosaurus*, which uses Loom as the language; *Common KADS* was developed by the University of Amsterdam; *OntoEdit* was developed by the University of Karlsruhe; others include MIKE (Studer, Benjamins & Fensel 1998), *Loom, WebODE* and *Protégé*. This research chose *Protégé* as an ontology construction tool. Protégé has been developed by experts from Stanford University since 1987. As open source software, it was available at no cost and could be easily applied in the Company context. The user community was growing and mailing list support was available, with 153,642 users registered (viewed on the 11th of October 2010) (Stanford University 2009). A *Protégé* conference was held every two years. *Protégé* used local installation, which meant the program could run on any computers with the software installed, unlike other software such as *OntoEdit* or *WebODE* that had to run through servers through the internet (Mizoguchi & Kozaki 2009). As it was available through open source and evaluation showed it would be easy for the Company employees to use, it was adopted for building the artefact. Ease of use, ease of application and the availability of support were primary reasons for the choice of Protégé for the development of a tool to solve the Company's problem of maintaining business continuity though capturing company and expert knowledge, and then making it both available and useable.

Researchers have proposed a number of methods of building knowledge-based systems with an ontology (Borst 1997; Delcambre et al. 2005; Gruber 1995; Kim, H & Grobler 2007; Noy & McGuinness 2000). Different types of ontology have different construction methods. The number of steps in each ontology development process also vary. This research uses a combination of ontology development processes from a number of researchers (Delcambre et al. 2005; Gruber 1995; Kim, H & Grobler 2007; Noy & McGuinness 2000).

a) First step: Ontology purpose identification

A product development ontology begins with identifying the purpose of the ontology (Noy & McGuinness 2000; Uschold & King 1995). This ontology purpose identification step overlaps with theme and scope identification (Li, Z., Raskin & Ramani 2007). Sure et al. (2009) also mentioned target focusing in the feasibility stage. This is because purpose, theme and scope of the ontology determine the structure of the ontology. The purposes of the Company's product development ontology were to retain expert knowledge for business continuity and to re-use expert knowledge to reduce excessive product make-span. These two purposes shaped the structure of the ontology.

The first purpose of developing the Company's ontology was to frame a structure to capture and retain organizational knowledge in a form able to be reused. The first task was to identify what kinds of knowledge the organization wanted to retain. It was immediately obvious in interviews with the CEO and COO that the Company did not really know what the engineers knew. Their engineering expertise was obvious and vitally important for the Company, but their knowledge was not captured in any form that could be used by anyone else. The CEO and COO also noted that the Company had knowledge stored in CAD drawings, plans, brochures and reports, stored in various places in the Company, but they were unsure if it was ever used.

The Company's explicit knowledge resided in many locations in their organization. For example, explicit knowledge about their refrigerated display-cabinet products was located in the Company catalogues, in testing reports of the manufactured products and in the actual products designed and built. This explicit knowledge could not be used by itself. The engineers had to combine these knowledge elements together to make the most effective use of the knowledge. For example, the engineers noted the modification tasks they have done to the cabinet during the product development process, using the testing log sheets which hung on the wall in the testing office. All of these testing log sheets had been kept in the engineering office in the main building, but the engineers noted that they rarely referred to them. As the cabinets were being tested in the laboratory, there were significant numbers of parameters being measured and recorded in computers in the testing office. They too were rarely used after the day they were referenced in the product development process. The modification notes in the testing log sheets and measured parameters by themselves could not be used in isolation. This was because the information recorded in the log sheets was static, while what really happened was that the testing process was dynamic. The engineers wrote only what they had done to the cabinet, together with the snapshot of the parameters measured from the cabinet. Therefore, the engineers had to look at these two sources in their product development meetings.

In addition, there was production process explicit knowledge. This knowledge was embedded in the refrigerated cabinet parts production process. There were many parts of the cabinet made in the Company. Each part had drawings and a production procedure. These drawings and process procedures were kept separate from the testing log sheets and the measured parameters stored in the computers. There was a universal view in the Company that this separation meant both knowledge and information loss, because each source of knowledge was being managed by different members in the team. If any engineers left the Company it would take time for the other team member to learn where things are and take over the job. Therefore, these elements of explicit knowledge needed to be captured and stored in a system to retain the organization's knowledge. The system then had to be constructed in a way that answered questions regarding how the organization could retain knowledge. The representation of that knowledge in the ontology needed to reflect the reality of what existed, how it was classified by the engineers and by how they used it.

The other purpose of developing an ontology for the Company was to reduce an excessive product make-span. At the start of the research the time period that the engineers required to develop the refrigerated display cabinets varied from four weeks up to one year. This product development process practice did not reflect knowledge sharing and reuse. The major problem the engineers identified was in the process used. Every morning the engineers had their product development meetings in the laboratory office. In the meetings the engineers reviewed the lab testing results from the previous day. The results include measured parameters from each cabinet. Then the engineers brainstormed possible modifications that could be done to the cabinets being tested. For example, if the temperatures of the M-package on the top shelf did not reach the standard the engineers adjusted the pressure of the refrigerant and the cut-out temperature of the cabinet. Based on the engineers' experience they believed that adjusting refrigerant pressure and cut-out temperature would decrease the temperature of the M-package on the shelf. Most of the possible modification tasks then were derived in this fashion. The engineers then noted only the final solution from the discussion in a testing log sheet. There was no actual record of the processes discussed or the reasons given. All of the modification notes were written in the testing log sheets until each cabinet was completed, ie. when the temperature of the M-package and total power consumption matched the National Standard. The finished cases were then ready to be manufactured.

Following completion of testing, the product was built, a report was delivered to the client and a hard copy customer report was filed in the engineering office in the main building. The electronic file format of the report was also kept in the Company's local network. However, the engineers all mentioned that they hardly ever looked at the reports. Each new cabinet was designed from scratch. They noted that the knowledge created with each new cabinet was kept in different places and in formats difficult to access. To find out what had been done to a particular case at a particular time and what was the result, was nearly impossible. Unable to reuse knowledge from previous product resulting, the engineers repeated many tasks that they had done before. In interviews some of the engineers mentioned that they would like to know 'I did this, this happened … I did that, that happened'. Their existing knowledge management was not enabling them to access the knowledge they needed. Therefore, creating an ontology as a tool for a system to store knowledge from multiple sources in an accessible format facilitated the engineers to both find and then re-use knowledge from previous product developments. The questions that the ontology answered to help the engineers in their product development process were as specific as: 'what happens when the fan speed is changed?' 'What happens with meat cases after the cut out temperature is changed, and is it same as dairy cases?' This was one way to shorten the product development time period because the engineers could recall their practice knowledge. The cabinet testing process was carried out more smoothly when both tacit and explicit knowledge were promptly available for re-use.

b) Second step: Knowledge and knowledge source identification

After the ontology purposes have been identified the literature states that the next step is that knowledge and knowledge source identification have to be carried out (Delcambre et al. 2005; Kim, H & Grobler 2007). Knowledge identification was undertaken to identify knowledge that the engineers needed to include in the ontology to cover knowledge retention and knowledge re-use and for sharing purposes. This knowledge included tacit and explicit knowledge. Explicit knowledge included information from previous products such as:

1. Calculation reports;
2. Manufactured refrigerated display cabinet testing reports, hard copies of which were located in the engineers office and electronic copy of which were located in the Company's local network;
3. Manufactured refrigerated display cabinets testing log sheets which were located with the testing reports;
4. Product catalogues;
5. Production procedures;
6. Measured parameters in the computer in the laboratory office;
7. All of the CAD drawings;
8. Actual refrigerated display cabinets, stored and used in clients' premises; and
9. Customer requirements.

Tacit knowledge sources included: engineering calculations from Engineers S1 and S2, tacit knowledge regarding the production process from Engineer S3, tacit knowledge regarding the testing procedure and operations from Engineers S4 and S5, tacit knowledge from the chief marketing officer who directly met with all clients, and knowledge about the business direction and strategy from the CEO and COO.

c) Third step: Ontology construction

There are numerous activities involved in the ontology development process. Researchers conduct these activities in a different order in their own research. For example, Li et al. (2008) constructed their taxonomies in the previous step and created relationship between these taxonomies in step three. Ontology construction is considered a fourth step in some research (Gennari et al. 2003; Li, Zhanjun, Raskin & Ramani 2008; Pinto, Tempich & Staab 2009; Sure, Staab & Studer 2009). However, they all agree that there are a number of tasks included in this step. These include knowledge capture, creating classes, sub-classes, and *individuals*, and definitions of the relationships of classes. The authors also note that for first timer ontology constructors, knowledge capture or acquisition and class creation cannot be separated. This is because during class construction knowledge engineers often overlook some details. Therefore, doing these two tasks in parallel is a good technique to cover all details in the ontology.

The ontology construction stage involves knowledge modelling. This includes class, sub-class and *individual* determination and relationship modelling. There are three knowledge modelling approaches that are often mentioned by researchers (Delcambre et al. 2005; Sure, Staab & Studer 2009). First, the top-down approach models knowledge by defining concepts or classes and relationships at a generic level then extend that into more specific detail. Second, a bottom-up approach is used when the identified concepts, or concept which has most specific detail, are defined first then acquire further knowledge and the ontology is built in parallel. Last, a middle-out approach is used when the concepts or classes, which are the most important, are defined first, then the remainder of the interested domain knowledge is obtained (Sure, Staab & Studer 2009; Uschold & Gruninger 1996). Each approach uses both generalization and specialization to form the ontology structure hierarchy. In this research a middle-out approach was applied to construct the Company's product development ontology. This was because the structure started with the known information and expanded to cover new information and knowledge throughout the research. Using the data, information and knowledge derived from this approach cannot enable the structure to be predicted. The process is organic and grows. The researcher used the information at hand to form the ontology structure and then expanded that by acquiring more information and knowledge during the research process and investigation, following the method suggested by Sure et al. (2009).

The tool used to construct the Company's product development ontology was *Protégé*, version *Protégé* 3.3.1. The constant growing *Protégé* user's community keeps development of this software to the latest version which is *Protégé* 4.1 beta (Stanford University 2009 viewed 3/11/2010). *Protégé* is a domain-neutral tool. It can be applied in broad range of applications and uses Ontology Web Language (OWL) as an ontology language.

In OWL the biggest element is a class. Class can be categorised into sub-class and sub-class contains the smallest element of the ontology called an *individual.* An *individual* contains one or more specific characteristic that can only be referred to that particular *individual* not to others. Users cannot make a use out of ontology which contains a single *individual*. Otherwise, it is not different from writing everything in the domain interest in a one page document. Normally, an ontology contains hundreds of *individuals*. The element that connects two *individual*s together is called '*Properties'* in OWL and '*Slot'* in Protégé. For example, the *individual* '*Car'* has a property '*has wheels*' that connects to the other *individual* call '*Wheels'*. Classes in OWL and Protégé both refer to the same things which are sets (Horridge 2009) which contain *individuals* that share the same characteristics. For example for the *individuals* '*cars'*, '*sport cars'* and '*convertible cars'*, all of these cars have the same specific characteristics which are engine, body, four wheels, fuel tank, doors etc. Therefore, these *individuals* can be stored in a class '*Car'*. Next, if another *individual* that has an engine, doors, fuel tank and wheels, and its wheels are not tyres, but are metal and this *individual* can only run on the track, this particular *individual* is a train. This train cannot be considered as a member in a class '*Car'* because there are a number of characteristics different from the *individual* 'cars'. Therefore this *individual* '*train'* has to be categorised in its own class instead. However, both classes '*Car'* and '*Train'* are vehicles. Therefore, it can be determined that classes '*Car'* and '*Train'* are sub-classes of a super class '*Vehicles'*. This logic was applied to the knowledge extracted from the engineers in developing the ontology for the Company.

The next step was to build the Company's product development ontology based on these ontology elements. The ontology structure also had to be designed to store knowledge that could serve all defined purposes of knowledge retention, knowledge re-use and knowledge sharing. The ontology development process was a combination of collecting data and developing the ontology iterations. As mentioned previously, this research used multilayered data collection research process and all had to be integrated into the ontology to make relationships easier to identify and use. The application of these principles through a collaborative process of interviews, observations etc, to collect the knowledge, through then codification of the knowledge, system building, discussion and collaborative evaluation with the engineers over a number of iterations, led to a structured knowledge-based system. The structure of that system is described in detail in the next chapter.

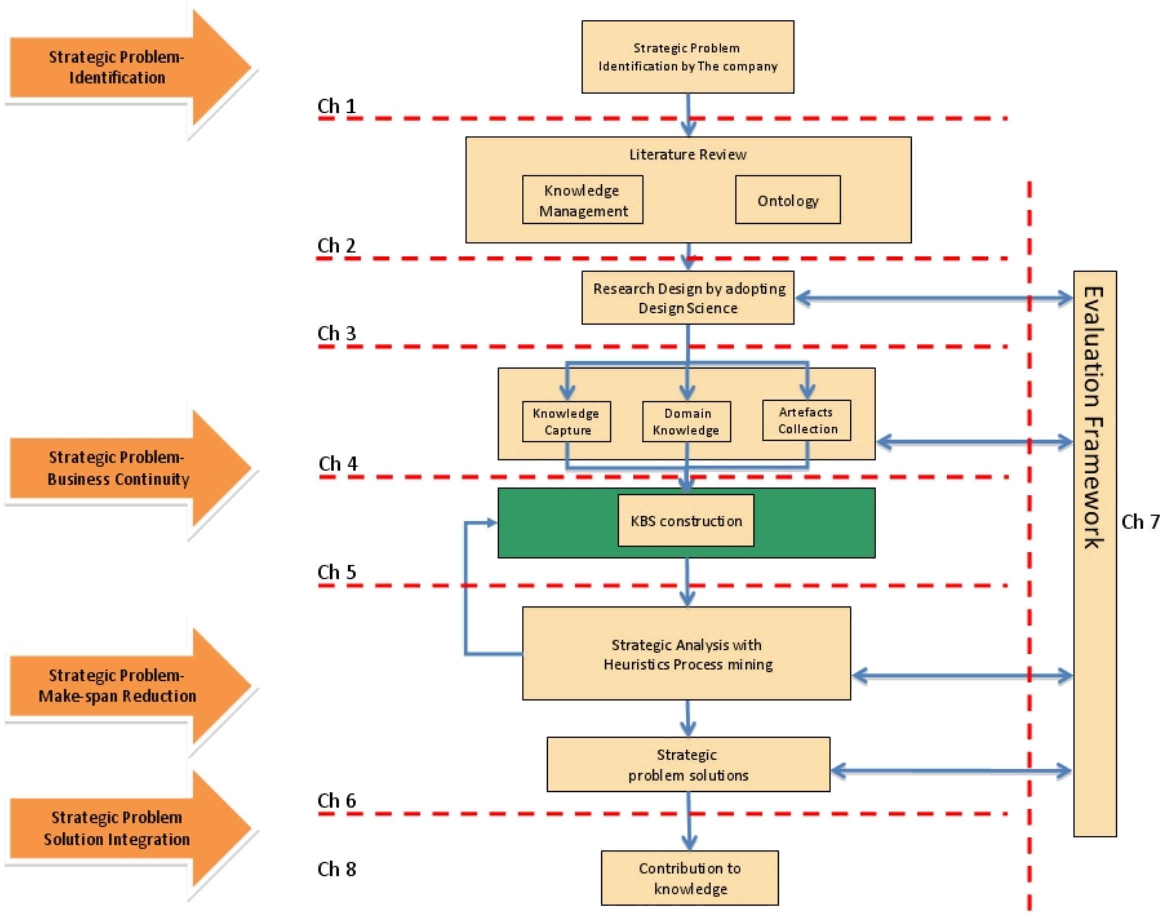
4.4 The system design, build, and develop iterations

The construction of the ontology was an iterative process which derived from the principles of Design Science research and the adoption of the middle-out approach for ontology development. This means the structure of the ontology was formed by what information was gained first and incrementally expanded throughout the research to cover what information was gained next in each iteration. The initial design of the ontology derived from the first set of information that the researcher collected from the factory during first meeting. These included the Company's products classification and the products terminologies. The researcher formed the initial structure of the ontology by creating a class 'Case Model' as a starting point. Details of 'Case Model' class are shown in Chapter 5. Then, the researcher evaluated the initial ontology structure with the engineers in a subsequent meeting at the factory and collected the next set of information. During the second meeting the researcher clarified what has been contained in the ontology to the engineers. The clarification process had helped the researcher to understand the domain knowledge better and help the researcher to correct elements in the ontology. The researcher had been collecting new information and clarified previously collected information on every factory visits. The structure of the ontology was then built up and expanded to cover all of the elements related to the Company's product development process. The details of the ontology construction process are shown in Chapter 5.

4.5 Conclusion

This chapter has described the general ontology construction method. These included the purpose for the ontology in its business context, domain knowledge that the Company required to be put into the ontology and the construction process. The ontology had to be developed to bring together existing explicit knowledge and captured tacit knowledge. The method of ontology construction was middle-out, based in this case, on initial data from the Company. This method was chosen as it enabled the dynamic processes in the Company and the researcher to be comprehensive and flexible. This chapter also has shown how the researcher had conducted the ontology construction process. The artefact that developed from this process and which was delivered to the Company is described in detail in Chapter 5.

Chapter 5 The Artefact - The Company Knowledge-Based System



5.1 Introduction

The chapter describes the system developed and its parts, leading to a description of the whole knowledge-based system designed for the Company. The chapter begins by showing the completed ontology. The ontology construction process started with 'what is known' then expanded to other elements to cover the Company's product development domain knowledge as shown in section 5.2. This chapter shows what information and knowledge that have been used to formed each *individual*, what class that they belong and what relationships that they have with other *individuals*. The chapter also shows how the ontology grows until it reached the complete model. The chapter also demonstrates the ontology structure evaluation through knowledge re-use scenarios based on the structure of the ontology (section 5.3).

The artefact is a key part of Design Science research and is included in detail here because it enables a better understanding of the collaborative research process and the iterative nature of that process. It is also important to give a better understanding of the evaluation process as this is central to determining the quality of Design Science research. The ontology development process used was middle-out creating a complex process of relationship building. It is important to understand these relationships as they significantly impact on the effectiveness of the solution for the Company. It is also important to understand the artefact in detail because it was designed to be transferable to other applications in different business contexts.

5.2 Building the ontology from existing data

5.2.1 The Completed Ontology

The artefact built for the Company as the first part of this research is shown in Figure 5.1 below. This ontology was an operating knowledge-based system enabling the engineers, COO and CEO of the Company to find all relevant knowledge, both explicit and tacit, about the design, building and testing of their refrigeration products. The system could be searched, mined and continually updated with new knowledge.

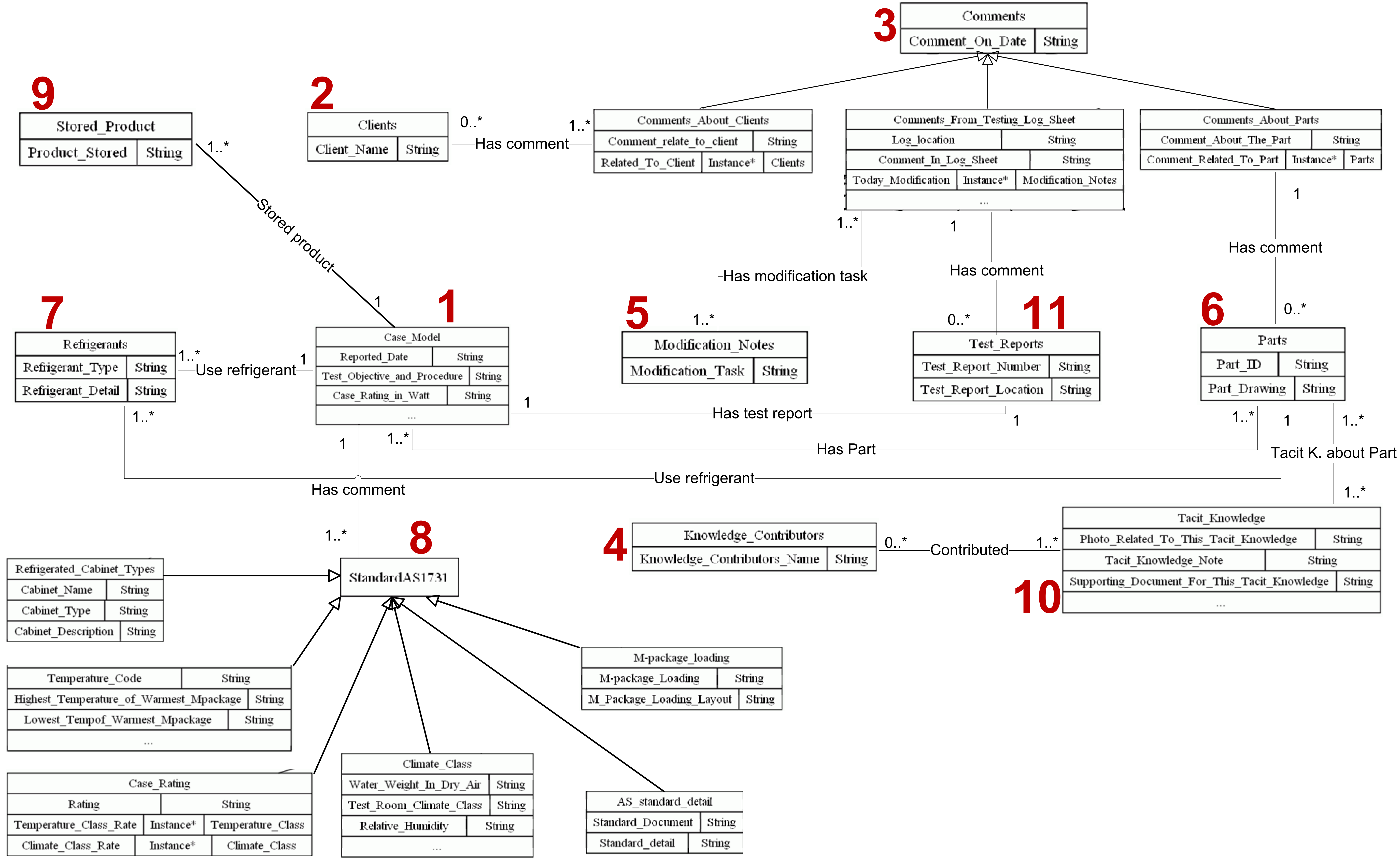


Figure 5.1 Knowledge-based system overall structure

Figure 5.1 show overall structure of the ontology which framed the knowledge-based system. There were 11 main classes in the ontology. Each class contained sub-classes and *individuals* related to them. The summary details are:

1. The *Case Model* class was the class that represented the refrigerated display cabinets that the Company have manufactured. *'Case Model'*, the Company's terminology was used throughout the Company. The Case Model had a number of sub-classes and *individuals* as shown later in the discussion in Figure 5.4
2. The *Client* class represented the clients for whom the Company manufactures cabinets. Each client had their own set of specific requirements as shown later in Figure 5.21
3. The *Comments* class represented all of the comments generated by the engineers during their product development processes. The Comments class contained three sub-classes: comments about clients, comments about parts, and comments from the testing log sheet, detailed later in Figure 5.19.
4. The *Knowledge Contributors* class represented a person who made notes or from whom tacit knowledge was captured. The purpose of this class was to assist new engineers who joined the team so that they could explore 'who knows what' in the Company. This class contained eight *individuals*, representing the engineers in the team, the CEO, the COO and the draftsman, as shown later in Figure 4.31.
5. The *Modification Notes* class represented the modification tasks that the engineers performed to the prototype cabinet during the product development process. This class contained 41 *individuals*. Each *individual* represented a single task, which the engineers could select, when recording their testing processes. Modification Notes is discussed later and is shown in Figure 5.28.
6. The *Parts class* represented all of the assemblies which are made up the refrigerated display cabinets. The Parts class had a number of sub-classes corresponding to the number of parts in the cabinet as shown in Figure 5.23.
7. The *Refrigerant* class represented the different types of refrigerant used in all of the refrigerated display cabinets that the Company manufactures. The

Refrigerant class contained four refrigerant *individuals*. Each *individual* represented the type of refrigerant and its thermodynamic characteristics. These are shown in Figure 5.7 as part of a more detailed discussion.

8. The *Standard AS 1731* class represented formal information about the National Standard AS 1731, with which all of the refrigerated display cabinets manufactured by the Company had to conform. Standard AS 1731 contained sub-classes and *individuals* according to details in each section in the Standard. The detail is shown in Figure 5.11.
9. The *Stored Product* class represented all of the types of commodities that the refrigerated display cabinets were designed to store. The Stored Product class contained six *individuals* who represented six types of products as shown later in Figure 5.8.
10. The *Tacit Knowledge* class represented captured tacit knowledge notes made by the researcher during the knowledge capture process as part of this research. This class contained a number of *individuals*. Each *individual* reflected the tacit knowledge. The numbers of *individuals* in this class kept expanding through the knowledge-based system implementation. Details are shown later in Figures 5.29.
11. The *Test Reports* class represented details of the client reports for each refrigerated display cabinet. The Testing Report class contained a number of *Individuals*. In each testing report each *individual* contained detail about characteristics of each particular cabinet as shown in Figure 5.18.

These classes were formed from an analysis of the key knowledge areas derived from the research when the researcher was embedded in the Company. The researcher developed a conceptualisation of the key knowledge areas, which formed the basis of the work processes of the engineers. These foundation knowledge areas are shown in Figure 5.2. Their development into classes and their characteristics are described in detail throughout the remainder of this chapter

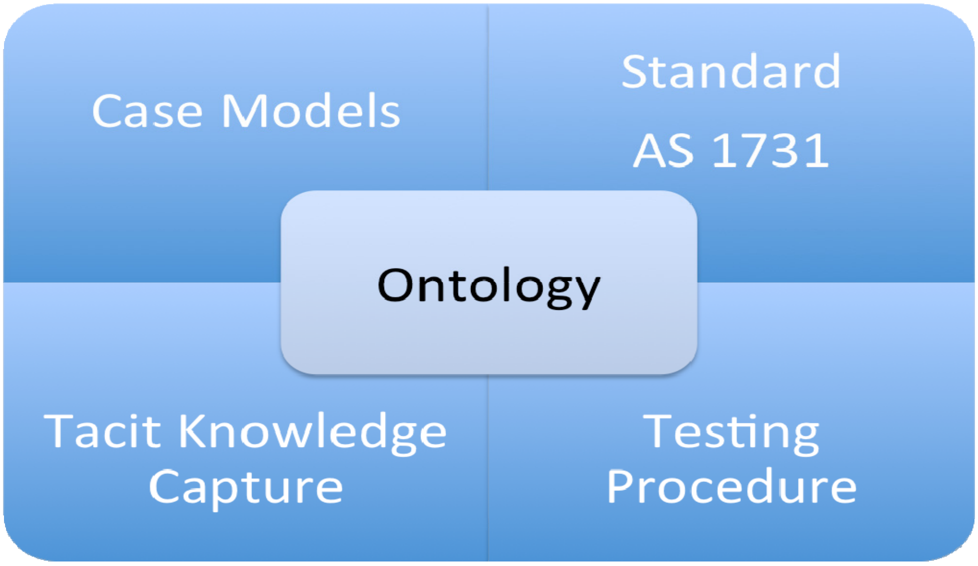


Figure 5.2 Ontology components

The structure of the knowledge-based system had been developed iteratively since the tacit knowledge capture process was conducted as shown in Figure 5.2. The methods used in this KBS structure development included collection of the Company's formal artefacts, interviews (both structured and unstructured), observations and shadowing. In addition the researcher, or knowledge engineer in this case, was a practising mechanical engineer. This facilitated the development of the structure of the ontology development process significantly. The outcome of the research process was a KBS with a structure that facilitated the Company's engineers to capture their knowledge, and to share and reuse that knowledge during the cabinet development process.

The next section provides the details behind each of the classes described above. The ontology was developed from a detailed analysis of the various forms of knowledge existing in the company. This was extracted from company records, from observations of the researcher, from interviews with the engineers, and from scenario testing of each component of the system with the engineers. The ontology developed from research in collaboration with the engineers through an iterative series of developments, designs, builds and evaluation, to produce the artefact described above. This ontology was not created by the research out of context of the Company. Rather, the ontology was developed by researching what the engineers did and what they needed to make the system useful to them.

5.2.2 Detailing the Ontology Building process

Seven cabinet testing reports were initially collected as data to store in the knowledge-based system. This was because seven samples gave adequate data to create the structure for knowledge-based system developed on classification of the knowledge, based on the information given by the engineers. The information found in the seven *individuals* of refrigerated display cabinet design/build and testing related to specified codes for each used in the company: 'GLS G 3 75 DAW, GLS G5 375 PRW and GLR 12 DAC, GLR 12 MTC, GLR 12 MTC, GLS G5 375 MTW and GLD 375 DLC'. Each cabinet could be determined as an *individual*. The Company refrigerated display cabinet codes consisted of three parts. Firstly, the three or four alphabets letters referred to the shape of the cabinet for example, GLS, GLR, GLH, GLD, GLSG and GLS G5, as shown in Figure 5.4. GLS, GLH, GLR and GLD were the code series of the Company's cabinet model. The products were used variously as meat, dairy and/or produce cabinets.

Figure 5.3 Samples of refrigerated display cabinet categorized by cabinet shape.

The next sets of numbers in the products code were the length of the cabinet, for example 12 referred to 12 feet and 375 referred to 375 millimetres in length. The last three alphabet letters comprised either one or two letters. For example in MTC, MT refers to the product that this cabinet stored and C referred to the name of the client who the Company is manufacturing the cabinet for. In an ontology, each cabinet *'Individual'* needed to belong to their class. As the engineers classified the cabinet by its shape therefore, the classes that referred to shape of the cabinet were created here to store cabinet '*individuals*' of their group. For example class *'GED'* contained cabinet *individual 'GED 375 DLC',* class *'GLR'* contains cabinet *individuals 'GLR 12 DAC', 'GLR 12 MTC'* and *'GLR 12 PRC'* and class *'GLS'* contains cabinet *'Individual' 'GLS G 375 DAW', 'GLS G5 375 MTW'* and *'GLS G5 375 PRW'*. As part of the OWL concept *'individual'* and *'class'* classification had to be completed. All of the cabinet type classes have to be defined as sub-classes of a class which represents them. Therefore, the

'CaseModel' was defined as a super-class of cabinet type classes, the fundamental building block of the knowledge-based system (Figure 5.4).

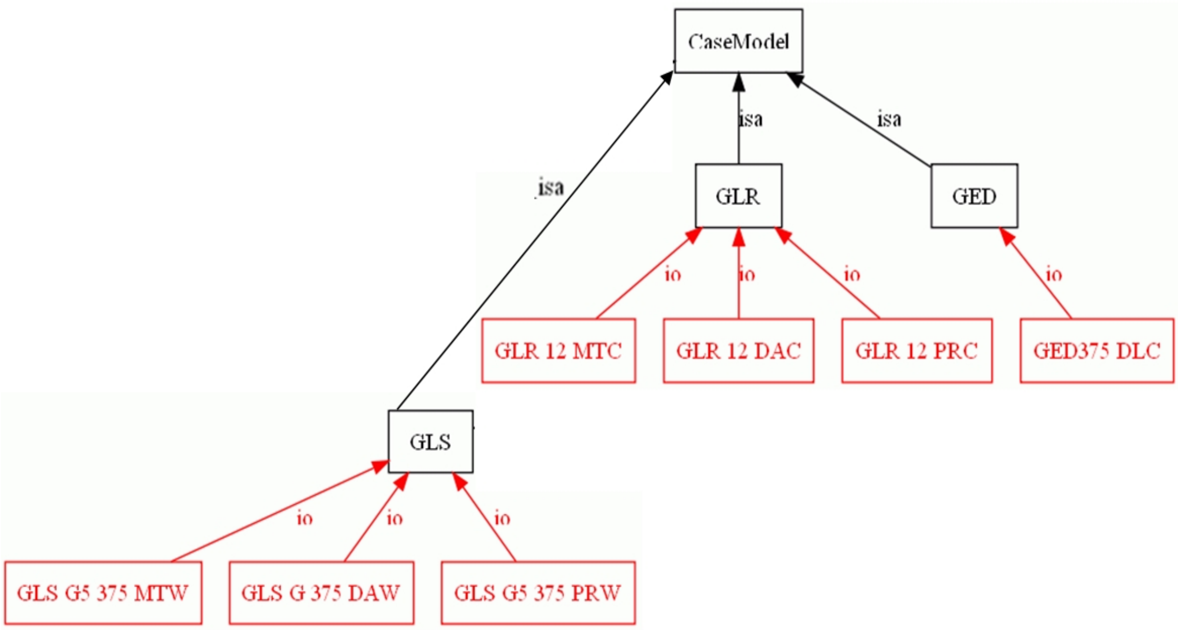
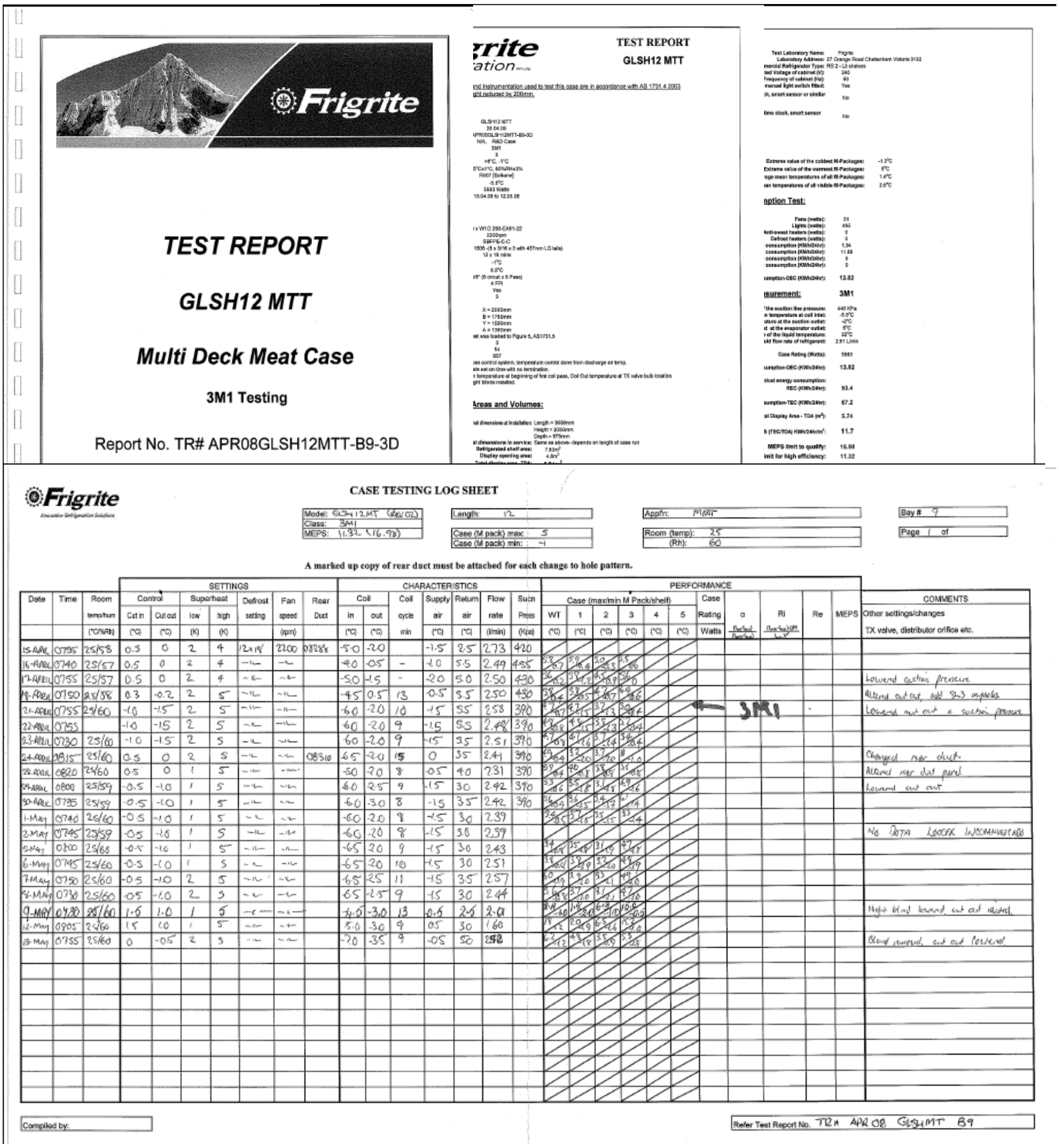


Figure 5.4 'CaseModel' class details.

The super-class '*CaseModel*' had three sub-classes which are '*GLS*', '*GLR'*, '*GLH'* and '*GED'*. Each sub-class contained *individuals* in their cabinet type class. Sharing the same properties in OWL did not mean that every *individual* was the same. *Individuals* could have the same properties. However, each property could contain different values. For example every refrigerated cabinet case had specific characteristics such as the cabinet's dimension length, depth and height and case rating capacity. Data from the collected testing reports showed that cabinet GLR 12 DAC was 3650 millimetres long, 975 millimetres deep and 1500 millimetres high with a 4397-watt rating, while GLSG 375 DAW was 3750 millimetres long, 975 millimetres deep and 2050 millimetres high, with a 5404-watt rating capacity. The next step involved creating all of the properties needed for each '*individual*'s' property determination within a refrigerated display cabinet. The properties determination process required explicit knowledge from the domain experts, in this case from the Company's engineers.

The structure of super-classes, classes, sub-class, *individuals* and their properties had to be created to suit the engineers' knowledge capture, sharing and re-use requirements. The character of the knowledge that the engineers wanted to retrieve was used to determine the ontology's structure. The first set of data collected from the engineers was testing reports.

The example of a cabinet testing report, which is one of many produced by the engineers after the testing process is finished, is shown in Figure 5.5.


Frigrite

TEST REPORT

GLSH12 MTT

Multi Deck Meat Case

3M1 Testing

Report No. TR# APR08GLSH12MTT-B9-3D

CASE TESTING LOG SHEET

A marked up copy of rear duct must be attached for each change to hole pattern.

Figure 5.5 Example of the Company testing report.

The engineers considered the data by classifications into 12 parts in their testing reports. Details of the 12 parts are as follows:

1. Testing detail - information from the National Standard that this particular cabinet case complied with. Details included information such as the cabinet model code, testing report number, serial number, cabinet class, testing room climate class, temperature limit, testing room conditions, refrigerant, case rating and testing period;
2. Case details - details about the physical setting and equipment assembled in the cabinet case. These included, the fan used in this cabinet, fan speed that has been set, refrigerant distributor, defrost setting, control cut-out, control temperature different, valves, coil, fins, heat exchanger, number of shelves, test cabinet location, cabinet package loading, number of lit shelves, number of M-packages, number of filler packages, case control, sensor location, and night blind;
3. Case linear dimensions, areas and volumes of the cabinet;
4. General information including data sources, case airflow, test laboratory name, laboratory address, and commercial refrigerator type, rated voltage, rated frequency and light switch;
5. Temperature test - temperature of the M-packages installed in the cabinet case while being tested, including the maximum coldest, warmest and average mean of the M-package temperature in the cabinet;
6. Electrical energy consumption showed details about the electrical energy that the cabinet case consumed during the testing period;
7. Heat exchange rate measurement showed information about the optimum class rated after the testing process was finished;
8. MEP (minimum energy performance) - the value of the amount of the electrical energy consumed by the total display area of the refrigerated cabinet. The MEP value was not to exceed the energy level stated in the standard;
9. Cabinet section drawings;
10. A number of graph reports, including evaporator temperature, refrigerant pressure, testing room temperature and humidity, M-packages temperature graph during cabinet testing period.

11. The temperature summary table showed the temperature of the M-package in various locations on each shelf in the cabinet; and
12. Testing log sheet from testing process. Testing log sheets were documents that recorded the activities the engineers performed to the testing cabinets during a cabinet testing process. The engineers wrote their comments regarding all items of the cabinet affected during the testing process from start until finish. The modification notes recorded the physical modifications made to the cabinets or to the parameter settings in the cabinets. Testing log sheets were internally recorded. The Company did not submit these reports to their clients.

Using the seven testing reports collected from the engineers during the initial data collection, questions arose as to which part of the data should be included in the properties of an individual. A knowledge-based structure could represent what kind of knowledge that the engineers wanted to retrieve and so records of their work processes and observations of their work processes were used to form the next stage of the structure.

To begin the process the researcher developed a clear methodology based on OWL, using Protégé, to build the ontology. There are two types of properties in OWL which are *datatype* property and *object* property (Antoniou & Harmelen 2009). *Datatype* property is used to describe the relationship of the *individual* to their data values. For example, in the Company each cabinet had a model name therefore, the *datatype* property was '*Model-Code'* that could contain a value such as '*GLR 12 DAC'*. The other type of property was an *object* property. Object property has been used to describe relationship between two *individuals*. At the initial point of the ontology development there was only one *individual* created in The Company ontology which was cabinet '*GLR 12 DAC' individual*. In Protégé all of the *datatype* and *object* properties needed to be created only once. Then it could be re-used with any *individual* that can be created later.

Starting with one *individual* in *'Case Model'* case, sub-class '*GLR'*, this *individual* was used to represent cabinet model '*GLR 12 DAC*'. As this '*GLR 12 DAC*' was a specific name and was unlikely to be repeated, it was defined as a *datatype* property. Its representation in the ontology is shown below in Figure 5.6 It was one of the cabinet cases that had been designed, built and tested by the engineers in the Company.

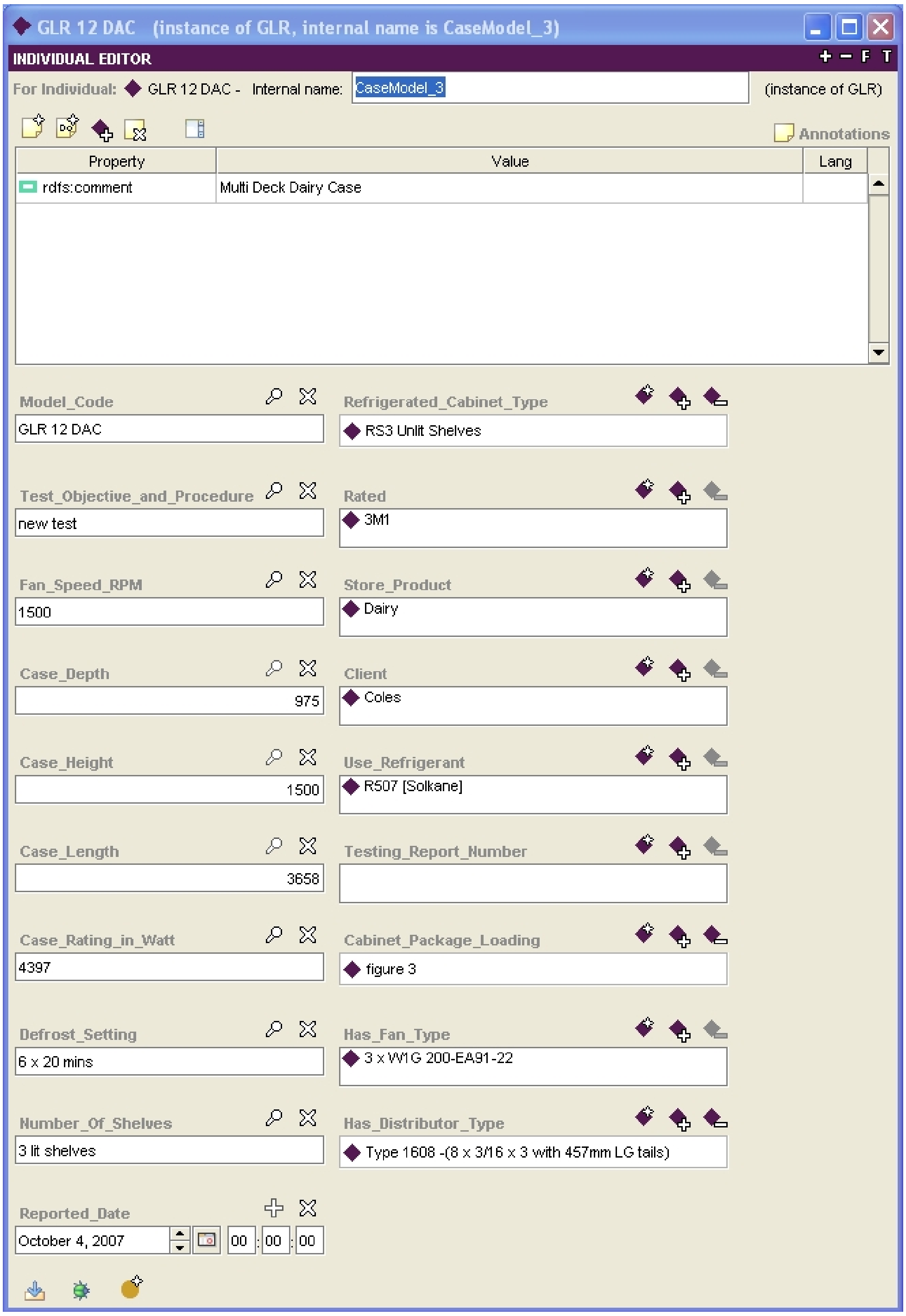


Figure 5.6 *Individual* '*GLR 12 DAC*' with *datatype* and *object* properties.

This *individual* contained other *datatype* properties. This was specific information which could be determined as a *datatype* property with a specific display name such as '*Test_Objective_and_Procedure'* which contains value *'new test'*. This is shown above, represented in the ontology, in Figure 5.6. The other *datatypes*, also represented in Figure 5.6 are described below.

- Fan speed was a value of the fan speed setting that had been set in the cabinet to ensure that it could pass the testing process and meet the required standards. During the testing period it was common for the engineers to keep changing the fan speed. This was because fan speed is one of the key factors that determine cabinet efficiency. The engineers recorded only the finalized fan speed in the reports. There was no reporting of how they determined these changes, that was tacit knowledge to be captured later in the research process and then added to the ontology. The *datatype* property's name created in the ontology was '*Fan_Speed_RPM'* which contained a value in this case of 1500. This meant this cabinet was running at fan speed 1500 revolutions/rounds per minute.

- Cabinet dimensions of length, width and height in millimetres were also an important *datatype* property. The names given to these *datatype* properties in this ontology were '*Case_Length'*, '*Case_Height'* and '*Case_Depth'*. The values contained in these properties were 3658 mm, 1500 mm and 975 mm for the initial example.

- Case rating was a measure of the cooling capacity of the cabinet at the rating level referred to in the standard. This could be at any level of rating such as *3M0, 3M1*, and *3M2* etc. The heat extraction capacity was measured and recorded. The name of this *datatype* property was '*Case_Rating_in_Watts'*. The value contained in this property was 4397 watts in the initial example.

- The number of shelves was information on the type and number of shelves a cabinet had, for example: two lit shelves, three unlit shelves. The name of this *datatype* property given was '*Number of Shelves'*.

- Defrost setting was information about the setting of the coil defrosting scheme in the cabinet. For example, 6X20 Mins meant in 24 hours the cabinet would be automatically defrosted six times for 20 minutes each time. The name of this *datatype* property given was ‘*Defrost_Setting’*.

- ‘*Reported date*’ showed the date that the report was created.

Structuring the ontology in this way with *datatype* properties provided a clear representation of what the engineers did and thus represented their knowledge. It also broadened the searching capability of the ontology, providing an enabler for the engineers to use the system and thus re-use their knowledge.

The next step in the development of the ontology was based on documented work practices of the engineers and observations of their work practices to determine the *object* property of the ‘*individual’*. If any characteristic of an *individual* was likely to be repeated or mentioned repeatedly, it was better defined as an *object* property. However, the users had to create other classes and *individuals* so that this *individual* could be linked to it. The advantages of this action were: first, users did not have to repeat data entry process when using the ontology, and second it gave flexibility to make any change or modify values of *individuals*.

There was significant information embedded in every cabinet that the Company manufactured. This information included the type of refrigerant used in the cabinet and the products stored in the cabinet. The refrigerant that the engineers used in the cabinets varied. Each type of refrigerant had its own specific thermodynamic properties. Different refrigerant types had differences in temperatures at different pressures. For example, the refrigerant R407C at minus 20 degrees Celsius recorded a pressure of 2.308 bar, while for refrigerant R134a at the same temperature the pressure was 0.064 bar. These refrigerant specific properties determined the physical settings of the cabinet. The current refrigerants used in the refrigeration industry have significant environmental impact. The Company was also aware of this issue and had been developing cabinets that used refrigerants such as R134a, which have significantly less environmental impact.

The other new technology that the Company considered as competitive advantage was C02 refrigerant. The researcher then included the '*Refrigerant'* class into the system with four types of refrigerants as shown in Figure 5.7.

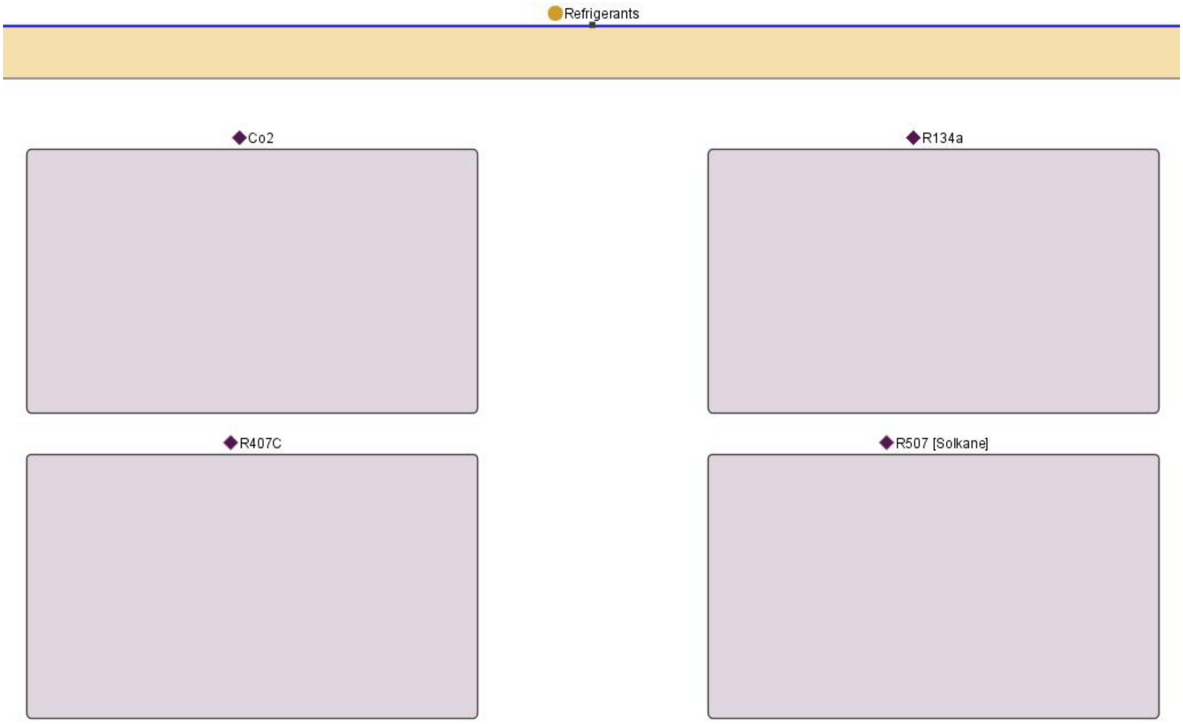


Figure 5.7 'Refrigerant' class

Each '*individual'* contained two *datatype* properties which were '*Refrigerant_Type'* and '*Refrigerant_Detail'*. '*Refrigerant Type'* contained a string value such as the name of the refrigerant. The researcher created a *datatype* property '*Refrigerant_Detail'* for the engineer's future use. The engineers could input file directories in this field. This property showed the folder that contained files about each particular refrigerant when clicked. This assisted them in determining decisions about the right sort of refrigerant for any new cabinets. These refrigerant *individuals* could also be selected in the '*Use_Refrigerant' object* property in the case model *individuals*.

The engineers developed each cabinet to suit their client's requirements. One of the requirements included products that were going to be sold in that cabinet. The researcher then created another class, a '*Stored_Product'* class, to represent the various types of products that would be stored in the cabinet. Figure 5.8 shows the '*Stored_Product*' class which contained various types of products '*individuals'*.

These included products such as dairy, deli, eats, produce seafood and others. The engineers could select the type of product stored in the system that represented what the cabinet would store in the case model '*individuals'*.

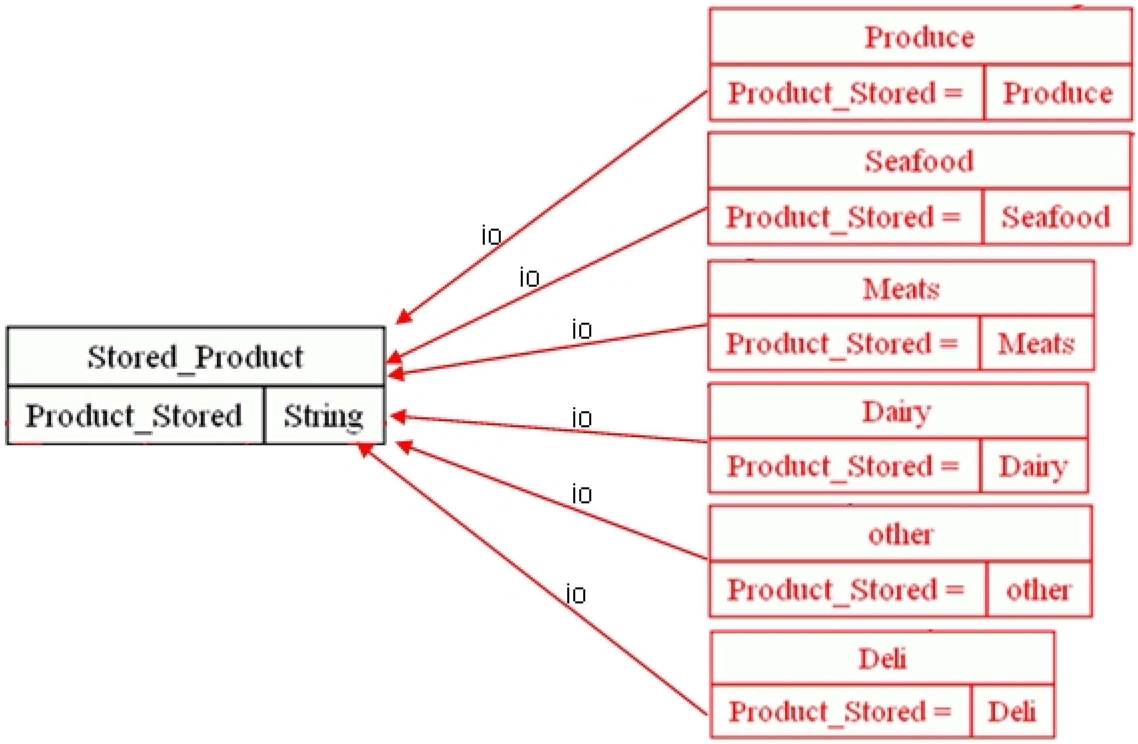


Figure 5.8 '*Stored_Product'* class

Structuring the '*Stored_Product'* sub-class, as shown in Figure 5.8 allowed the engineers to make specific queries about the products that the cabinet was designed and tested for. The structure also allowed the engineers to add more specific details about each stored product which related to the National Standard.

The Company product development process revolved around making the refrigerated cabinet pass the test rating in terms of temperature and energy consumption. In the testing reports the engineers used the term "*Cabinet Class"* to represent the cabinet capacity level with codes such as *3M0*, *3M1*, *3M2* and etc. to describe how that cabinet could perform. The details about these codes are derived from the National Standard AS 1731. This cabinet class characteristic of the cabinet individual could be created as a *datatype* property. However, this property was likely to be repeated when new cabinet *individuals* were created in the future. Therefore, the class was created in the ontology to enable users not to have to do data entry but instead by selecting the class. Furthermore, in using this ontology to retain organizational knowledge for new staff, it was better to create this characteristic as an *object* property, and then create another standard class with other *individuals* for further details for new staff to browse for knowledge about the Standard.

To gain adequate details to create *classes* and *individuals* the researcher collaborated with the engineers to find the details of the Standard -AS 1731 which consists of 14 parts:

Part 1 contains details about terms and definitions.
Part 2 contains details about general mechanical and physical requirements.
Part 3 contains details about linear dimensions areas and volumes.
Part 4 contains details about general test conditions.
Part 5 contains details about temperature tests.
Part 6 contains details about classification according to temperatures.
Part 7 contains details about defrosting tests.
Part 8 contains details about water vapour condensation tests.
Part 9 contains details about electrical energy consumption tests.
Part 10 contains details about tests for absence of odour and taste.
Part 11 contains details about installation maintenance and a user guide.
Part 12 contains details about measurement of the heat extraction rate of the cabinets when the condensing unit is remote from the cabinet.
Part 13 contains details about test reports, and
Part 14 contains details about minimum energy performance standard MEPS requirements.

All of refrigerated display cabinets that the Company manufactured had to pass the requirements of the Standard. Firstly, before starting to develop a prototype of a cabinet, the engineers had to set up the targets that the cabinet aimed to achieve. The target is the rating class. There were 16 classes of refrigerated cabinet case rating, for example *0L0*, *0L1*, *0L2*, *1M0*, *1M1* and etc. A Class rating code consisted of two parts. For example class rating *3M0* consisted of its climate class which is *3*, and its temperature class which is *M0*. The climate class had eight levels from 0-7, and each level had specific parameters. For example climate class 0 determined the testing conditions at dry bulb temperature 20 °C, 50% relative humidity, 9.3 °C dew point and 7.3 g/kg water weight in dry air. Climate classes 1-7 have different values. This information was derived from the Standard, part 4. The temperature class contained details about the temperature level that the cabinet had to cool the M-package down to. Details included the highest temperature of the warmest M-package, the lowest temperature of the warmest M-package and lowest temperature of the coldest M-package in Celsius.

The researcher then created the class called '*Standard AS 1731'*. Within this class the sub-class '*Case_Rating'* was created. In the '*Case_Rating'* sub-class a number of *individuals* were created. These included *1L1, 1L2, 1L3, 1M1, 1M2, 2L1, 2L2, 2L3, 2M1, 2M2, 3L1, 3L2, 3L3, 3M0, 3M1* and *3M2*. The reason that the researcher did not create all of the case rating *individuals* was because the Company only manufactured certain case ratings. Figure 5.9 shows the class '*CaseRating'* with 16 rating *individuals*. It also showed that cabinet *individual* '*GLR 12 DAC'* which has an *object* property '*Rated'* linked to the '*3M1'* case rating *individual*.

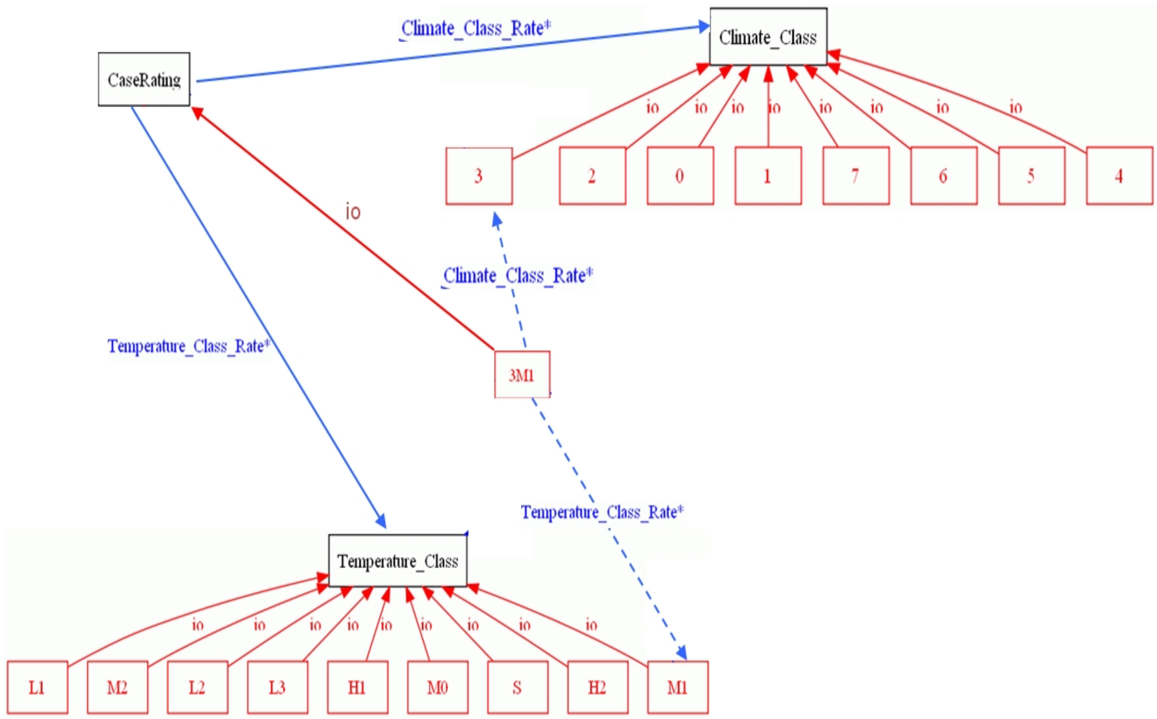


Figure 5.9 '*Case Rating'* class detail.

GLR 12 DAC was rated at a 3M1 class. The researcher then created the *object* property name 'Rated' to link '*GLR 12 DAC'* with '*3M1'*. Figure 5.10 shows properties detail of an *individual* '*3M1'*.

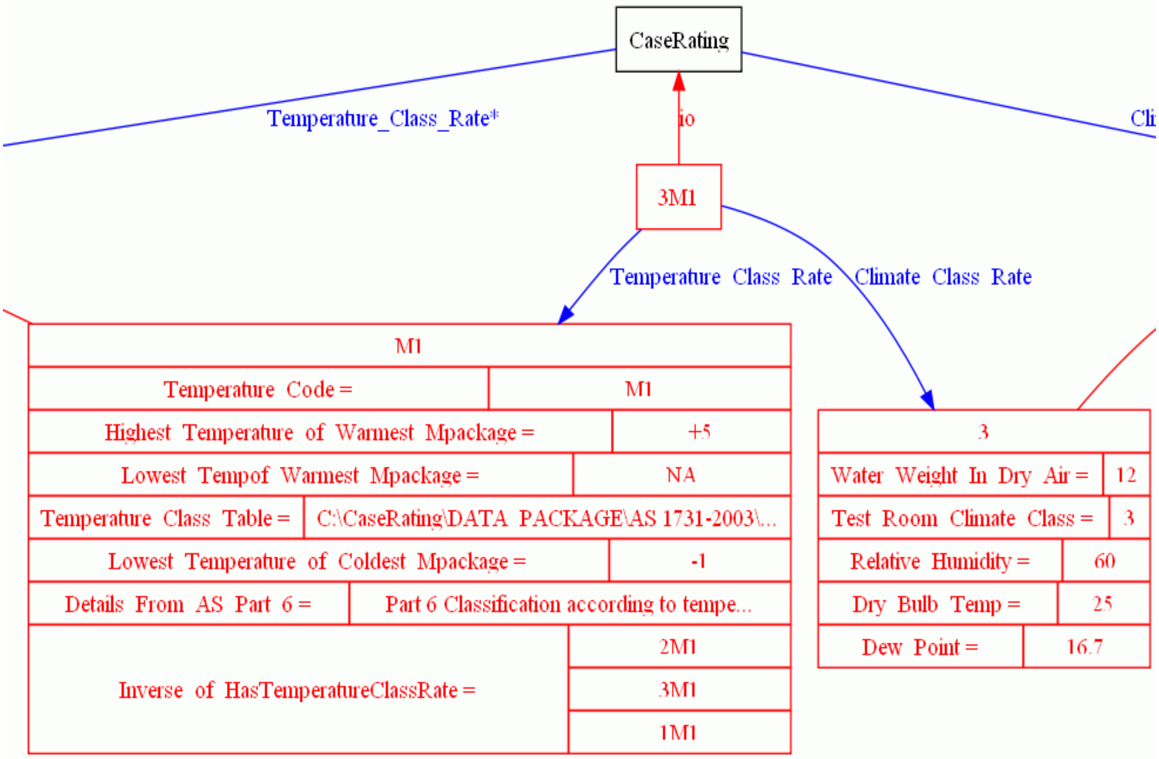


Figure 5.10 '*Case rating' individual* properties.

The '*CaseRating'* class contained *individuals* such as 1L1, 1L2, 1L3, 1M1, 1M2, 2L1, 2L2 etc. Each case rating was a combination of '*Climate_Class*' and '*Temperature_Class'*. Every individual in the '*CaseRating'* class had one *datatype* property and two *object* properties. For example case rating 3M1 has *datatype* property name '*Rating'* which contains value 3M1. Another two *object* properties are '*Climate_Class_Rate'*, which contains the value '*3'* and '*Temperature_Class_Rate'* contains the value M1. The diagram also shows all of the *datatype* properties of *individual* '*3'* and '*M1'*. Data in the *datatype* properties was derived from the Standard AS 1731. *Protégé* allows the developer to include any kind of information into the ontology. For example it is possible to include an image file that can be displayed in *Protégé*. Structuring the ontology in this way could help new engineers to retrieve information in one place. This is because this information had been kept in different parts in the Standard and the system allowed it to be included and displayed. Figure 5.11 shows '*StandardAS1731*' class with all of its sub-classes. These include '*Case_Rating', 'Climate_Class'* and '*Temperature_Class'* that have already been mentioned. The others are *'AS_standard_detail', 'Refrigerated_Cabinet_Type'* and '*M-package_loading'* sub-classes.

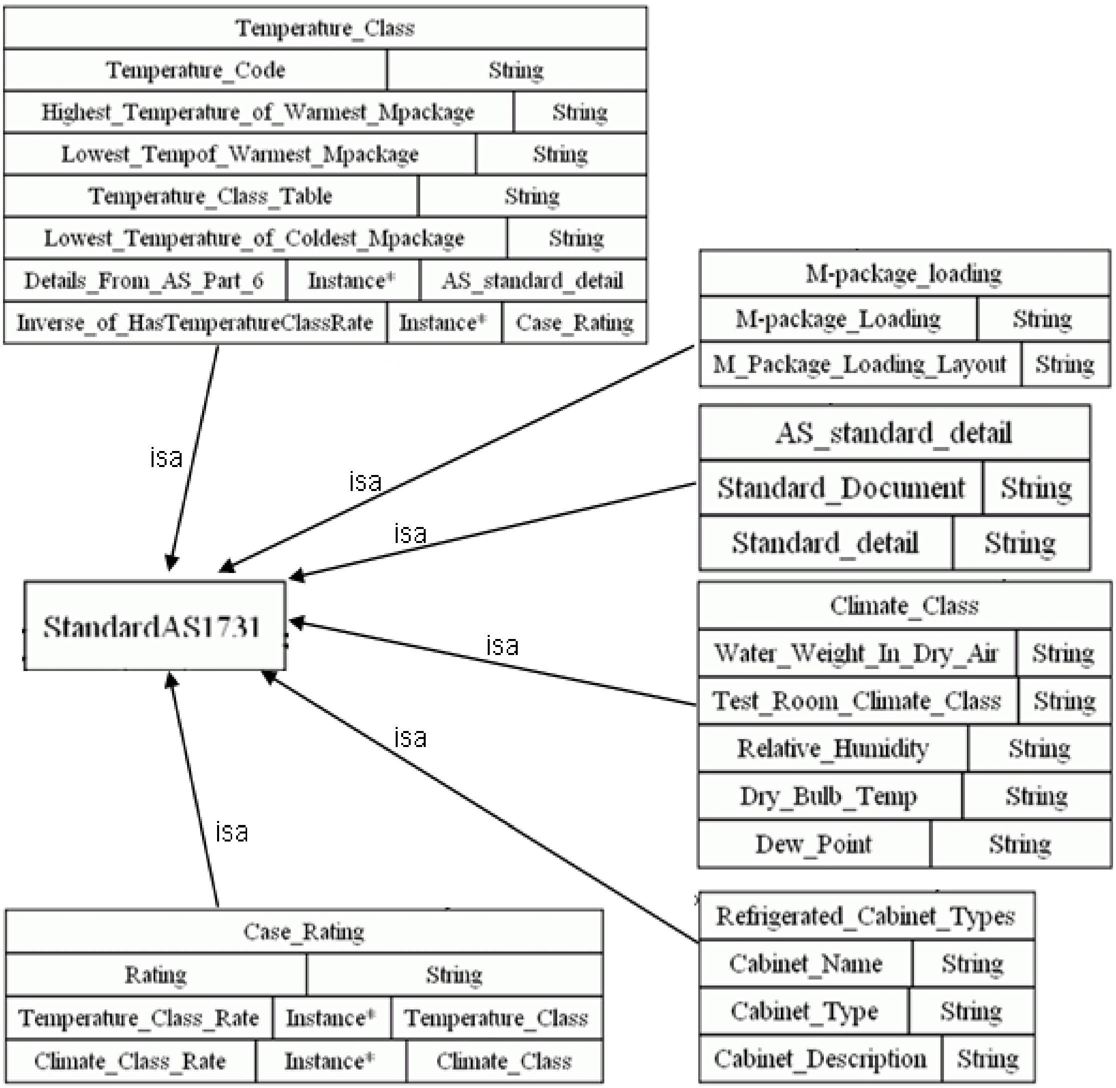


Figure 5.11 '*StandardAS1731*' class and its sub-class.

Sub-class '*AS_standard_detail'* has two *datatype* properties: '*Standard_detail'* and *'Standard_Document'*. The *datatype* property '*Standard_detail'* contained values which were part numbers plus the topic of the standard, for example [Part 1 terms and definitions], [Part 2 general mechanical and physical requirements] etc. The other *datatype* property, '*Standard_document'*, contained values [directory of that part of the standard].

Figure 5.12 shows '*Standard_detail'* and '*Standard_Document' datatype* properties as they appeared to users in the system. *Protégé* allowed the users to put files directly in the *datatype* property. When users clicked on the magnifying glass icon, the ontology opened that specific file. Figure 5.12 also shows the PDF file of part 10 of the standard which is opened in the way described.

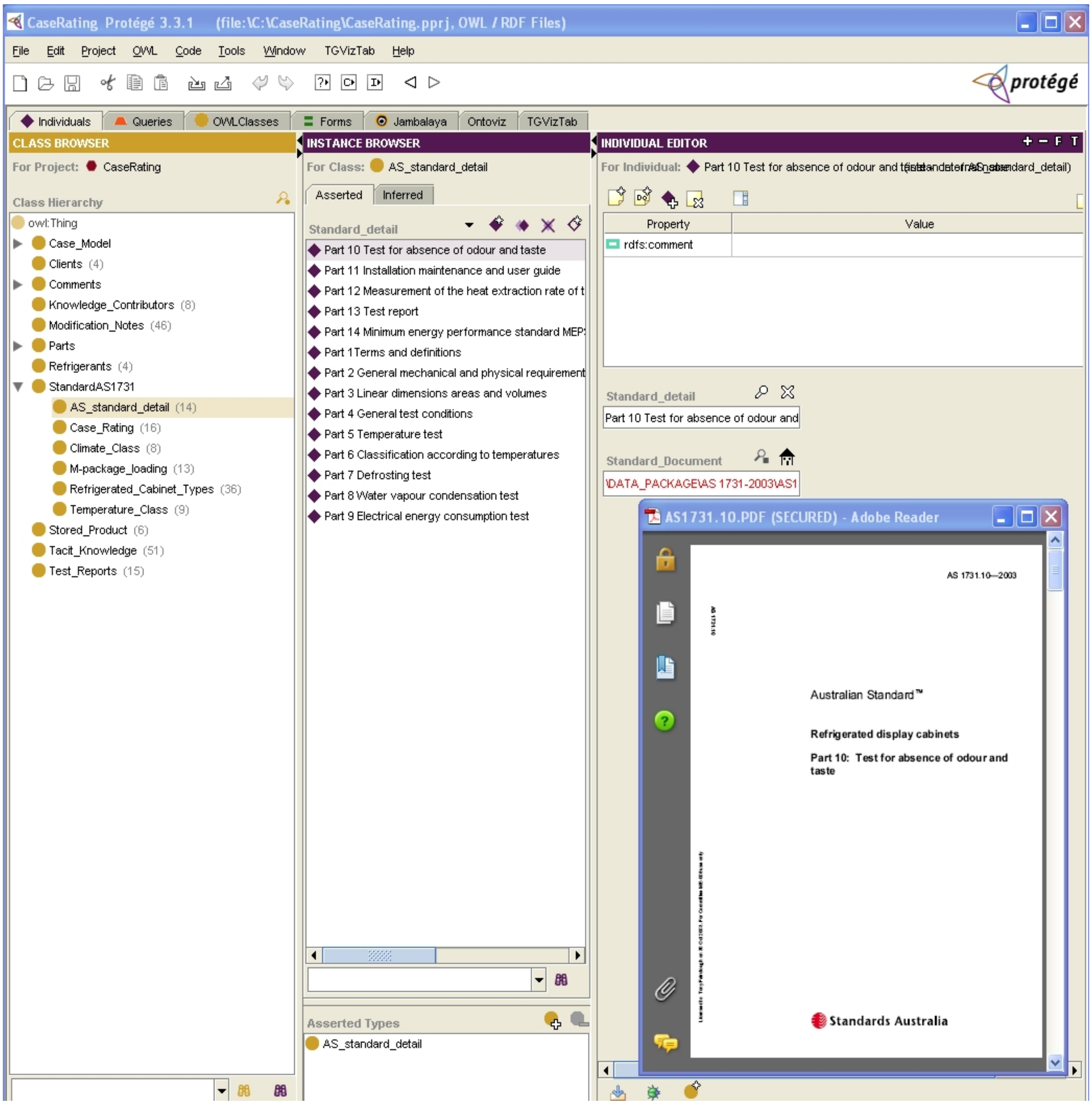


Figure 5.12 '*AS_standard_detail'* class with properties.

One of the key aspects of dealing with the Standards for the engineers is how they applied the measurement standards to their design, build and testing procedures. The focus for them in this work was the M-package. Therefore following development of the classes dealing with Standards it was necessary to form the relationships with the M-Package in the ontology. The '*M-package loading'* class had two *datatype* properties. The Standard determined the M-package configuration setting during the cabinet testing process. The engineers had to set up the M-package location to comply with the Standard. Each type of cabinet had a different M-package configuration. This part of the Standard also determined the location of the temperature sensors that had to be installed in the M-package. This is because the cabinet manufacturers had to ensure that when the products were out in the market, they cooled the commodities down to the temperature so that the product would not spoil.

Figure 5.13 shows the '*M-package loading'* class containing 13 *individuals*. Each *individual* represented the M-package setting configuration in the cabinet. For example, *individual* "Figure1" had *datatype* property '*M-package loading'* and contained the value [Figure1]. The other *datatype* property, *'M-package Loading_Layout'* contained the value which was the directory of the image file. *Protégé* allowed users to put a file directory in the *datatype* property value and the image file would then be automatically displayed in the ontology.

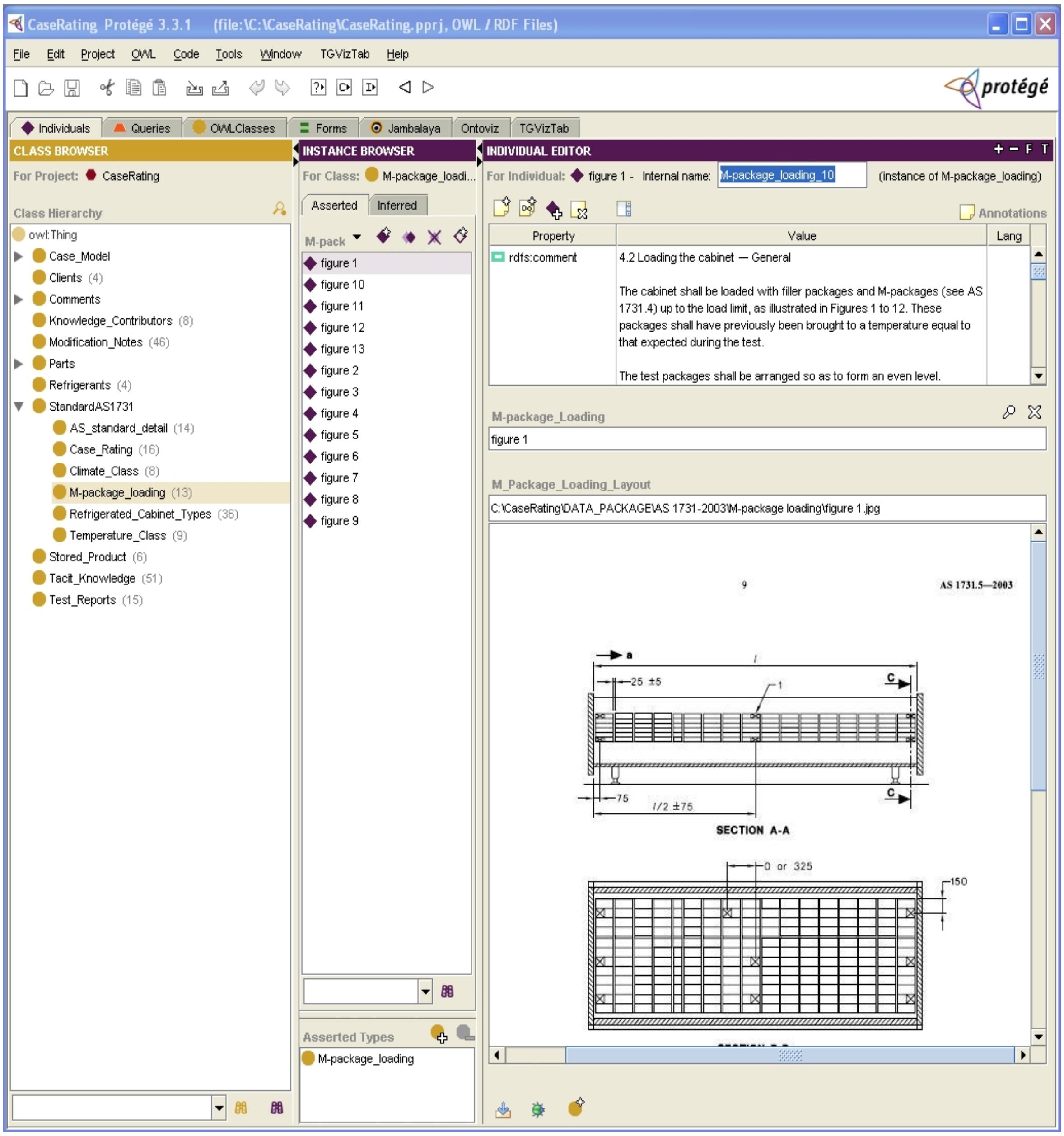


Figure 5.13 '*M-package loading'* class and properties.

Following discussion with the engineers and from observation, it was then important to link the M-package class to the cabinet type in the ontology. The '*Refrigerated_Cabinet_Type*' class contained 36 *individuals* which described the physical characteristics of the cabinet. In the marketplace each manufacturer has their own idea of how their refrigerated display cabinet will look. However, to be able to ensure that only good quality products would be manufactured, the government set up the National Standard (2003) to which every manufacturer's product had to conform to. Cabinet manufactures have to categorise their refrigerated cabinet into one of these types stated in the Standard and adapt them to the client's needs.

Figure 5.14 shows the diagram of '*Refrigerated_Cabinet_Type'* class containing 36 *individuals*. Examples include RS 1 High open multi-deck, RS 2 Medium open multi-deck, RS 3 Low open multi-deck, RS 4 Self service and storage closed cabinet, RS 5 Self service and storage closed cabinet-under counter, RS 6, Flat glass-fronted-single deck, etc. Each *individual* has 3 *datatype* properties and 1 *object* property. The *datatype* properties are '*Cabinet_Description'* containing values such as [Medium temperature multi-deck, length of air curtain 1.5-1.9 m.; Cabinet height contains values including 1.8-2.19 m and depth 0.6-2.1 m.], '*Cabinet_Name'* contains values such as [High open multi-deck] and '*Cabinet_Type'* contains values such as [RS1 Lit Shelves]. The details about the cabinet type are also derived from the Standard Part 14. The detail has been included in the individual description section.

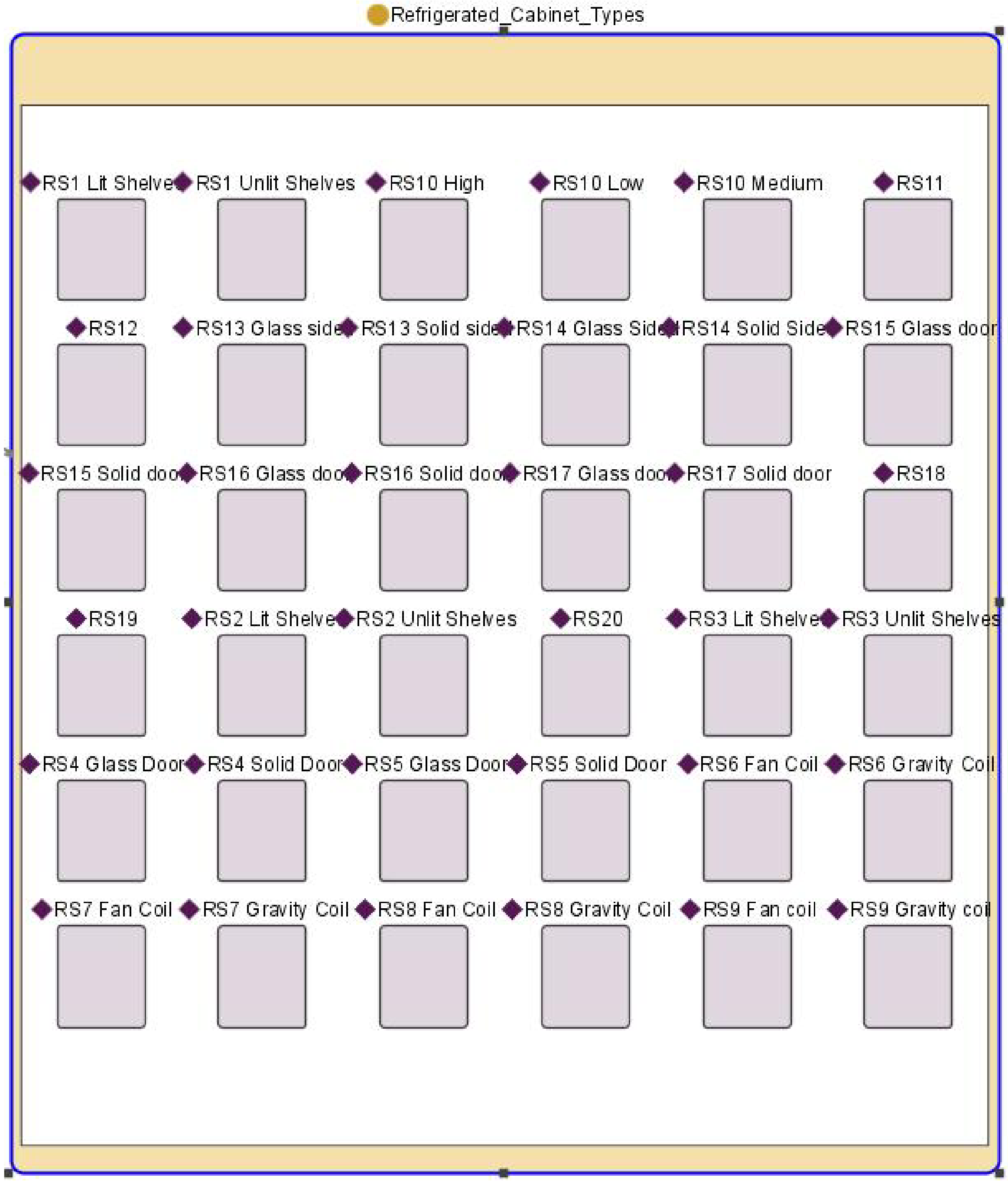


Figure 5.14 '*Refrigerated_Cabinet_Type'* which contains 36 *individuals*

Figure 5.15 shows one sample of the refrigerated cabinet type *individual* '*RS15 solid door*' designed from the ontology into *Protégé* for the engineers in the Company to use. When the user double clicked at the *individual* form (Figure 5.15), *Protégé* showed the details of that particular *individual*. Details shown in the *individual* included the source of this cabinet type, its physical characteristic, cabinet name and code.

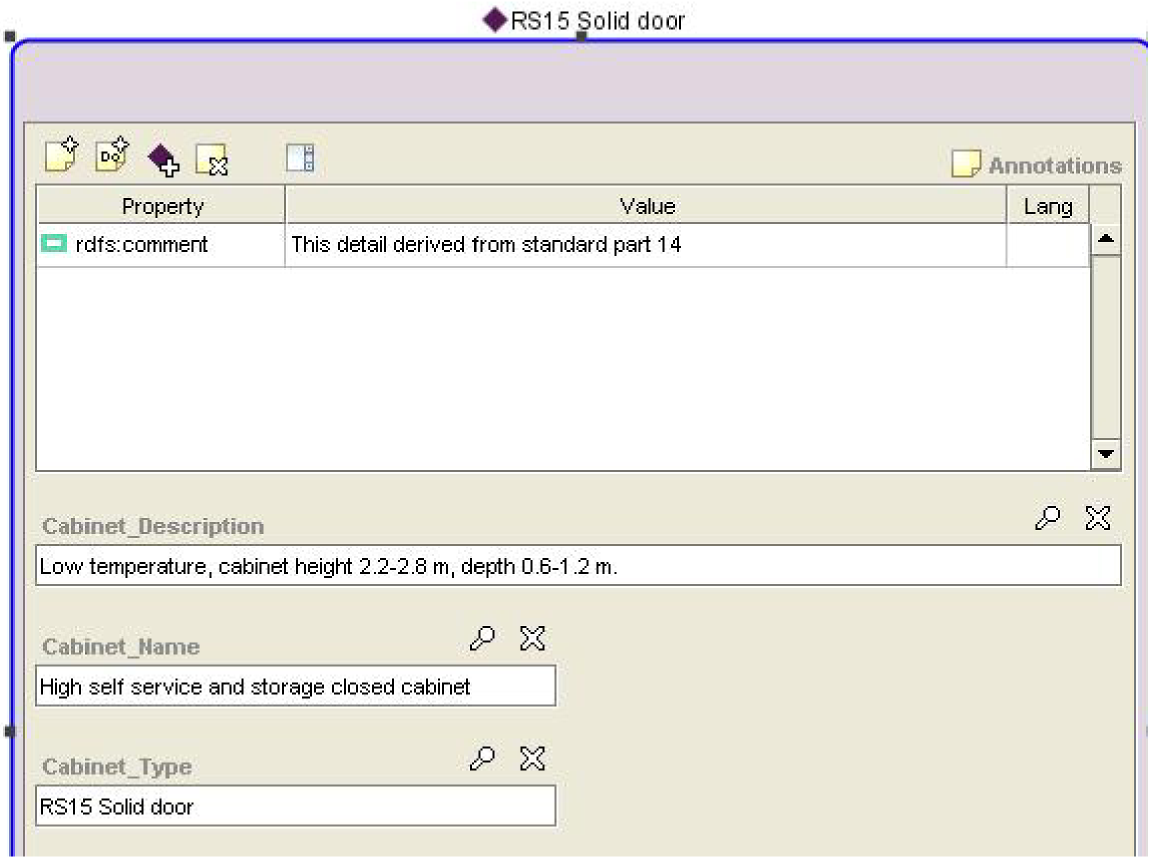


Figure 5.15 Sample of the cabinet type *individual* type '*RS 15*'.

Up to this point in the development process, all of the details about the Standard AS 1731 were classified and created in the product development ontology. These included *'AS_standard_detail', 'Temperature_Class', 'M-package loading', 'Case_Rating', 'Refrigerated_Cabinet_Type'* and *'Climate_Class'* classes. *Individuals* in each class were created with their properties. At the beginning of the new cabinet development process the engineers set up their targets. These targets were the conditions which determined the design and then the cabinet testing process. The engineers gathered information from clients and their experience with previous products and determined how the new cabinet would look. Then the engineers defined the type of the cabinet they were going to develop from the Standard. The types of the cabinet that the Company manufactured had similar characteristics compared to the Standard. If the new cabinet that the Company was developing did not have the exact same characteristics as defined in the Standard, the engineers would define the type of their cabinet as the one with the closest characteristics to the Standard. Therefore the ontology developed for them had to place significant emphasis on the details in the National Standard. The researcher's observations and discussions with the engineers highlighted the central importance of this, determining fundamental structures and relationships in the ontology. The following description derived from those discussions shows how the design, build and testing process happened.

The engineers set up their cabinet's desired performance in rating terms. For example if the engineers wanted to develop the case GLR 12 DAC with the cabinet type RS3 Unlit Shelves, then the engineers first designed and built a prototype. They looked at how they could set up the cabinet for the testing process from M-package loading configurations in the Standard Part 5. Then the engineers considered the rating levels from their set testing room conditions and climate class, for example 3M1. They then built in Part 14 of the Standard which defines the maximum energy consumption limit they had to comply with. For example cabinet type RS3 Unlit Shelves with 3M1 rating has a defined maximum energy consumption at 18.39 (kWh/day/m2). This meant that the cabinet the engineers set up in the testing room could not consume energy exceeding the determined levels of energy consumption. The next step was running the refrigerated display cabinet prototype in the testing room until the energy consumption measures meet the Standard. However practically, the cabinet testing took 12 – 16 weeks to get this energy consumption level to meet the standard. There were then a number of activities that the engineers performed to the prototype cabinet during the cabinet design, build and testing process. The Standard framed much of that work and was crucial to product output and therefore to the ontology structure. However, there were other processes and classes that the research showed had an impact and needed to be included in the ontology

At the beginning of prototype cabinet testing process the prototype was set up in the testing room. The engineers then let the prototype cabinet run for 48 hours to get results stability. The engineers reviewed the result from running the tests. The results that the engineers reviewed included temperature of the M-package across every shelf and the electrical consumption figures. There were many factors that determined the result of the cabinet testing based on the parameters of temperature and power use. These included the amount of air flow through the cabinet's front duct, refrigerant suction pressure, cut-in and cut-out temperature, lighting turn-on or turn-off, location of the M-package, fan speed, fan type etc. The engineers spent time modifying these parameters to get the temperature and energy consumption to meet the Standard. After the first test results emerged the engineers brainstormed for possible modifications that they believed would make the cabinet performance approach the Standard. Only the finalised decisions from the brainstorming were recorded in the testing log sheets as shown in Figure 5.16.

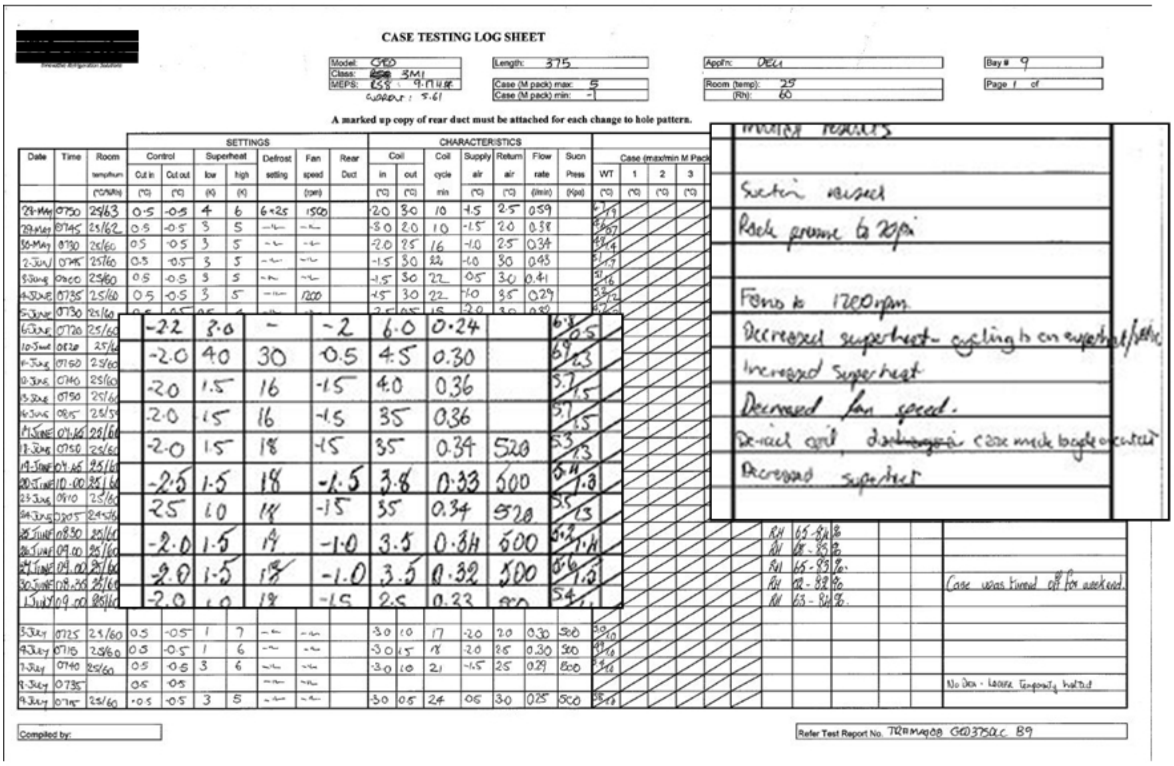


Figure 5.16 Sample of the Company's cabinet testing log sheet.

Figure 5.17 shows a sample of the Company cabinet testing log sheet. The engineers recorded what activities occurred with each prototype cabinet case in a separate paper every day. Every morning engineers S3 and S4 would write the previous days measured parameters from the measurement equipment onto the log sheet. The details noted in the log sheet consisted of four parts. The first part was cabinet setting parameters including testing room conditions, cut-in and cut-out temperatures, super heat temperature, defrost setting, fan speed, and rear duct detail. The second part detailed cabinet characteristics. These included coil temperature, coil cycle, supply and return air temperature, refrigerant flow rate and suction pressure. Thirdly, cabinet performance was recorded and included temperature of the M-package at various locations across the whole cabinet, case rating in watts and MEP (minimum energy performance) value.

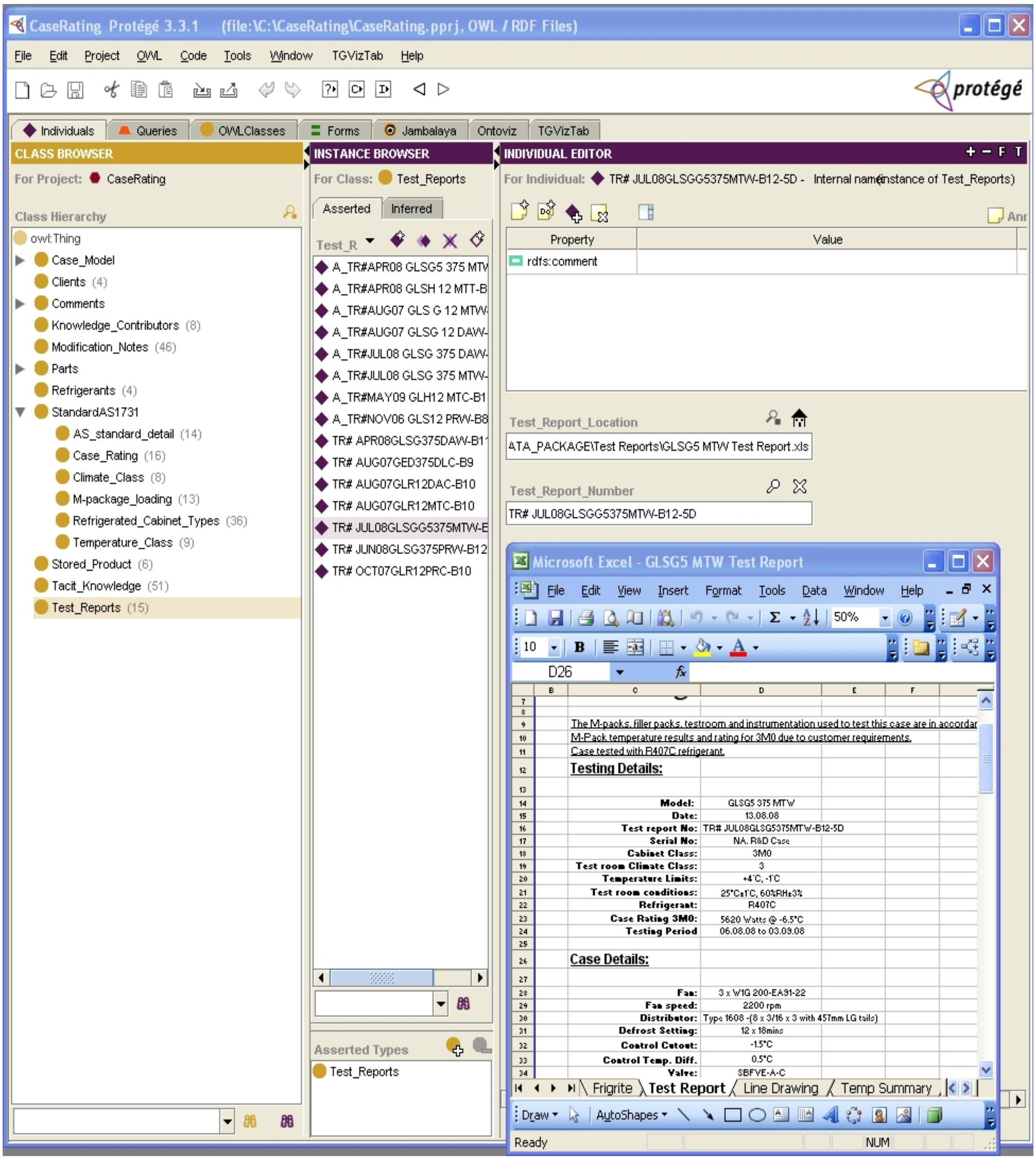


Figure 5.17 Testing report in an *individual* details.

In the last part, the engineers noted modification details they had applied to the cabinet each day. For example if the parameters measured from the cabinet showed that the M-package on the right hand side of the cabinet had a higher temperature than the M-package on the left hand side of the cabinet, then the engineers modified the cabinet by blocking some supply air slots on the left hand side of the cabinet. From experience the engineers found that if they reduced the airflow on the left hand side of the cabinet the rest of the airflow would force its way out to the right hand side of the cabinet. The engineers wrote only ‘block shelves, 2 rows’ in the testing log sheet.

Whilst these modification notes were written down they were only the finalised messages. Other ideas discussed during the brainstorming process were not recorded. No capturing of new knowledge ever occurred. Part of the research process in building this ontology has been to capture this type of information and add it into the system. Later in this chapter, the researcher will show that through observations at these meetings and from interviews and discussion with the engineers much of this tacit knowledge could be captured and added to the system for re–use. If new engineers came to work with the Company they had to take time to learn these short summary notes out of context of the discussions. However, the engineers also mentioned that they hardly looked at the information on the testing log sheets after the testing process was finished. This did not surprise the researcher, because the hand writing data format, as seen in the log sheet, was nearly impossible to read at times and therefore they tended not to re-use information in it. The engineers spent time modifying and re-testing the cabinet until the temperature and energy consumption met the Standard and was ready to be manufactured. The engineers then produced a testing report of the cabinet that they had finished testing. This report was submitted to the client as shown in Figure 5.5. The testing log sheets were only for internal records. This important knowledge of what the engineers had been through during the cabinet testing needed to be re-used. Therefore the ontology had to provide a structure where the engineers could store knowledge related to the cabinet designing, building, and testing processes. The ontology structure to store cabinet designing, building and testing knowledge will be described in next section.

Every cabinet case had its own report that the engineers produced when the testing process was finished. The ontology needed a class that could be used to store these reports. Therefore, the ‘*Test_Reports’* class was created. The purpose of this class was to store testing reports *individual*. Every testing report had its own number. This number is a combination of cabinet name, the time that the report was created and the location where the case was tested. For example case *GLR 12 DAC* had testing report number *#TR APR07GLR12DAC-B10.* This meant it was the testing report of cabinet *GLR 12 DAC* which had been created in April 2007 in testing bay#10. Each test report *individual* contained two *datatype* properties: firstly, the property name '*Test_Report_Location'* which contained values such as '*TR# AUG07GLR12DAC-B10'*; the second property name '*Test report Location'* contained values such as '*C:\ CaseRating\DATA_PACKAGE\Test Reports\Test Report GLR12 DAC.xls'.* Structuring test report class and individual like this helped users to gain easier access to the actual testing reports.

Figure 5.17 shows an example of the testing report *individual 'TR# AUG07GLR12DAC-B10'* in the *'Test_Report'* class. For example in *individual 'TR# AUG07GLR12DAC-B10'* contained two fields of data which are derived form two *datatype* properties as mentioned above. If users clicked on the magnifying glass symbol, the ontology opened the test report file, generated by separate software. The engineers created all of their testing reports in Microsoft Excel format. The *'Test_Report_Number'* contains a string value of the test report.

Once the class structure and *individual* and its' properties was created the researcher then created the other 14 test reports *individuals* and input their values. Figure 5.18 shows Test Reports class which contains 15 testing report *individuals*. These 15 test reports derived from 15 cases collected during data collection.

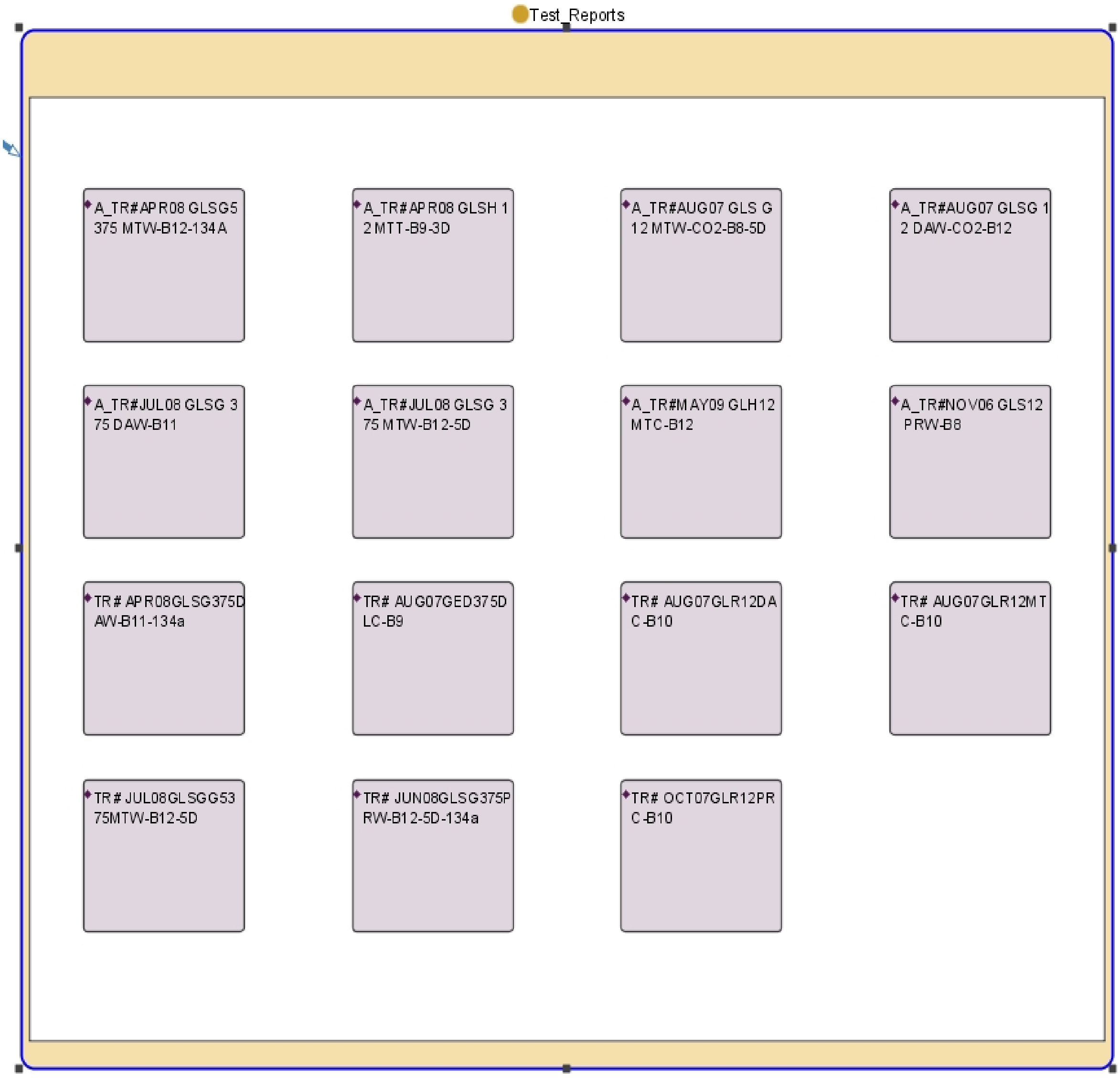


Figure 5.18 ‘*Test Reports’* class.

There are a number of key knowledge elements that were found during the process of shadowing the engineers in their daily work, used in the research:

(1) The data on the log sheets was recorded and transferred to paper from the lab computers and this was stored in the local network; and

(2) The engineers brainstorming process relied on these measured parameters, testing reports and everyday modification tasks.

These modification tasks were crucial to the design, build and testing processes but were never recorded. The engineers relied on their memories. Up to this point the ontology structure has covered ‘*Case_Model’, ‘Standard’* and ‘*Testing report’*. These modifications had to be added to the ontology. These measured parameters and cabinet modification tasks were bound together in the product development process. Therefore, these two parts should also be in the same individual in the KMS.

The next step in the development of the ontology was to create a class that contained *individuals* that have details about everyday modification tasks and the measured parameters. The word used in the testing log sheet for everyday modification tasks was '*Comments'*. Therefore the researcher used that term, one the engineers were familiar with, in the ontology. This also formed part of overcoming problems with knowledge capture. Knowledge capture and re-use fail because, almost always, knowledge engineers capture and store knowledge in the knowledge engineer's context, instead of in the domain expert's knowledge (Bryson, Cox & Carson 2009). The class 'Comments' was therefore created. During interviews, the engineers also talked about the complicated and specific requirements of their clients and that they differed from each other. These requirements determined the details of the cabinet parts and overall cabinet details. There were then three types of comments that needed to be recorded: the engineers' comments from the log sheets, the comments about clients and their requirements and comments about cabinet parts. The class '*Comments'* contained three sub-classes: *'Comments About Clients', 'Comments From Testing Log Sheet'* and '*Comments About Parts'* as shown in Figure 5.19. Each class contained *individuals* with different details.

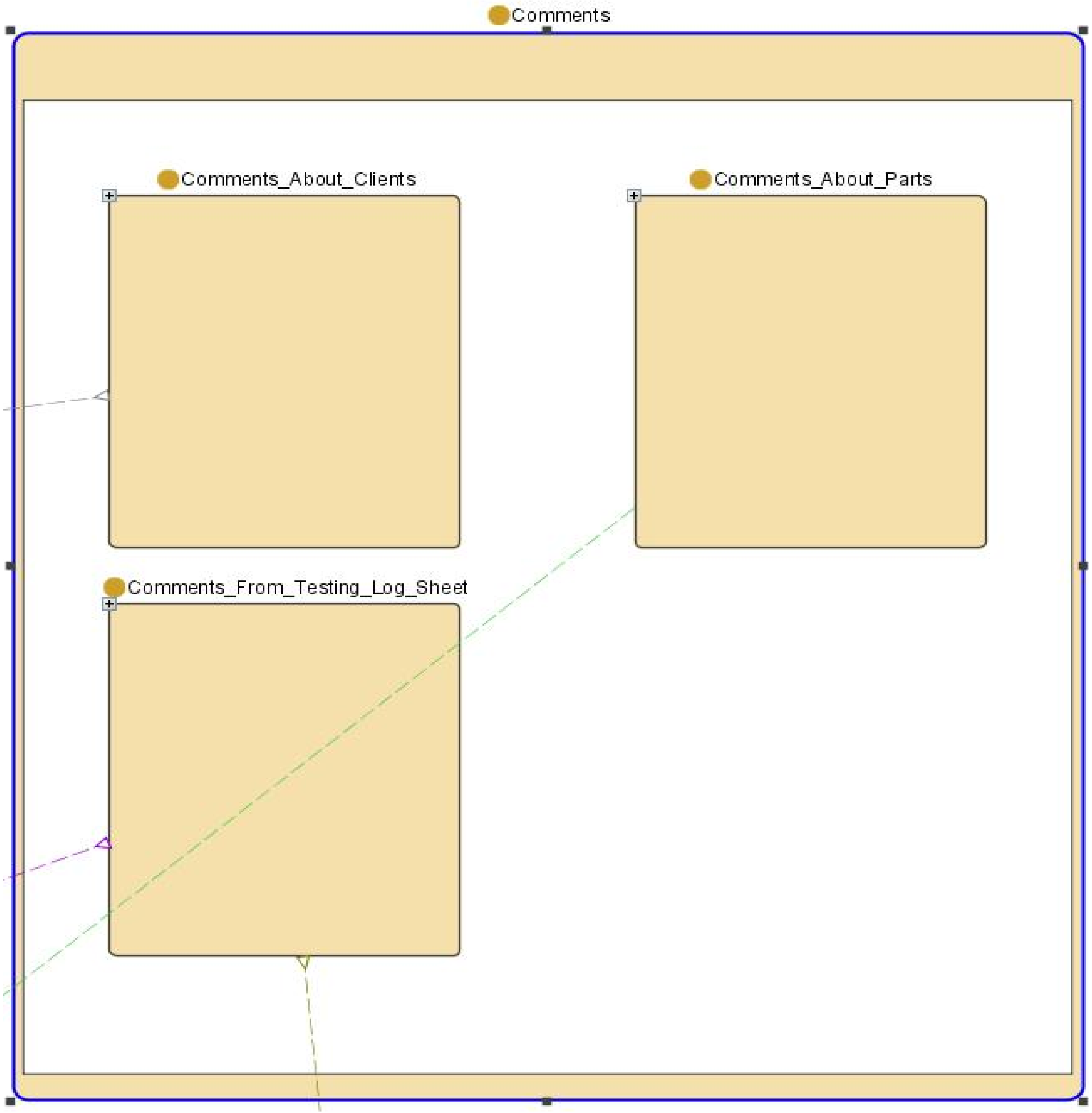


Figure 5.19 '*Comments'* class and its sub-class.

Each sub-class contained *individuals* which related to each type of comment. For example the sub-class '*Comments About Clients*' contained *individuals* with comments about each specific clients. An *individual* in this class had two *datatype* properties and one *object* property. The first *datatype* property, '*Comment_On_Date'*, contained the date that the users entered the comment. The second *datatype* property, '*Comment_related_to_client'* contained comments such as "now Coles is constructing for a green rating (environmental friendly) supermarket in Bendigo". The only *object* property was '*Related_To_Client'* which linked to the client '*individual'* in the '*Clients'* class. Details about class '*Clients*' and its' *individual* will be described later.

Figure 5.20 shows an example of the comments in the client *individual*. This individual is about one of the Company's clients who was building a new supermarket. The *individual* had an *object* property that linked this particular comment to *individual* Clients.

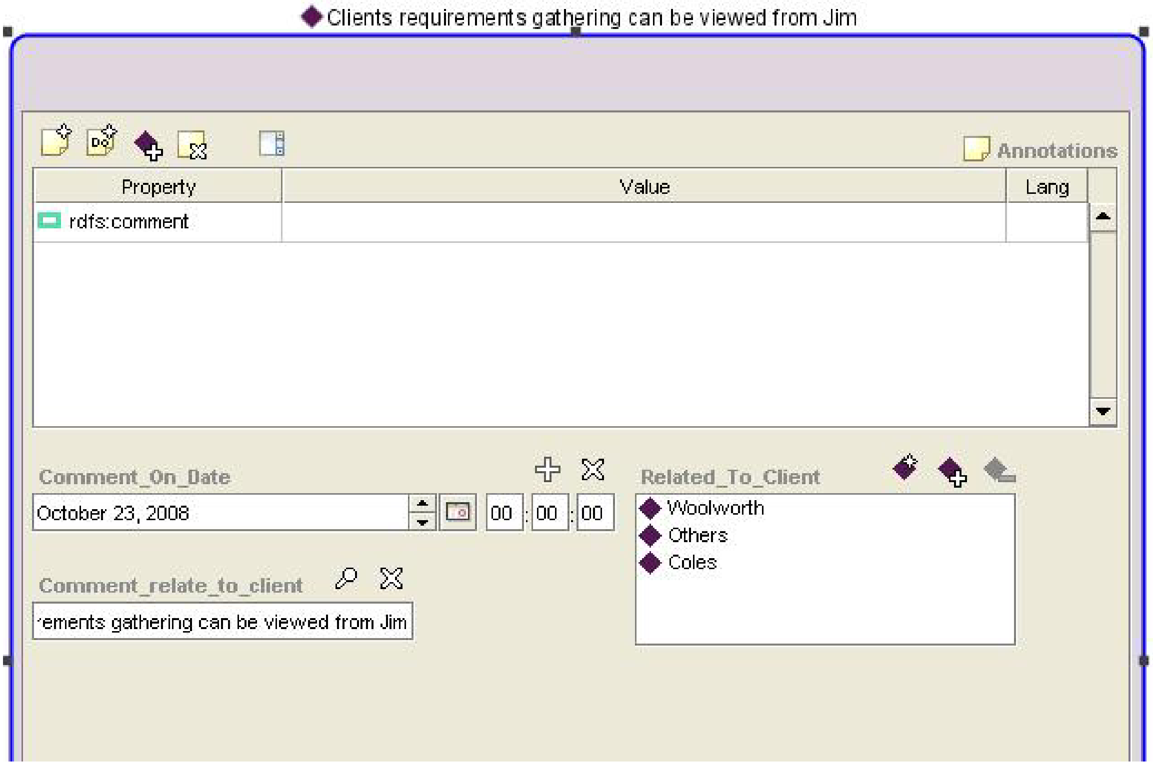


Figure 5.20 '*Comments_About_Clients' individual*

This meant that the other class called '*Clients'* needed to be constructed. The *individual* related to client also had to be created. Therefore, the researcher created a '*Client class*" with four *individuals*.

Figure 5.21 shows the Client class with four *individuals*. Two of the *individuals* were the Company's main clients. These included *Coles* and *Woolworths*, who were the main supermarket operators in Australia. Each client individual had only one *datatype* properties which contains the value, '*name of the client'*. During construction of the ontology, the engineers mentioned that there was nothing else to be added into the individual in this client class. However, structuring the system in this way provided flexibility for future system modification.

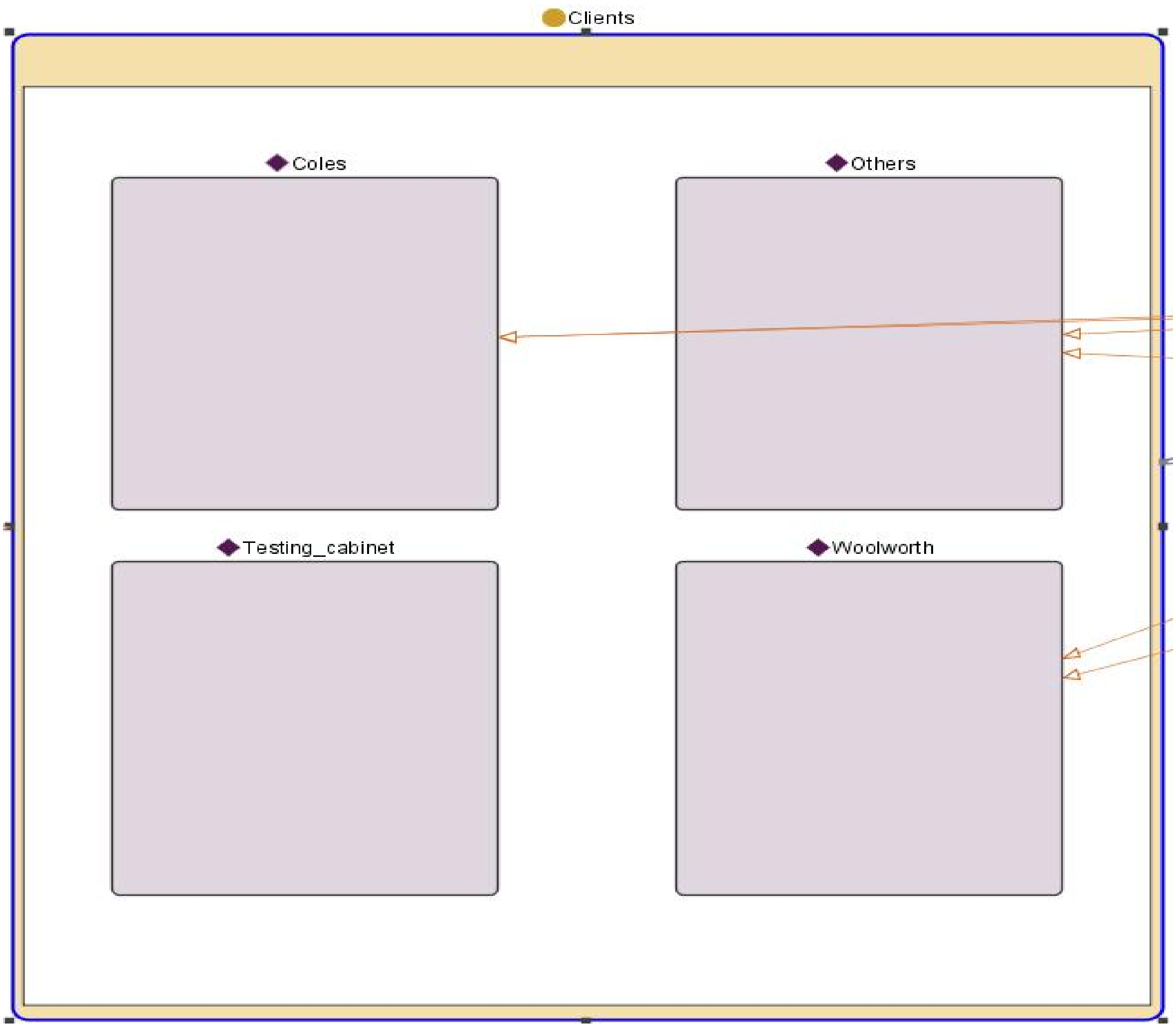


Figure 5.21 '*Client'* class.

The other sub-class in the '*Comments'* class is '*Comments_About_Parts*'. This sub-class contained *individual* that related to the cabinet parts. *Individual* in this class had two *datatype* properties and one *object* property. The *datatype* properties included '*Comment_About_part'* which had a value as a 'note about the parts'. The other *datatype* property, *'Comment_On_date'*, had a value as a 'date of comment entry'. The *object* property, '*Comment_Related_ToPart'*, links the *individual 'comment'* to the *individual 'cabinet part'* in '*Parts'* class.

Figure 5.22 shows the *individual* '*Comment_About_Part'* which has comment *'Detail about fan panel'* for cabinet model 12 FLS 'Co2 has been revised to revision 3'. "The holes have been added". This comment has been added on the 29th of August 2008. This comment links the 'comment' to the part 'Fan_Panel_8', the class that contains information about cabinet parts that needed to be created.

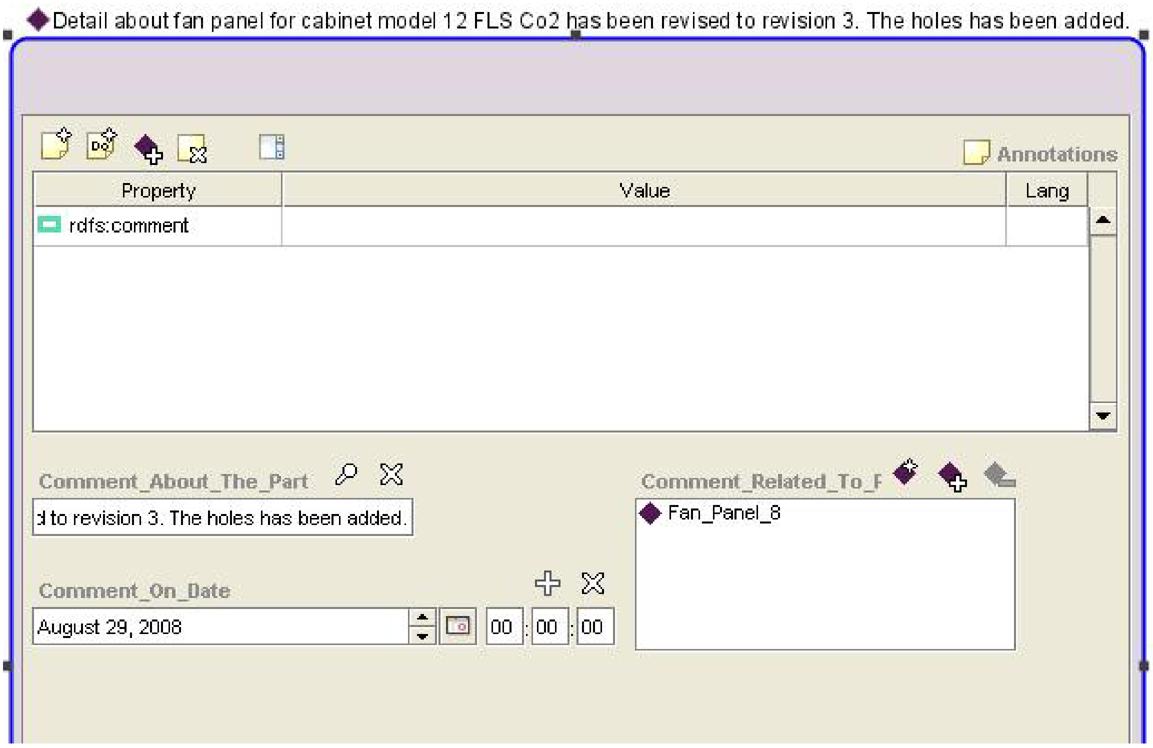


Figure 5.22 '*Comment_About_Part' individual*

The researcher created the class called '*Parts*'. Information from a study of the existing plans and brochures in the company and from interviews with the engineers showed that every cabinet part had more than one model. For example the refrigerant distributor that was used in the cabinets had at least six types.

Figure 5.23 shows the class '*Parts'* with a number of sub-classes. For example, sub-class '*Air_Deflector', 'Air_Duct', 'Center_upright_Assembly', 'Coil_Assembly',* *‘Coil_Cover’, ‘Coil_endPlate’, ‘Distributor’* etc. Each sub-class contains a number of *individuals*.

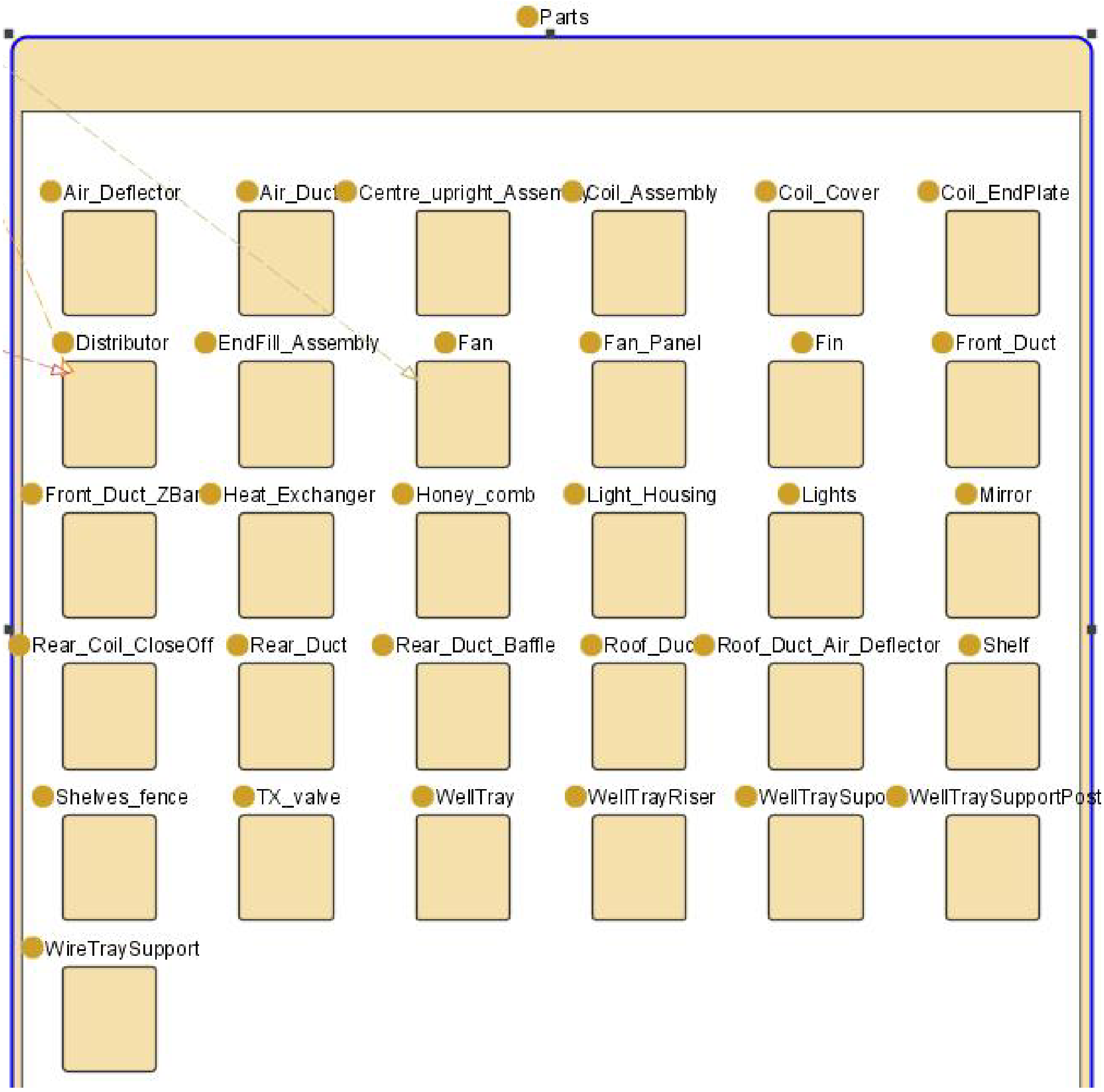


Figure 5.23 ‘*Parts’* class and its’ sub-class

Figure 5.24 shows the sub-class ‘*Distributor’* which contained six *individuals* of the distributor types. These include ‘Type 1608 - (8 x 3/16 x 2.5 with 457mm LG tails)’, Type 1608 - (8 x 5/32 x 2.5 with 300mm tails), Type 1608 - (8 x 3/16 x 3 with 457mm LG tails), Type 1608 - (8x5/32 x 2 orifices with 457 mm tails) and Type 1608 - (8 x 5/32 x 1.5 with 300mm tails). For users this meant that creating sub-class of the class ‘*Parts’* was more flexible for system data entry and modification. Therefore, the researcher created a number of sub-classes in the class ‘*Parts’*.

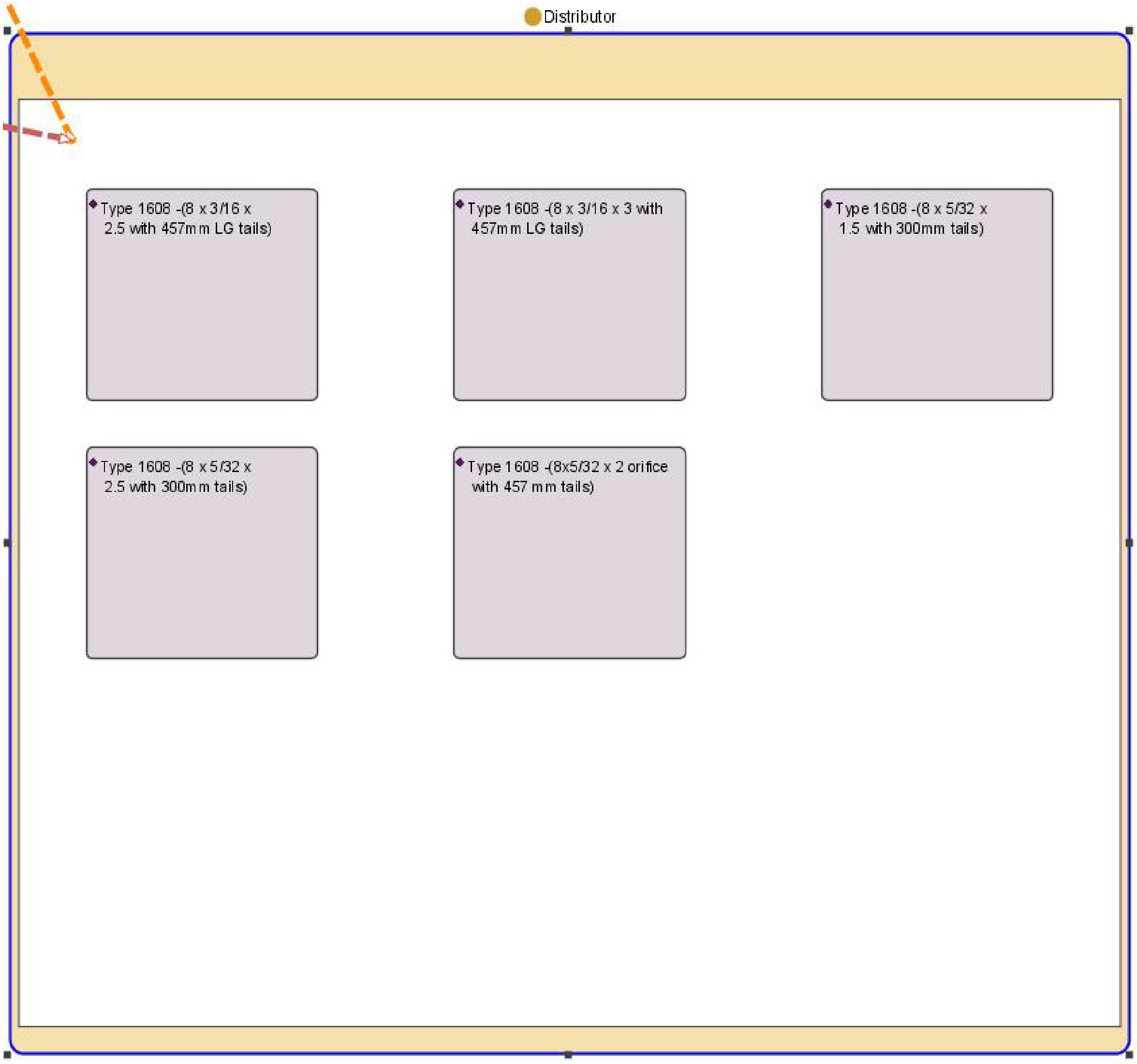


Figure 5.24 '*Distributor'* sub-class.

The last sub-class of the class '*Comments'* was '*Comments _From_Testing_Log_Sheet'*. This sub-class contained a number of sub-classes that matched the number of testing reports. The researcher separated this comment into another class for flexibility reasons. If this comment from testing log sheets was included in the testing report *individuals*, users had to repeat report data entry every time that the comments were added.

Figure 5.25 shows '*Comments_From_Testing_Log_Sheet'*, one of the sub-classes of the '*Comments'* class. This class contains a number of sub-classes that matched testing reports numbers.

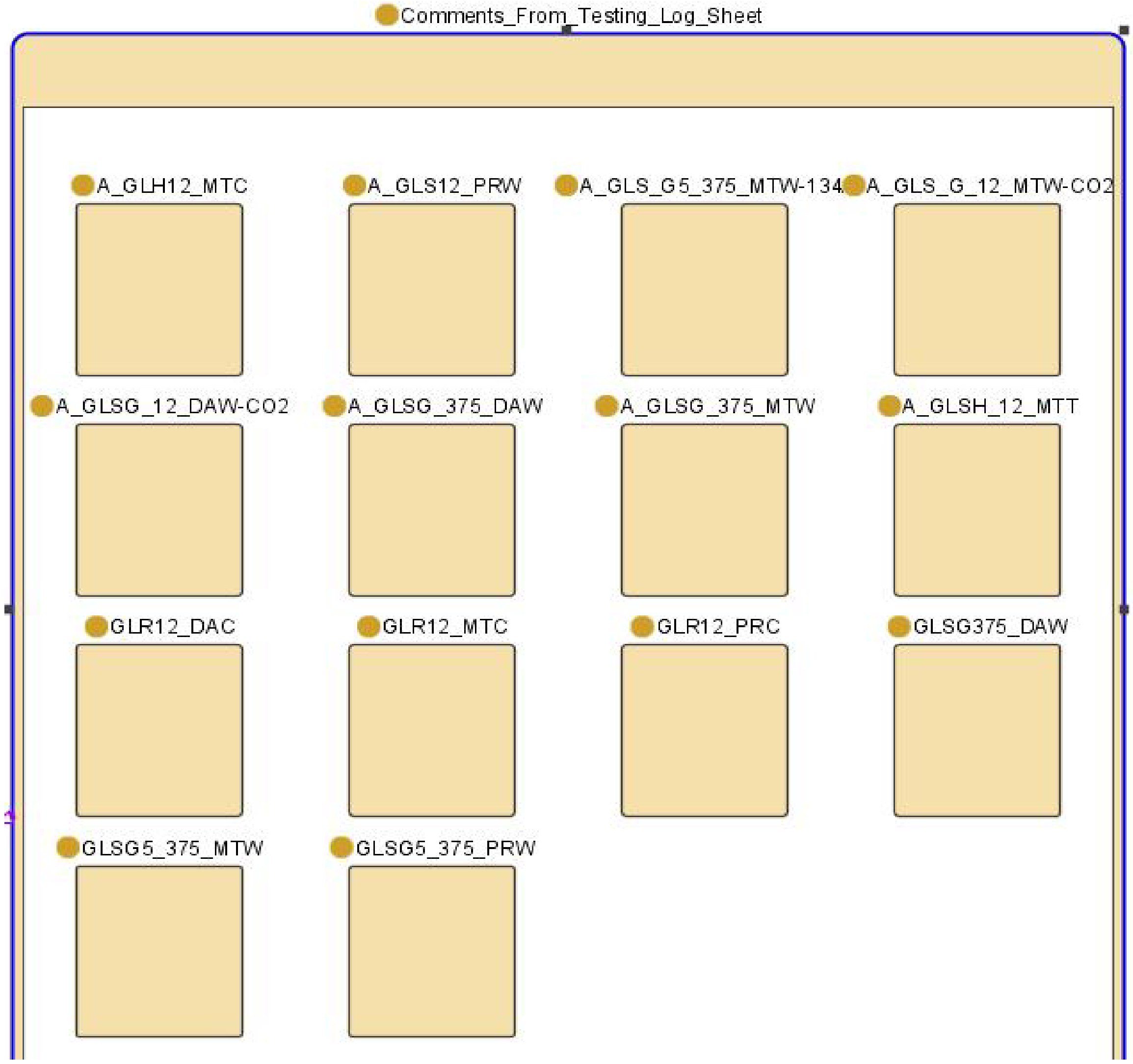


Figure 5.25 '*Comments_From_Testing_Log_Sheet'* sub-class.

Figure 5.26 shows sub-class GLR 12 DAC which contains a number of *individual* '*comments from testing log sheets'*. These individual comments were derived from the testing log sheets that the engineers wrote in the testing office. Each *individual* contained three *datatype* properties and two *object* properties. The *datatype* properties included '*Comment_in Log_Sheet'*, which contained integer values that the engineers could type with the modification note on what they had done to the cabinet each day. The next *datatype* property was '*Comment _On_Date*', which contained the calendar from which the engineers could select the data entry date. Another *datatype* property, '*Log location'*, contained the files directory of the local network where the measured parameters were kept. The first *object* property, '*Comments_From_Report_Number'*, links this comment to an *individual* in the

'*Test_Reports'* class. '*Test_Reports'* class and its *individual* have therefore been created.

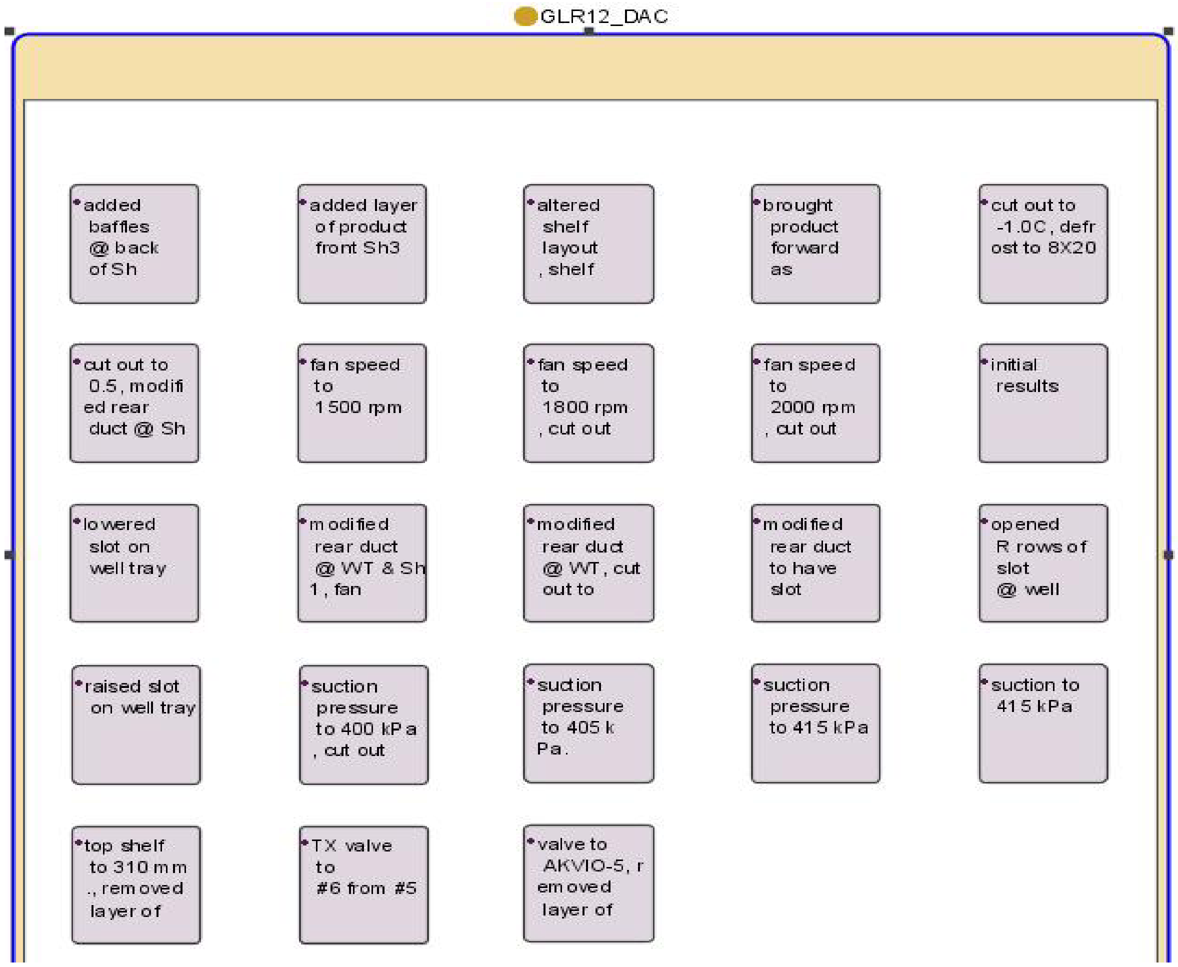


Figure 5.26 Comment from testing log sheet '*GLR 12 DAC'* sub-class.

The final *object* property in this *individual* was '*Today_Modification'* which linked this comment to the *individual* in the '*Modification_Tasks'* class. This meant that the class which contained *individual* related to modification tasks had to be created.

Figure 5.27 shows an example of the *'Comment_From_Log_Sheet' individual* from the cabinet GLR 12 DAC. This comment has '*Comment_In_Log_Sheet' datatype* property. The engineers could enter specific details when they next modified the cabinet. For example, Figure 4.23 shows '*Comment_In_Log_Sheet'* with value *'modified rear duct @ WT & Sh1, fan speed to 1500 rpm, cut out to 1.5 C'*. The next *datatype* property is *'Comment_On_Date'*, which in *Protégé* had a calendar for users to store information such as date, month, years and time. This example showed the value: '*September 18, 2007*'. The next *datatype* property, '*Log_Location*' contains '*C:\CaseRating\DATA_PACKAGE\LOG Files\TR# AUG07GLR12DAC-B10*'. The engineers could access the directory where measured parameters had been stored by clicking on the magnifying glass symbol on the right hand side of this field and Windows Explorer would open the specified directory. At the bottom of this *datatype* property all of the file names listed in the directory was shown. The '*Comments_From_Report_Number*' *object* property contains the *individual* TR# AUG07GLR12DAC-B10 which was linked to one of the testing report *individual* from the '*Test_Reports*' class.

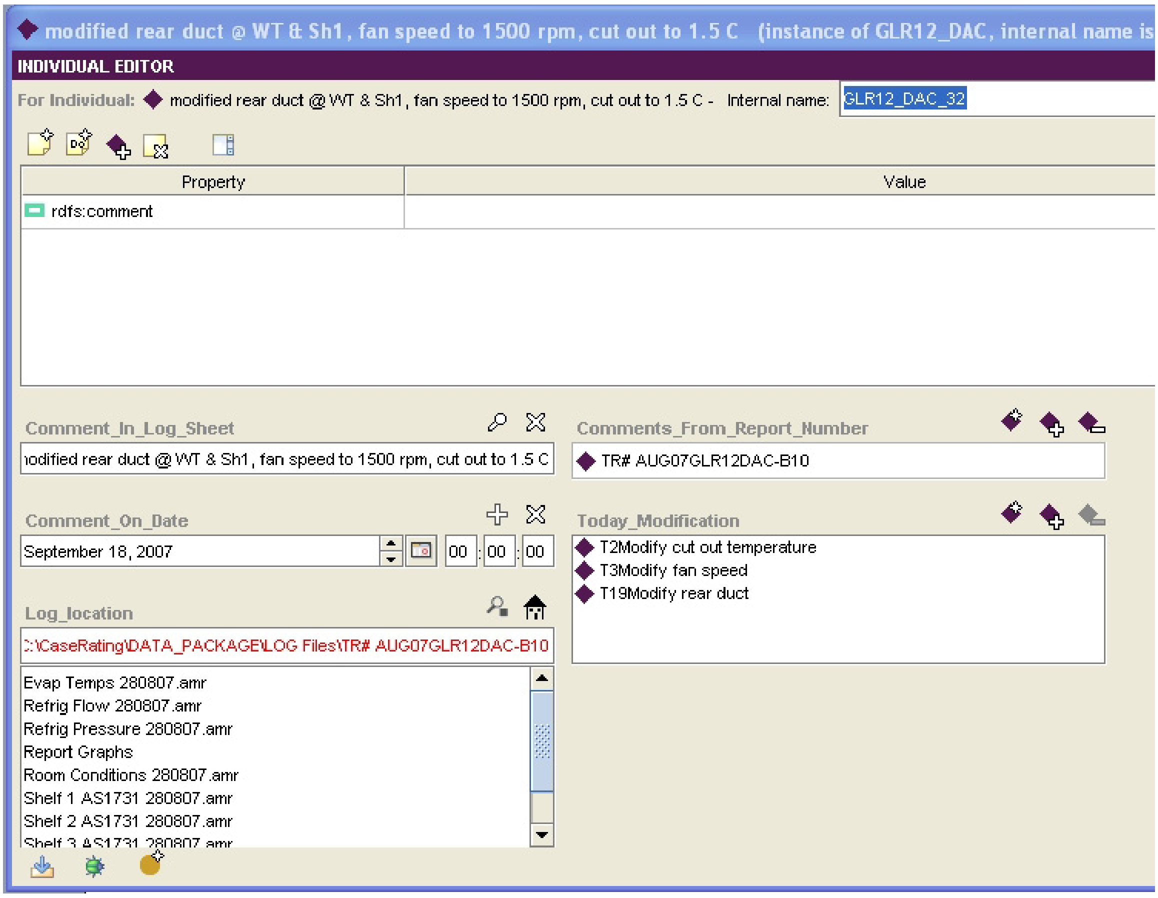


Figure 5.27 *'Comment_From_Log_Sheet' individual*

The next *object* property added to the ontology is '*Today_Modification*'. This property contains the value '*T7 Modify shelf layout*' which is the *individual* that has been linked from '*Today_Modification*' class. This T7 modification task is one of many such tasks. These modification tasks were investigated by the researcher at the beginning of the ontology construction period. The modification tasks that the engineers have noted in the testing log sheets vary. Sometimes the engineers make only one modification to the cabinet. Sometimes the engineers make multiple modifications to the cabinet. The maximum number of tasks that the engineers have made to the cabinet in one day was 5. Each task is different from each other. The first version of the ontology, included modifications as *datatype* properties in '*Comment_From_Testing_Log_Sheets'.* This means the engineers has to type their modification notes into the system and not write them down on paper. Structuring the system in this way was similar to the process that the engineers already undertook. In the evaluation the engineers reacted positively to this in the system.

However, after continual investigation over many months the researcher discovered that the tasks were repeated many times. During the research process the researcher listed all of the tasks that have been used as modifications to the cabinet. There are 41 tasks that the engineers have done in their work. This is based on 15 cabinet testing reports collected. Therefore, the researcher has created the *'Modification_Notes'* class which contains all 41 modification tasks as *individuals*, shown in Figure 5.28.

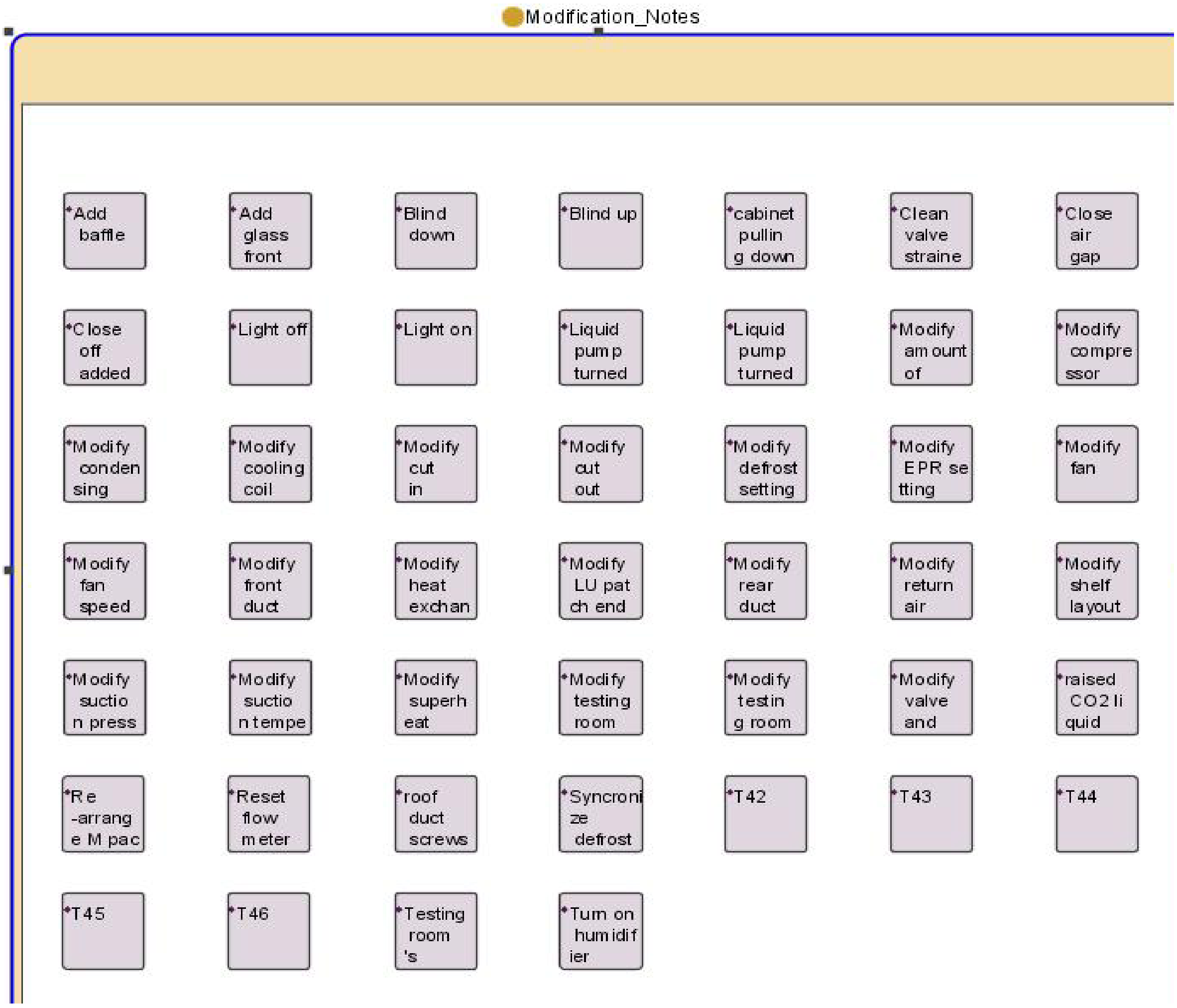


Figure 5.28 '*Modification_Notes'* class

These included tasks such as '*add glass front', 'modify cut in', 'Modify cut out'* and *'modify suction pressure'* etc. Each modification task *individual* contained only one *datatype* property with its value being the name of the modification task. Instead of typing string data into the system, the engineers could now select the tasks related to the cabinet. The tasks and the results could now be retrieved after they were modified.

It could now be seen that the modifications tasks were classified in their own entity. This meant that the product development processes were now flexible and compatible to further analysis. Details about how these tasks were used in analysis to solve the make-span problem are detailed in the next chapter.

The engineers brainstormed to decide on possible solutions and therefore tasks they could use to modify the cabinet. This was tacit knowledge that each engineer had gained over the years of their working experience. As each engineer had their own role in the product development process, the tacit knowledge was different from one to another. The team needed this diversity of knowledge to combine and create new knowledge to solve the upcoming cabinet conditions. This knowledge needed to be captured and stored in a format, other than written note form, that the engineers could re-use. The researcher therefore created a '*Tacit knowledge'* class containing tacit knowledge *individuals* (Figure 5.29). The numbers of tacit knowledge *individuals* were derived from the research during multiple data collections over a nine-month period in the Company.

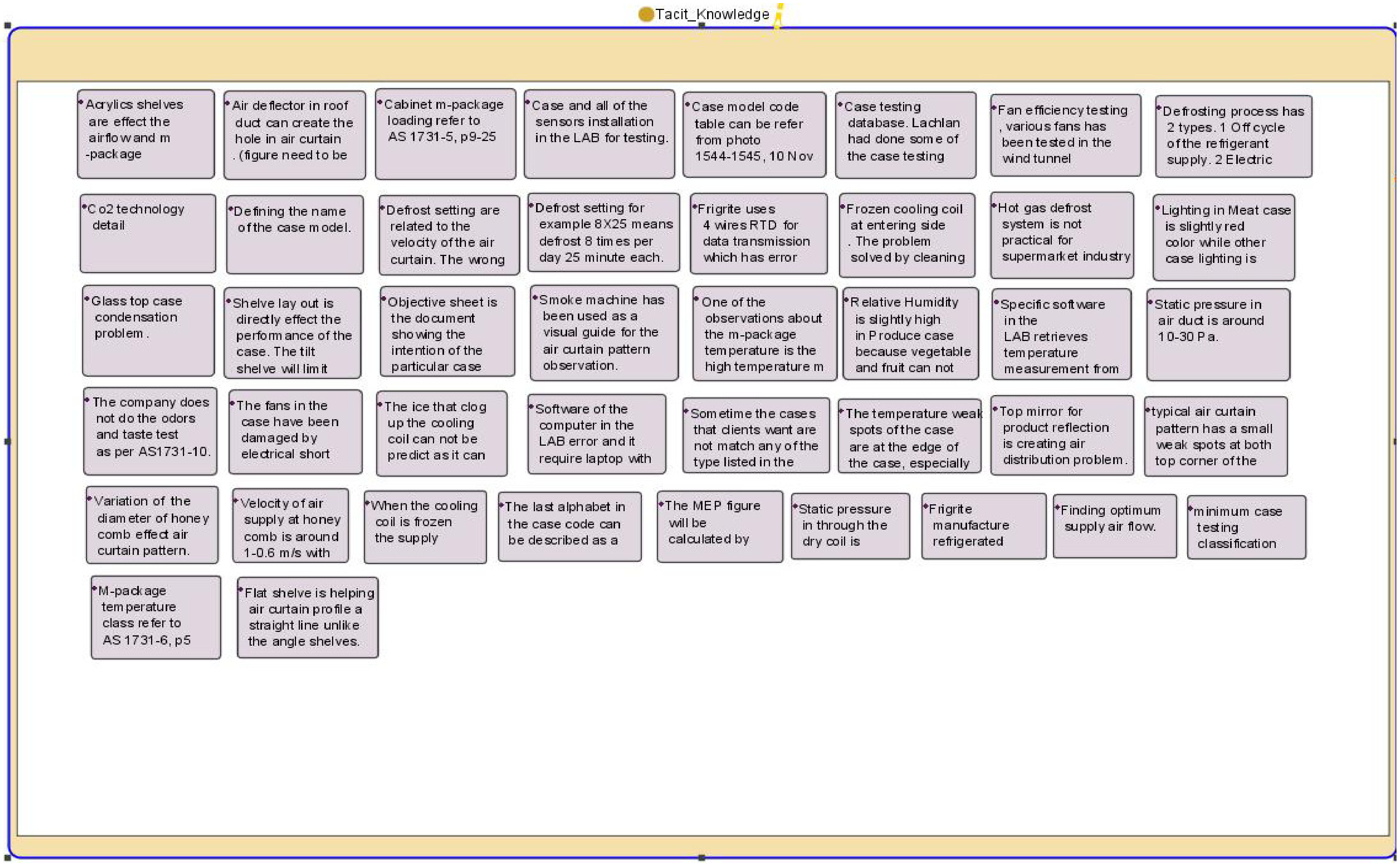


Figure 5.29 *'Tacit_Knowledge'* class.

Figure 5.30 shows a sample of the tacit knowledge *individuals* from the '*Tacit Knowledge'* class. Every *individual* in the same class had the same number of properties. It is different only in the value that is contained in the property. There are three *datatype* properties in the individual. First, *'Supporting Document For This Tacit Knowledge' datatype* property contains string data. The engineers could enter the file directory in this field and the system would give access to the file stored. *Protégé* provided flexibility to users. Users could put any kind of file type into the knowledge-based system. The system would open the software required when users double clicked on the magnifying glass symbol. The second *datatype* property was *'Tacit_Knowledge_Note,* in which the engineers could type notes about tacit knowledge that they knew in this field. The third *datatype* property contained a photo file directory. When the engineers entered file directory in the system it automatically showed the photo in the *individual*. There were two *object* properties. The first property, *'This_Tacit_Knowledge_Related to Part'*, enabled the engineers to select the particular *individual* of cabinet part that related to this particular item of tacit knowledge from the '*Parts'* class. The second *object* property, *'Knowledge_Contributor'*, had the feature where the engineers could select the name of the engineers who noted this tacit knowledge.

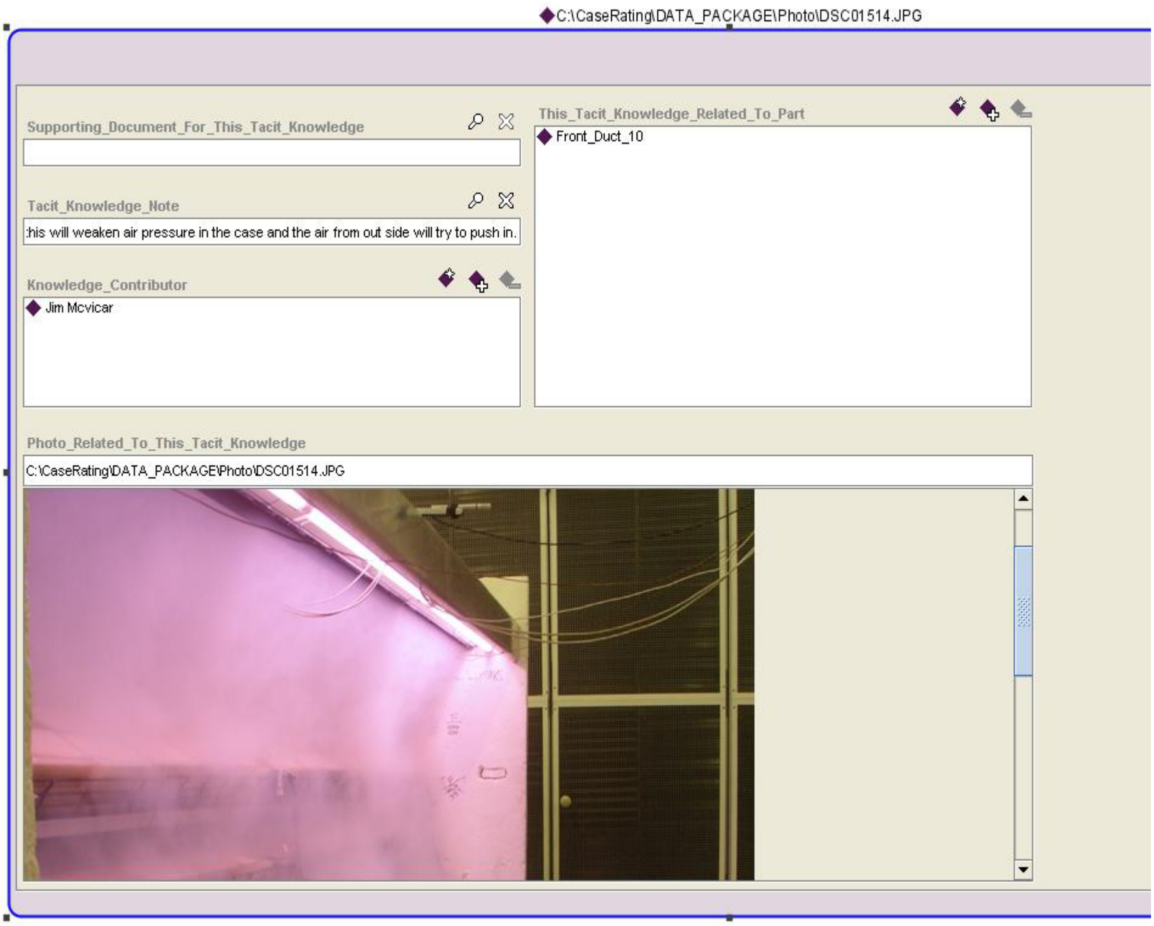


Figure 5.30 '*Tacit knowledge' individual*

The system did not have the class containing details about knowledge contributors at this stage. Therefore the researcher created the *'Knowledge_Contributors'* class as shown in Figure 5.31.

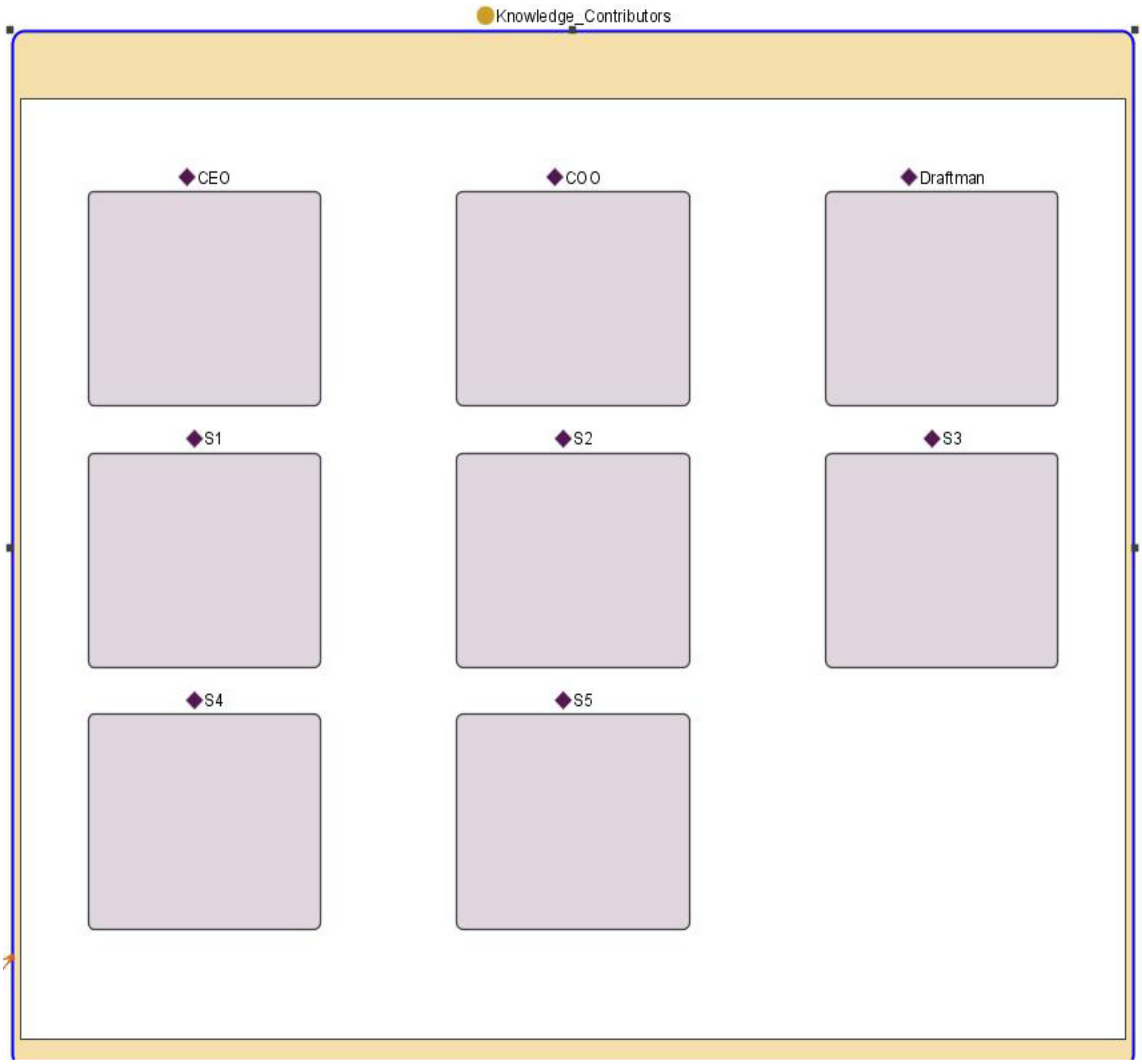


Figure 5.31 *'Knowledge_Contributors'* class contain the Company's engineer *individual*

Figure 5.31 shows the class '*Knowledge_Contributors'* with eight *individuals*. Each *individual* represented a person in the Company who was part of the product development process. Apart from five engineers other people involved include the CEO and COO, executives who were directly connected to clients. They contributed tacit knowledge to the cabinet designs during early stages of the product development process by bringing in the client's ideas to make it possible. There was also a draftsman who was responsible for the CAD drawing process. He too contributed tacit knowledge more directly into the cabinet parts production, rather than the cabinet testing process. However, there were a number of times during the shadowing process where the researcher found that the engineers had discussions about cabinet parts with the draftsman. In the tacit knowledge entry the engineers could enter the knowledge contributor into the system as a reference. This benefited the users who could view the tacit knowledge captured because if the viewers did not clearly understand the tacit knowledge note they could still find out by asking questions.

Figure 5.32 is an example of captured tacit knowledge. During the shadowing process the researcher saw Engineer S4 adjusting the settings of the front ducts. The question arose, why he was doing that? The researcher asked further questions regarding the actions that S4 had taken. Engineer S4 discovered that a 'typical air curtain pattern has small weak spots at both of the top corners of the case'. This was clearly tacit knowledge that needed to be shared with the other engineers. The researcher recorded this tacit knowledge and took a photo of the diagram where S4 explains what he found. The structure of the ontology then also facilitated information accessibility.

The researcher also created a *datatype* property with a photo file directory as seen in Figure 5.32. Sometime graphic images can reflect complicate knowledge better than plain text. In engineering sometimes diagrams can convey the message better than text (Blair 1992; Otondo et al. 2008).

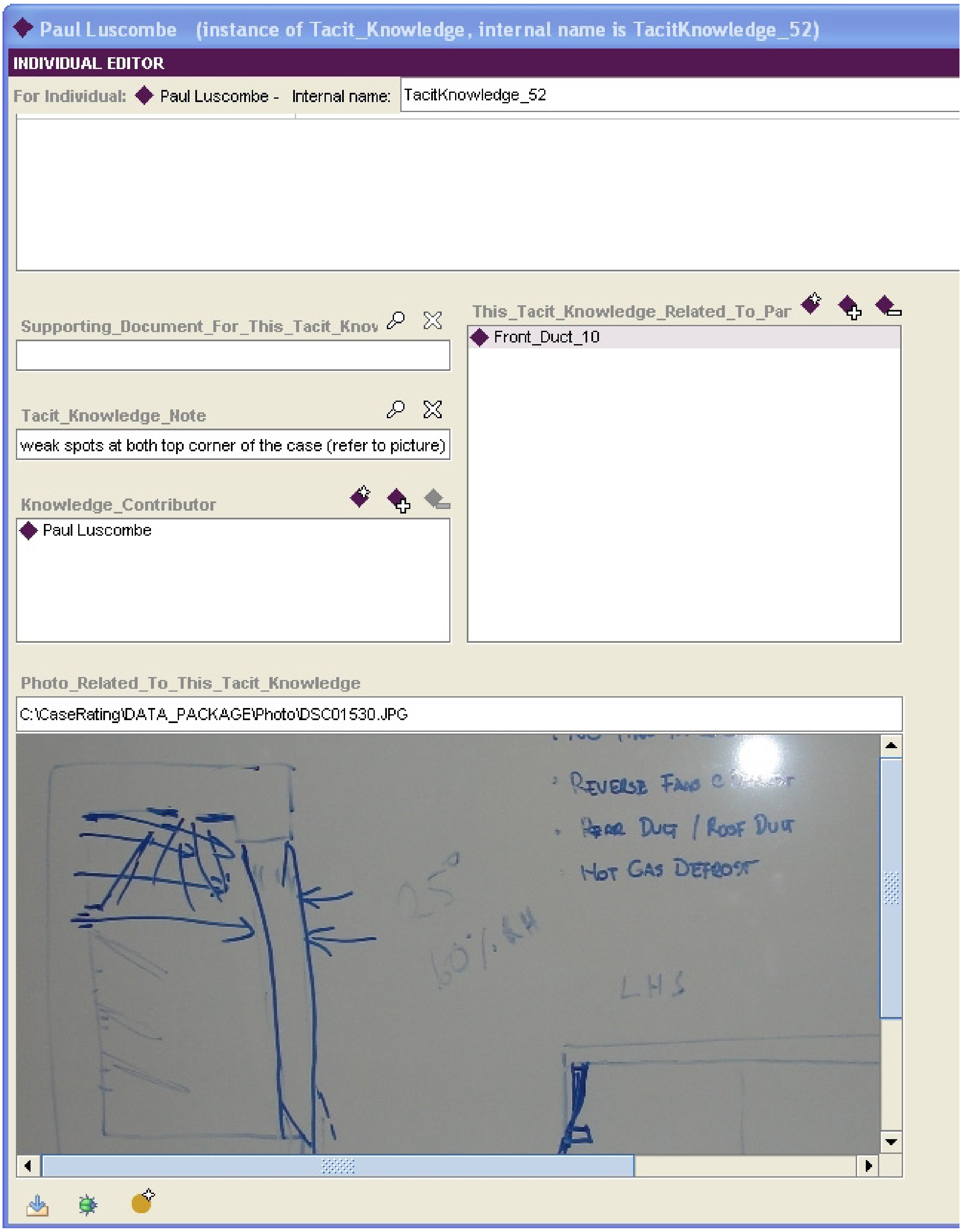


Figure 5.32 Example of a '*Tacit_Knowledge' individual*

As a result of building these classes, the researcher, with the collaborative assistance of the engineers, CEO and COO, developed a comprehensive, dynamic ontology based knowledge-based system using *Protégé*. The structure of the ontology was shown in Figure 5.1. The system enabled existing knowledge to be found. It could record new knowledge and store captured tacit knowledge. The ontology was built on the premise that relationships between classes are logical and represent the needs of the working engineers. The ontology was a representation of their domain knowledge, built in a way that reflected their needs so that the knowledge stored could be used and re-used. In the next section the researcher will demonstrate the usefulness and the logic behind the knowledge-based system structure determination.

5.3 Evaluating the ontology structure

The reason the researcher captured their knowledge and stored it in the system was because the engineers liked to retrieve and use their knowledge. Before this research the engineers stored their documents in various locations in the factory and made little use of that information because the information and knowledge were stored in different locations and were not cross-referenced. There was no link that could connect them together. The format of the engineers recorded information and knowledge were irretrievable. For example the testing log sheets, which were a crucial piece of information, were hand written. The information and knowledge was not recorded properly. By their admission, this led to them not using their knowledge properly. The engineers relied on remembering everything they had done. The following paragraphs describe how the engineers played a collaborative role in the system development to ensure it met their requirements and could answer their questions. The researcher used a series of scenarios to assist the engineers in working with him in the collaborative development of the system.

5.3.1 Scenario 1

The first example was used with the engineers to show how to use the system's query feature, and then suggest modifications to the system. The question used related to the specific physical characteristics of the cabinet such as case dimensions. Traditionally the engineers either remembered this information or had to open multiple testing report files to find out which cabinet had the required information. This often took hours. The knowledge-based system in *Protégé* had a query feature that enabled the engineers to search for single specific information.

Figure 5.33 shows the query tab in the knowledge-based system. The engineers could search for specific information. With the query tab, users could select the specific information from the slots available. For example, how many cabinet cases has the Company manufactured and what are the details? To do that the engineers have to select what class where the information required is stored. In this example they selected *'Class_Model'* class because the information required was in the cabinet individual. Then in the second field they selected the specific information wanted such as '*Case_Height'*. In the third field they select query criteria. In this example they select '*is'*. In the last field the engineers could type an integer value such as '*1500'* in this field. They then clicked the '*Find*' button. The system showed the query results in the right hand box. In this example the system showed two cabinet cases that were both 1500 millimetres high. For further details the engineers just double clicked at the individual that they wanted. This shows that the engineers could gain access to the information more easily, quicker and with greater accuracy than their previous search method.

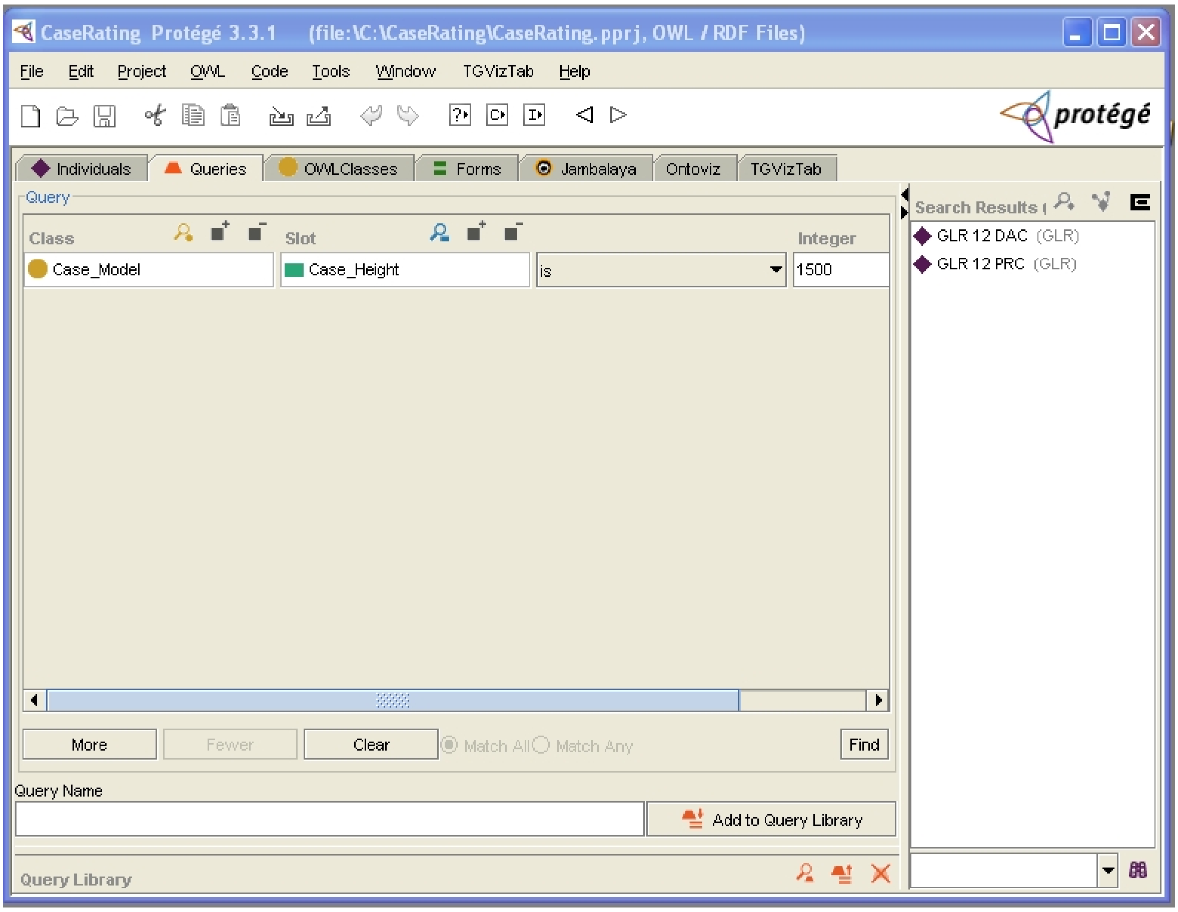


Figure 5.33 Query for single physical information of the cabinet

5.3.2 Scenario 2

The second example was about finding information about the cabinet which related to the Standard. Every cabinet which passed the Standard had a specific rating. The knowledge-based system could find this information. Figure 5.34 shows a query about cabinets related to the standard. In the first field the engineers still selected *'Class_Model'* class because the information required was in the cabinet individual. Then they select 'Rated' in the second field. Then they selected 'contains' in the third field and '*3M1'* was selected from the list in the last field. They then clicked the '*Find'* button. The system showed every cabinet in the system which was 3M1 rated.

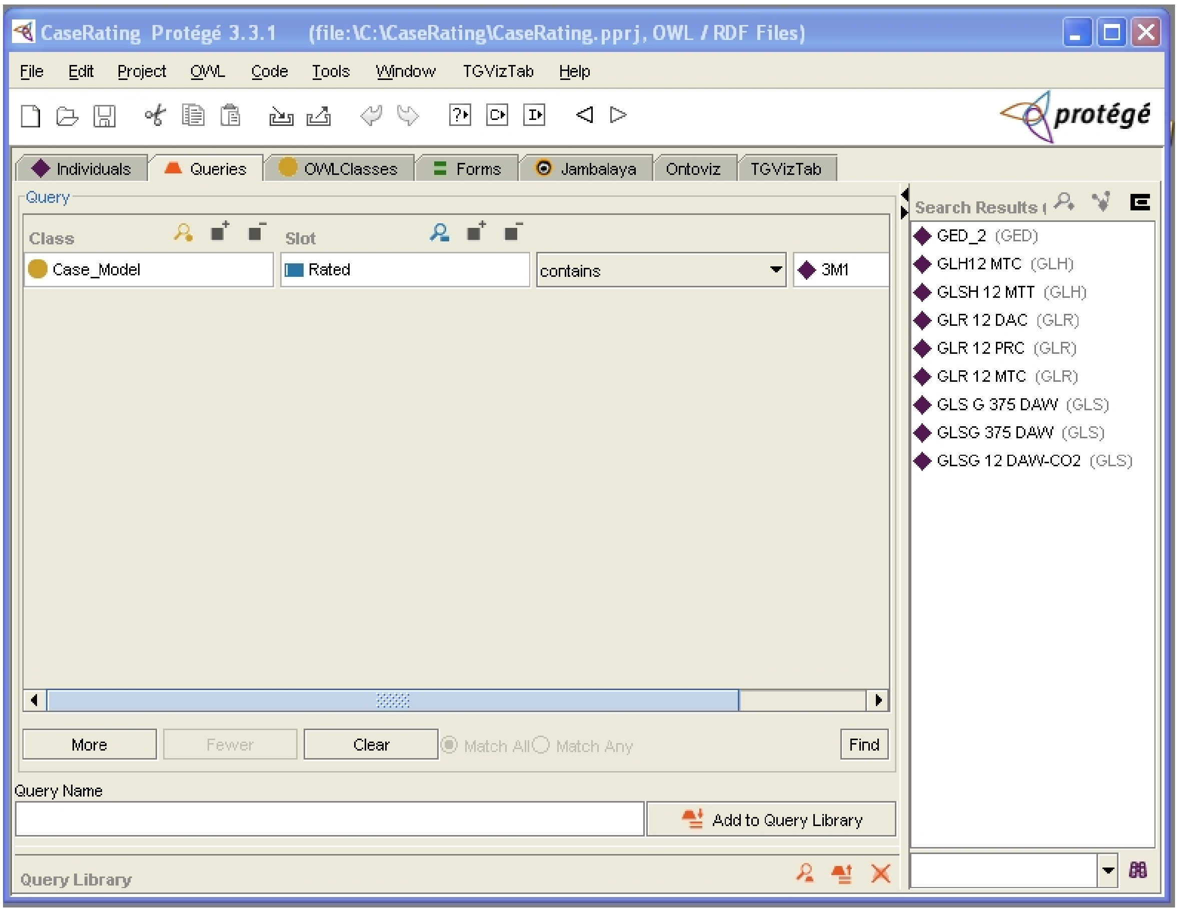


Figure 5.34 Query for single information regarding to standard.

5.3.3 Scenario 3

The third example was finding information from multiple criteria. *Protégé* allowed users to search for anything in the system. However, it was limited to how the users created the system structure. This system was developed with the engineers to overcome this limitation.

Figure 5.35 shows multiple selection criteria in the query tab. In this example the system could answer questions such as how many cabinets had the Company have manufactured that were 3M1 rated and which used refrigerant R134a. The engineers could use the select procedure as in the previous examples. However, this time they had to add a second selection criteria by clicking at the '*More'* button on the bottom of the query tab. Then in the second row the engineers had to select '*Case_Model'* in first field. In the second field they selected '*Use_Refrigerant*'. Then in the third field they selected '*contains'* and in the final field selected '*R134a'* from the list. They clicked '*Find'* and the system displayed the result, which was '*GLS G 375 DAW*', the only cabinet which was 3M1 rated and used R134a as the refrigerant.

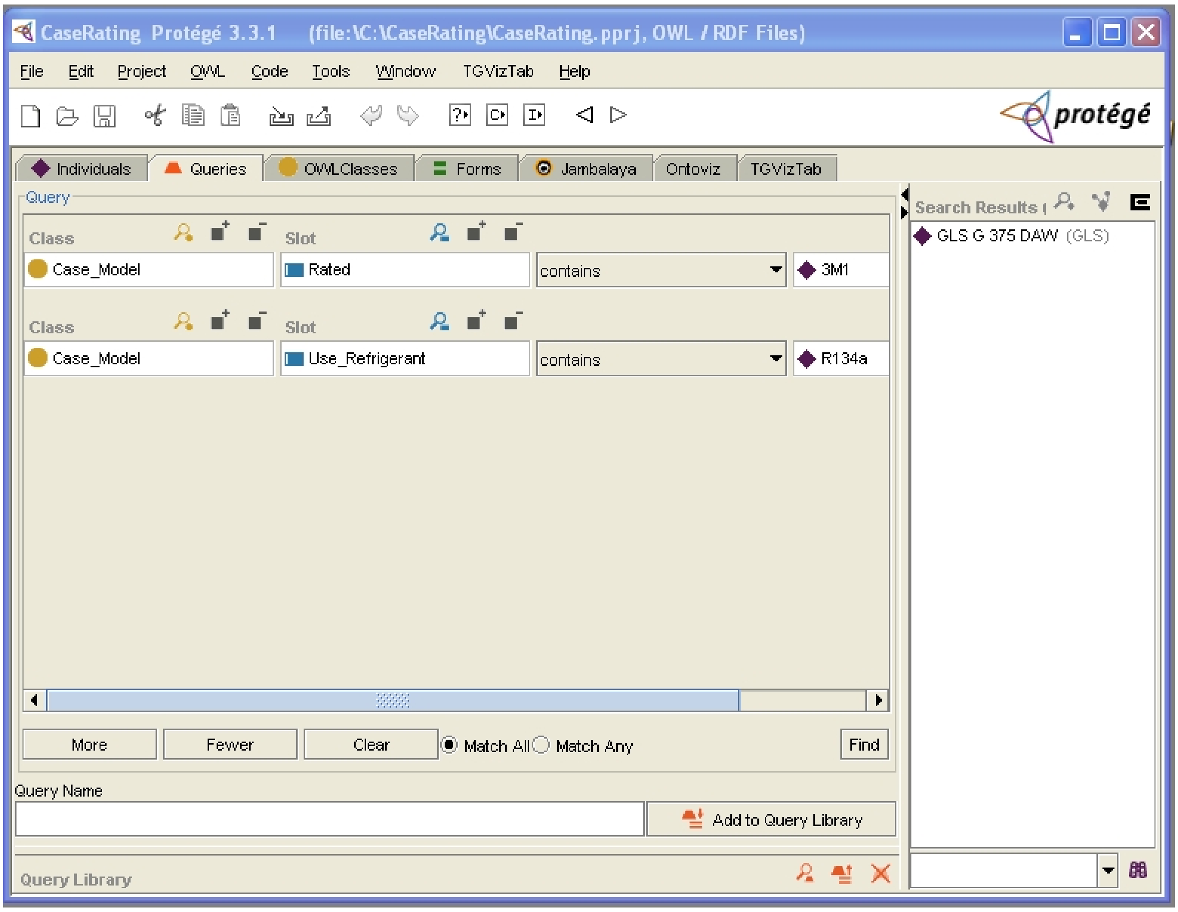


Figure 5.35 Query for information form two selection criteria

The system can also show the inverse value of the information as shown in Figure 5.36.

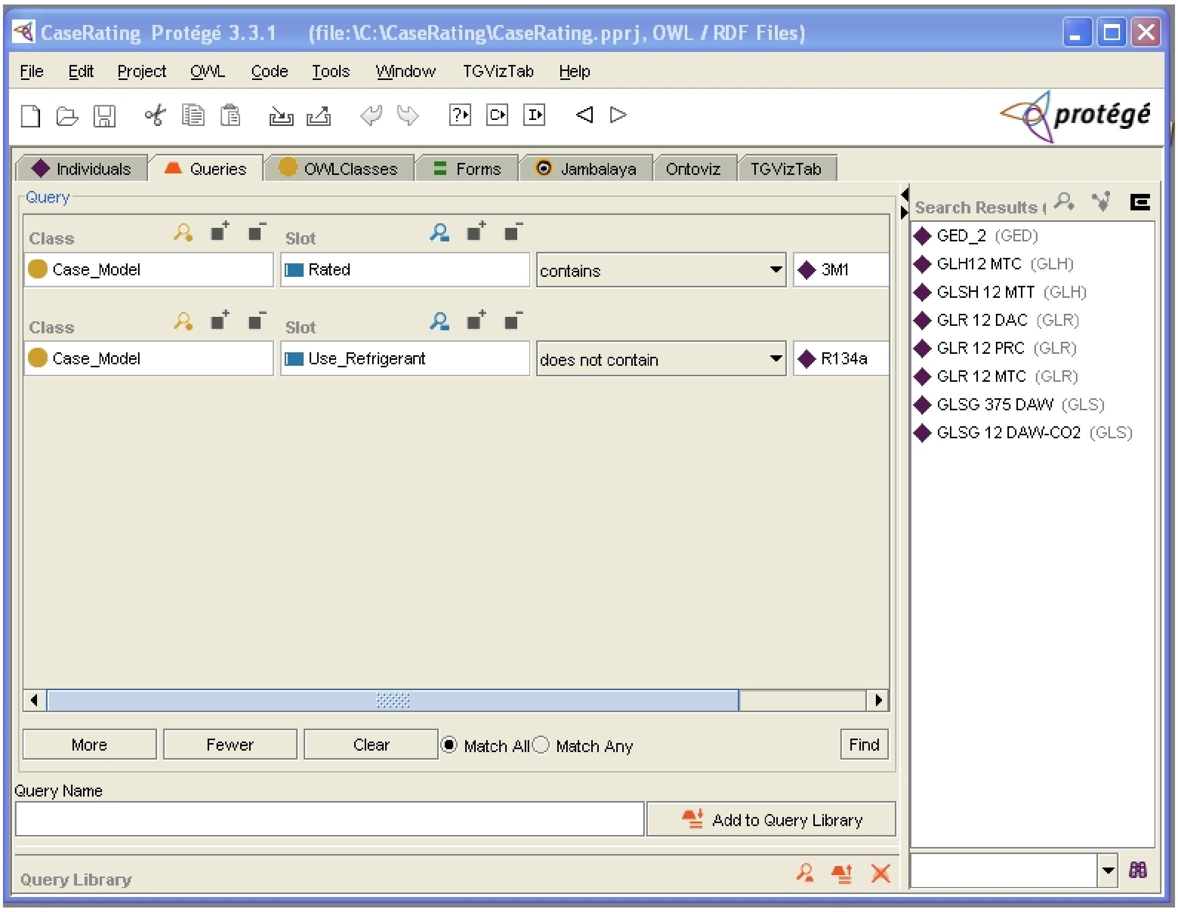


Figure 5.36 Query for information with opposite criteria

The system previously showed all of the cabinets which were 3M1 rated. However, in this *individual* it showed the cabinets which did not use R134a refrigerant. In the third field the word 'does not contain' was selected. This example and the previous one showed that searching for specific information about the cabinet was very accurate and quick in the system developed. The engineers confirmed that their traditional way of finding information could not find the same information as quickly.

5.3.4 Scenario 4

The fourth example showed how to make a query about the Standard. The engineers had kept the National Standard in two locations. First, there was a hard copy Standard kept in the testing office and electronic files were kept in each engineer's computer. The Standard, in electronic format, was divided into 14 files, each file representing a chapter. The knowledge-based system helped the engineers search information about the Standard as shown in Figure 5.34 because it was stored as part of the ontology and thus in the same place as their other knowledge.

As with the previous examples the engineers had to select criteria in each field. *'AS_standard_detail', 'Standard_detail', 'contains'* were selected in each field accordingly. The word 'dimension' was typed in the last field. Then they clicked the '*Find'* button. The system showed the 'Part 3 Linear dimensions areas and volumes' individual from '*AS_standard_detail'* class. The engineers could then double click at that part 3 individual to gain access to the Standard in electronic form.

5.3.5 Scenario 5

The fifth example shows a query related to the testing log sheet. This query gave the engineers access to their testing log sheets, as they had never had before. The engineers noted their modification by hand writing on paper. To look at testing previous product's log sheets was nearly impossible because the engineers did not have time and the log sheets were not easily identified, as they had been poorly coded. Figure 5.37 shows the query for the testing log sheets. In the first field '*Comments_From_Testing_Log_Sheet'* class was selected. In the second field the *'Comments_In_Log_Sheets'* was selected. In the third field '*contains'* was selected. In the last field the word 'rear duct' had been typed in. Then they clicked '*find'*. The system showed the results from multiple testing multiple cabinets, multiple log sheets and every day that the '*rear duct'* had been modified. The engineers could also click at each *individual* result to see further information such as what happened after the rear duct had been modified. The engineers noted in their evaluation that they had never gained access like this before. This query was crucial to their product development process. The engineers needed the ability to access this knowledge efficiently to avoid having to 'reinvent the wheel'.

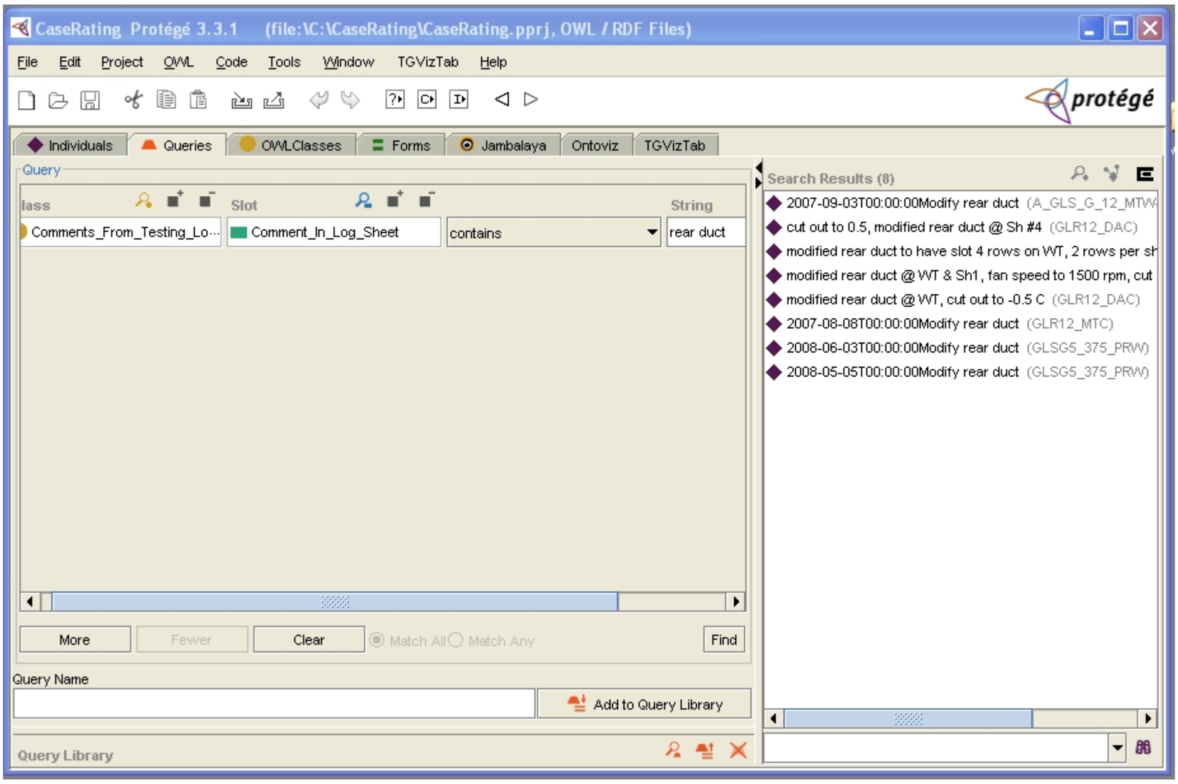


Figure 5.37 Query form testing log sheets

5.3.6 Scenario 6

The sixth example used with the engineers shows a query related to captured tacit knowledge. The engineers had never recorded any of the tacit knowledge that each member had discovered when doing their tasks. The best scenario was that they told their colleagues verbally in the daily meetings. The knowledge-based system structure facilitated tacit knowledge capture. This is because it provided a channel to store things related to it. This included photos, documents, personal notes and cabinet parts. Figure 5.38 shows a single criteria query about tacit knowledge. This example showed tacit knowledge related to cabinet parts. In the first field the class '*Tacit_Knowledge*' was selected. In the next field '*This_Tacit_Knowledge_Related_To_Part*' was selected. The element '*contains*' was then selected. In the last field '*Rear_Duct_6*' was selected. Then they clicked the '*Find*' button. The system showed the result as the individual "*Finding optimum supply air flow*." The engineers could double click at the *individual* and find further information.

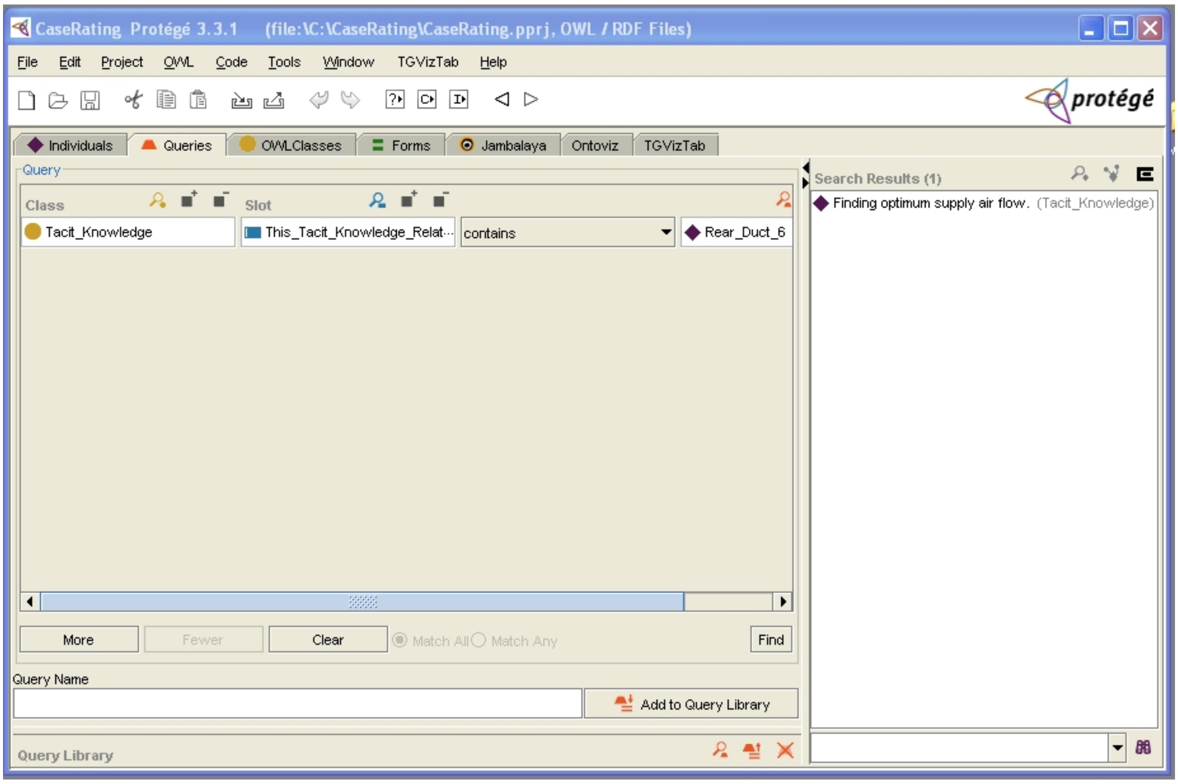


Figure 5.38 Query about tacit knowledge.

The last example used with the engineers was also a query about tacit knowledge. However, this time the selection criteria were string values. The engineers could type the word in the query.

Figure 5.39 shows how they could make a query about tacit knowledge by using keywords. This time in the second field '*Tacit_knowledge_Note'* was selected. By doing that, the last field was automatically prompted for a string value entry. The word '*defrost'* was typed in the field. Then they clicked the '*Find'* button and the system showed the results drawn out of the tacit knowledge that related to the defrost parameter. The engineers could also look for further details by double clicking at the *individual* of interest.

This knowledge-based system then provided a query feature, a fundamental contribution to making the engineers' work processes more efficient. The system provided access to existing information in a short time. It provided access to multiple sources of information that the engineers needed to retrieve in a way that they had never done before. This query feature was a decision-making support tool to the engineers during their daily product development meeting.

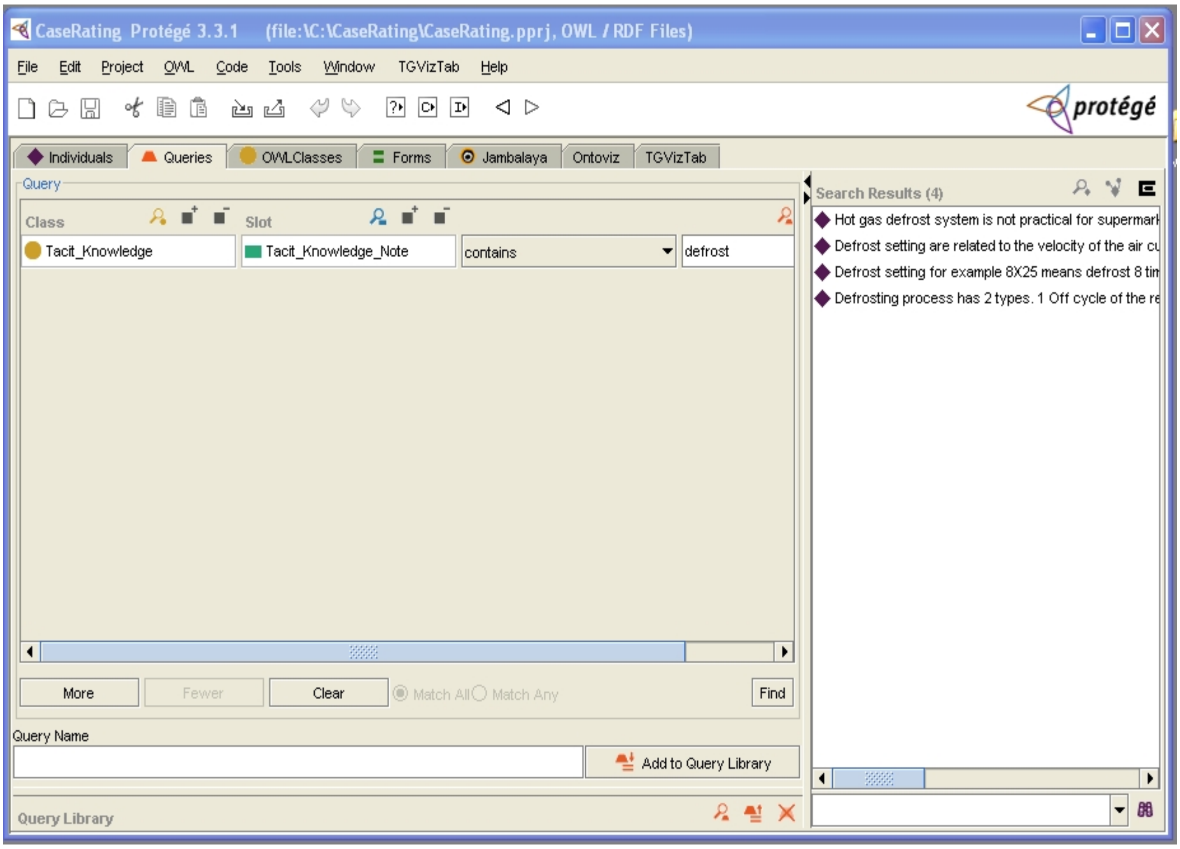


Figure 5.39 Query about tacit knowledge by using the keyword.

A detailed evaluation of the efficacy, effectiveness and usefulness of this artefact and the efficacy of its operations was undertaken throughout each of the iterations of the building of the ontology. The results of that evaluation are presented in detail in Chapter 6.

5.4 Conclusion

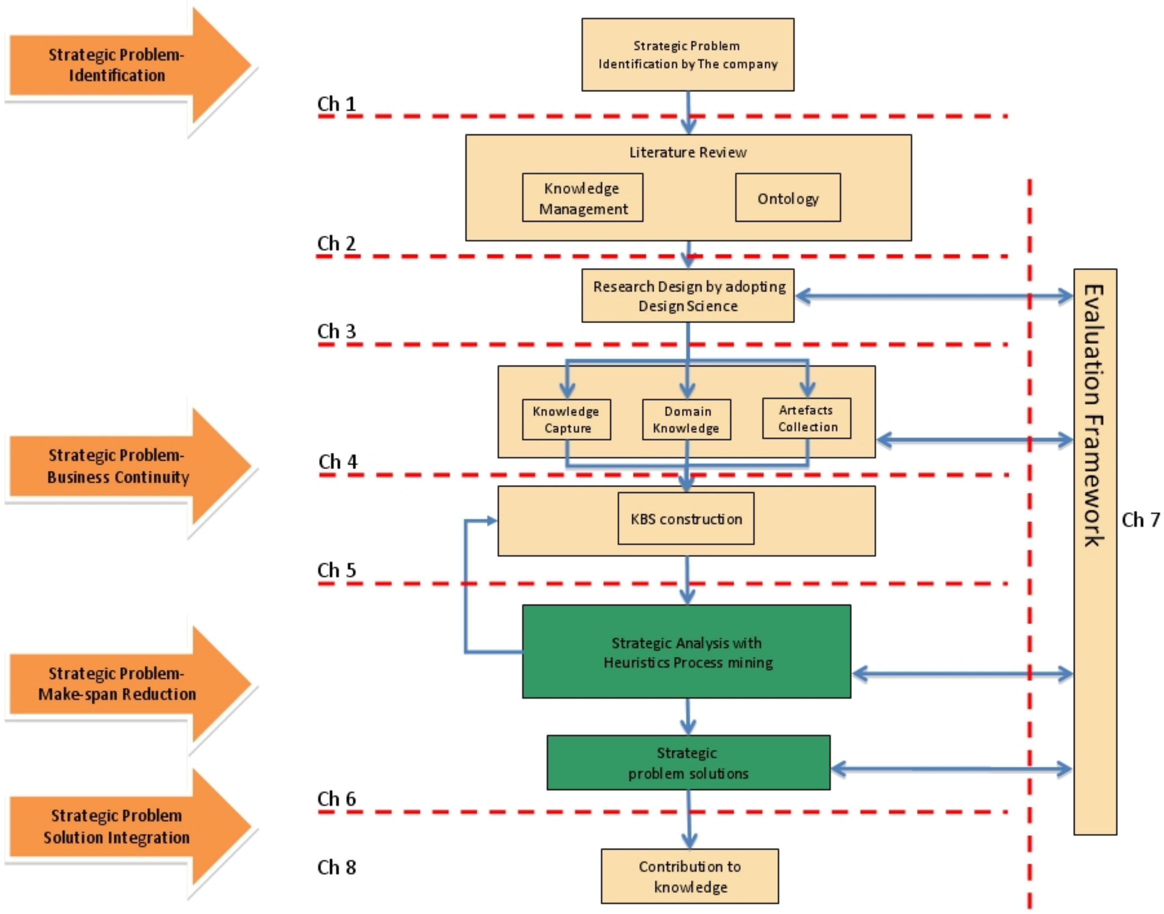
The ontology construction methodology (Object Oriented) is not new. Applying this methodology to create knowledge management system is also not new. Empirical studies have used *Protégé* to build knowledge management systems. This included work by Kim et al. (2009). However, creating a specific ontology structure to the specific refrigerated displayed cabinet development process domain knowledge is new. Furthermore, creating an unique ontology to solve a company's specific business strategic problem is new.

Previous knowledge management research has focused on large scale systems. Researchers were trying to capture the whole organization's knowledge. In this research the knowledge management system created focused only on capturing specific domain knowledge (cabinet development process knowledge) from specific group of people in the organization (a small group of engineers in product development department). The knowledge from this group of people was vital for organizational business continuity through their products design and testing. The knowledge management system was designed to solve specific business strategic problems which were firstly, business continuity, because staff were leaving the Company, and secondly the product make-span was too long.

This knowledge management system helped the engineers to capture their day-to-day product development process knowledge which was constantly generated. It also enabled knowledge re-use. Through the iterative nature of Design Science the knowledge management system was a collaboration between the researcher and the engineers and was iteratively built and evaluated through out a period of two years. The structure of the knowledge management system contains elements that are a reflection of the Company reality. This was confirmed by the engineers.

The ontology developed by a collaborative process of building and testing with the engineers, the CEO and COO of the company, supplemented by longitudinal research whilst the researcher was embedded in the Company, was designed to meet the working needs of the engineers and the strategic needs of the Company executives. The system captured and organised the Company's knowledge, both explicit and tacit. It provided an organised storage of the knowledge wealth of the Company in a form that was searchable, and able to be built upon dynamically. The system, illustrated in Figure 5.1 at the start of the chapter, was needed by the company as a solution to its strategic intent of retaining its competitive advantage by capturing the knowledge of its design engineers. In addition, the system facilitated knowledge sharing where relevant knowledge could be shared among the engineers in their product development process. The system also facilitated knowledge sharing vertically, which meant knowledge could be shared among different generations of employees. The knowledge-based system could be seen as a strategic business tool for the Company to gain competitive advantage. However, the researcher was also interested to test how the knowledge stored in the system could also be used to solve other business problems. In the following chapter, the researcher mines this knowledge stored in the system to enable an analysis to be undertaken which will resolve the other problem of the Company, that of a too-long make-span.

Chapter 6 Improving the Company's make-span problem



6.1 Introduction

This chapter reports the outcomes of research into the Company's make-span problems. The solutions derive from a knowledge mining exercise using extraction of information and knowledge stored in the Knowledge Management System described in the previous chapter. The knowledge mining activity was undertaken to assess the capability of the KMS to enable solutions to the identified problem. A knowledge management system can be used to mine the knowledge effectively, it is argued, to solve other strategic needs. In this case, the strategic need is to reduce the make-span of new products. This chapter describes the existing design make-span process and then uses heuristic process mining to generate and evaluate solutions to reduce the make-span/design time processes.

6.2 The Problem: The existing design process.

The Company's testing process of their refrigerated cabinets began with development of a prototype. An initial setup was established in a laboratory and initial measurements of cabinet performance result were recorded. Engineers then brain-stormed for possible modification tasks that could be made to the prototype cabinet because the prototype did not meet National Standard and/or the client's requirements. These possible modifications came from the personal experience (domain knowledge) of each engineer. The Engineers had to look at every aspect before making a decision about what needed to be changed. On some days engineers came up with one modification, and on other days multiple modifications occurred. The engineers then turned the modification tasks, decided by the group, into an action by physically adjusting and changing settings of the prototype cabinet in the laboratory. The modified cabinet was re-tested for another 48 hours before the next results were reviewed. There were many instances where single and multiple modifications were immediately repeated on the following day. Some single modifications derived from evaluation of previous modifications. In other instances, multiple changes were made and the processes were repeated.

Two observations are clear about the design process in use:

- The modification processes were iterative. The modifications often emerged on the basis of which engineer was in at the morning meetings to determine what had to be done on that day. On any given day there could be either single or multiple modifications.
- The modifications derived from the morning group meeting on any day occurred in an arbitrary fashion. There was no defined sequence for testing. There were no set processes. The engineers kept testing the prototype cabinet until the results met the required National Standard in terms of temperature and overall power consumption and customer requirements. The standard states that any given refrigerated cabinet to be sold in Australia has to be able to cool the products to temperature determined in their own temperature and cabinet class as well as, overall electrical power consumption cannot exceed what is stated in the standard.

Each cabinet modification and re-test consumed at least 24 hours. Collected data from cabinet testing was placed on a log sheet. An examination of all the existing log sheets collected for inclusion in the KMS (Chapter 5) showed that, in general, the testing processes took from a minimum of one week up to a maximum of one year. Most commonly the latter was the norm. In the initial phase of this research, the CEO of the Company made it quite clear that this process was too long and that efficiency had to be achieved by changing that process. His problem though was he didn't know how.

Figure 6.1 shows some of the cabinet structures. The problem regarding product development was very complex and involved many factors. For example, on the left side of Figure 6.1 the bare structure of the cabinet, in which four fans had been installed, is shown. The centre of Figure 6.1 shows a part called the 'rear duct', which is a metal sheet that has been punch died to make holes on it. The rear duct was installed at the back of the cabinet to cover the fans as shown in Figure 6.1 (shown right). The engineers knew that the amount of air required to cool the M-package (white) would form their calculations.

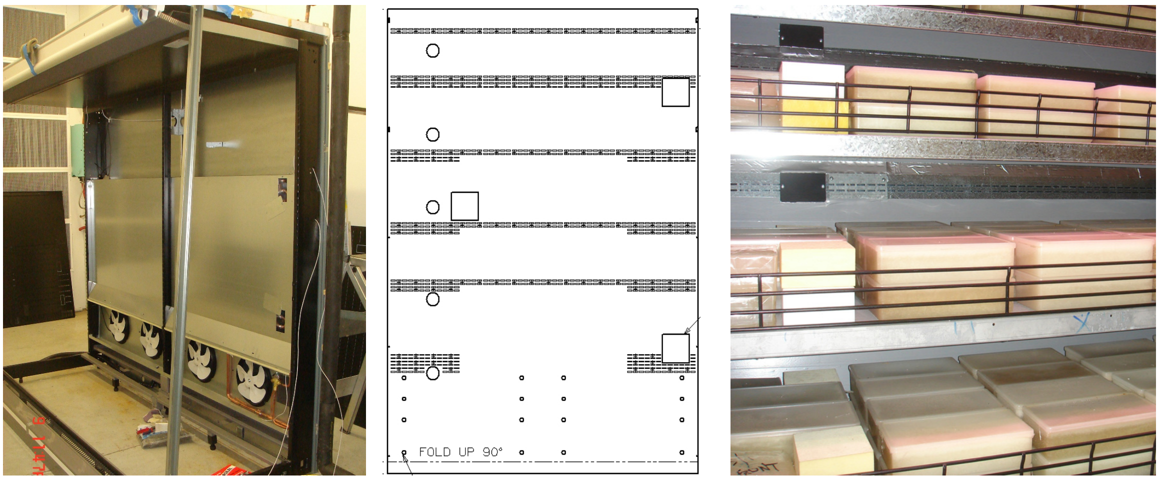


Figure 6.1 Cabinet components.

However, the engineers didn't know how much air came out of each hole, or how it affected the temperature of the M-package on each shelf. Engineering an open system (i.e., the refrigerated display cabinet has no door) is complex and it is difficult to control the temperature of the M-package. The other factor which played an important role in the design was total electrical power consumption. The engineers adjusted the fan speed, number of holes, locations of holes on rear duct, cut in and cut out working cycle, defrost cycle, pressure and temperature of refrigerant on trial and error basis to get the temperature of the M-package and power consumption to meet the standard.

This raised a series of questions for the research:

- Which modification tasks were necessary?
- Which modifications determined the best result for a cabinet in meeting both the required standards of performance and the demands of the customer?
- Which tasks were not necessary to do?
- How well did the engineers build up their expertise from past decisions with respect to making multiple modifications to the cabinet?
- Could the engineers distinguish necessary tasks from all of the regular tasks that they had been undertaking?

The answers to these questions, it was decided, would help the engineers to eliminate unnecessary tasks. This would result in shortening the testing process period. To enable this process to be shortened the researcher decided to apply a heuristic mining process to the data stored in the KMS.

6.3 Heuristic Process Mining

6.3.1 Heuristic Mining

The heuristic mining technique is an analytic process (HPM) and has been used by many researchers in various applications. Weijters & Van der Aalst (2003) used this technique to construct software called 'Little Thumb'. The purpose of the software was to measure dependency relations between tasks in specific finance business processes such as a mortgage, a tax declaration, an order and/or request for information (Weijters & Van der Aalst 2003, p. 4). The sample processes used in that research are static. In other words, tasks in the process are limited to the sequence of tasks in work procedures where large numbers of workflow logs have been recorded from many cases. The majority of tasks in the recorded logs of the Company are repetitive tasks. Many tasks in the workflow had to be executed in a specific order. For instance, ‘evaluate’ cannot occur before ‘register’. This means the event route in the workflows are limited to certain amounts. The number of times that any given tasks have been executed varies from 900 to 4000 times in sequences. In other words there are 900 to 4000 process instances. HPM can deal with large numbers of instances and therefore is useful in transactional analysis in workflows.

Empirical studies of process mining have shown that it can identify actual phenomena embedded in process logs and suggest possible solutions to improve those processes. Kim and Ellis (2007) proposed a number of workflow mining techniques to cover various kinds of processes. These included transition sequential, conjunctive (AND) and disjunctive (OR) transitions. The purposes of these are to find the actual flow of information in the office, identify inconsistency and suggest possible restructuring to solve the problem (Kim, K & Ellis 2007). Fusun et al. (2009) proposed Workflow Inference from Trace (WIT) to approximate target workflow (Fusun, Tim & Mark 2009). Gu et al. (2008) have extended the algorithm to mine duplicate tasks such as task loops in workflow nets (Gu, Chang & Yi 2008). This loop process was a limitation identified when Van der Aalst and Weijters originally proposed this technique in 2003 (Weijters & Van der Aalst 2003).

Researchers have applied HPM in other applications. Cordova et al. (2008) have applied coloured Petri nets to an underground mining process to improve mining productivity (Cordova et al. 2008). Prashant et al. (2001) applied Petri nets and a genetic algorithm to minimize costs in project management. Febbraro and Sacco (2004) have applied Petri nets to a traffic light system to improve traffic flow (Febbraro & Sacco 2004).

The heuristic mining technique has also been used in research because it can deal with noise in the workflow. Weijters and Van der Aalst (2003) did two process mining experiments. In the first experiment they applied the heuristic mining technique in different cases with 16 process instances of workflows with varied noise levels, starting with no noise, 5% noise and 10% noise. Then in the second experiment they applied the heuristic mining technique in 12, 22, 32 and 42 process instances workflows with three noise levels of 5, 10 and 20%. The experiments demonstrated that the technique can be used to reconstruct the workflow with correct dependency and frequency (D/F) graphs. The result also showed that the heuristic process mining technique was vigorous against the impact of noise. However, the result started to become less valid when they applied 20% noise. The error also occurred in short loop sequences. They stated early in the paper that the rule does not cover the short loop condition. Then, when they reported the results of their experiments, they said there were errors which occurred in short loops but didn't say what the errors were.

This process mining technique has been applied on specific data workflows. The data embedded in this workflow has a simple characteristic. The routes of the process from different cases did not excessively vary from one task to another within the procedures studied. The amount of self-repeated tasks were limited and some tasks can happen only once in a single case. Unlike this case, the Company's workflow (where data embedded in the workflow) was derived from knowledge, thus the research data was more complex than transactional data used by (Rozinat et al. 2007). Each modification task that the engineers made to a prototype cabinet was generated from experience (knowledge) accumulated over time. Most often, this knowledge was not a single task or transaction. The engineers selected the possible modification tasks in combinations that they thought would operate the prototype cabinet. These tasks affected the testing cabinet's efficiency in approaching the required standard. Task A could happen at any time in the process as well as task B. Sometimes the Company's processes contained multiple instances in one job step. All of these instances could be repeated at any time during the process. Therefore, in this research some modification of previous applications of HPM were necessary.

In the semiconductor industry wafer scanner machines play an important role in the chip-making process. The wafer scanner machines operate by using a lithographic method, similar to how images are printed on film in a camera (Martijn, Barend van den & Frits 2006). The machine is used to make circuit patterns to appear on a wafer which was a slice of silicon (Mans et al. 2009). The patterns on the microchip were very small. The assemblies of the wafer scanner machines are very precise and exactly the same. To manufacture wafer scanner machines the precision of assembly in the machine was of great concern. Misalignment of any parts in the machine results in microchip production failure. The wafer scanner manufacturer spends an enormous amount of time testing the machines. During machine manufacturing time in the factory the wafer scanner machine was tested until the machine passes all tests. Then the machines were dissembled and send to be re-assembled again at the client's site. Testing began again at the client site until the machine passed all test procedures. Wafer scanner machine testing was a time consuming process. Testing too many times results in a long make-span which leads to competitive disadvantage from increased make-span costs. Insufficient testing processes can result in machine malfunction. Rozinat et al. (2007) applied heuristic process mining to this problem by using 'The Heuristic Miner' to optimize the wafer scanner testing time. Tasks in wafer scanner testing were varied. Some tasks can happen only when another task is finished. For example, the calibration task can be done only when other testing actions are finished. Some tasks cannot be done because of waiting for available spare parts. Some single tasks were repeated. Some group tasks repeat within their own loop. For instance, the repetition of sequence tasks 'ABC' and then 'ABC'. The life cycle of each task was uneven and some tasks take longer to execute than others. This heuristic process mining was used to analyse the processes to see which repetitive processes were indispensable for the testing process. This heuristic analysis was anchored in chronological data. The method concentrates on the frequency of the occurrence of a pair of tasks that happen in the workflow. The heuristic showed that there were significant relationships between tasks in some job steps, and how many times that specific tasks occurred. However, comparing actual execution from the reference process found that there were differences. This is because the worker deviates in their application of the process from the manual. Feedback loops were also found in the mined process. However, further investigations were required to improve process deviation and feedback closed loop problems so the feedback close loop can be removed and reduce idle times in the testing process.

In the health care industry pressure has been put on hospitals by many stakeholders involved in the industry (Mans et al. 2009). The stakeholders were concerned with financial management, government policy and action, patients, insurance companies, hospital competitors and with technology. For the hospital to be able to encounter these pressures they had to perform their processes well and fast. A hospital consists of many disciplines and consequently, people from different disciplines built up their own applications without knowing what other people were working on in other disciplines. This resulted in people in different disciplines working on different directions to solve the problems of patients who have equivalent diagnoses. The ways different disciplines work together to carry the data and service is complex and flexible. The time patients spend in a hospital from admission to discharge is called a 'careflow'. Health care applications have been developed to ease hospital processes such as managing beds and operating rooms. These applications have been used to record 'careflows' from a business perspective. Each element in the 'careflow' is called an 'event log'. Examples of events in the applications include systems which record patient's treatments or examinations in the intensive care unit; events logged in the radiology department recording the whole process from patients' admittance until the film photographs have been archived. These two systems work separately and independently, while the billing department have to monitor that these patients' bills have to be paid.

In response to the problem outlines above, Mans et al. (2009) applied heuristic process mining techniques to mine event logs recorded for business purposes from a hospital in the Netherlands. The purpose of using a heuristic process mining technique was to discover the 'careflow' paths and look at how individual patients have been treated in the care path compared with the procedure. Process mining is used to see what actually happens, not what is supposed to happen.

Mans et al. (2009) considered process mining as three basic types:

1) Process discovery used Petri Nets based on 'event logs' and an α-algorithm to observe process behaviour in the 'event logs'. The process discovery looked at the behaviour of the process in three perspectives which were data, performance, and organization. The use of a Petri Net provides visualized performance for business to monitor how information, people and software work together and how efficient that times have been spent in the process;
2) Conformance was used to check how well that the process conformed to

the model. Conformance checking was able to show and measure the deviation of the process from the model; and

3) Extension was used to improve the model from data derived from event log.

In this research as the Company's process had no prior model as a set up Configuration, Conformance and Extension process mining type were not relevant here. In (van der Aalst et al. 2007), the event logs were collected from different applications used in different departments. The results contained non-trivial processes. More than 300 names of tasks were recorded in the event logs. Therefore, event log pre-processing had to be carried out to be able to make sense out of the non-trivial data. The pre-processing log process began with eliminating low-level tasks. There are many low level tasks that can be clustered together into one category. The Lab process contained various kinds of tests. If the prior event before lab tests had to connect to too many distinctive lab test events, it would result in a 'spaghetti-like' process that was difficult to understand. Therefore, all types of testing were combined into a single 'lab test'. This method was also applied to other department tasks, for example in the radiology department where various kinds of examinations such as ultra sound, TC Scan and X-ray were carried out. This event log simplification process decreased the number of excessive low-level tasks and regrouped them in the representation where they belonged. This particular problem also happened in the Company's product design, build and test processes. The engineers entered their modification notes in the testing log sheet in an unsystematic way. Consequentially, there were too many duplicate task names which could mean the same activities.

Mans et al. (2009) then applied heuristic process mining to the pre-processed logs. Heuristic mining focuses on dependency relationships using frequency of tasks on the process flow. However, applying heuristic mining to pre-processed event logs still gave *spaghetti-like* outcomes. This is because there was no standard flow case in the hospital environment. The 'careflow' was determined by patients and by relevant diseases. Therefore, the flow was different from patient to patient. A clustering technique was applied to the data. The pre-processed data had been separated into two or more sub logs to make it easier to analyse. At this stage the case which had the same properties was put in the same cluster. Then a trace clustering plug-in was used to analyse these clusters. This time the outcome was understandable. The heuristic net was sound and embodied the procedure, confirmed by domain experts who reflected the mainstream of the *careflow associated with* most *gynecological oncology* patients.

The Public Works Department in the Netherlands applied heuristic process mining techniques to their work processes (van der Aalst et al. 2007). The department provided services for construction and maintenance of road and water infrastructures. The authors mentioned that there were many forms of enterprise information system software available on the market. These software types can record vast amounts of information on business processes. For instance, the data can contain task performers, work steps, time stamps and coordinating organizations. However, this information has not been analysed further in terms of 'causal and dynamic dependency' of the process. In the (Rozinat et al. 2007; Mans et al. 2009; Martijn, Barend van den & Frits 2006; Weijters & Van der Aalst 2003) research, business administration processes were the focus, particularly in the Finance Department, which was responsible for invoice handling. The department contains about 1000 workers who handle work with all parties involved in road and water infrastructure construction in the province. The focal point in the research was on invoices travelling between the department administration, suppliers, contractors, sub-contractors construction and the maintenance team. More than 14,000 invoices were collected for investigation. Three mining perspectives were considered. First, the process perspective which answers 'How?' questions in the process; secondly, the organizational perspective which answers 'Who?' questions in the process; and thirdly, case perspective which answers 'What?' questions in the process. In the next round of heuristic mining used in the research, closed looping tasks that were identified as an executor error and which had low frequency, were eliminated from the analysis. The result came out with a high dependency value and the mined workflow was a lot simpler.

Only the process or control-flow perspective from Van Der Aalst et al (2003) paper was applicable to and used in this research. This is because the Company's event logs contained no originators who executed the cabinet modification tasks and time stamped them. All cabinet modification tasks derived from team decisions.

The heuristic process mining technique was applied to the department's event logs in the Company. The process perspective in this research was focused on the ordering of the tasks. Then a possible optimum workflow path was extracted from the logs stored in the KMS.

There were a number of differences found from these samples of heuristic process mining compared with the processes used in the Company's design and build process. Firstly, in four previous papers (Weijters & Van der Aalst 2003) tasks were considered as linear processes. This was because some of the tasks could not happen if other tasks were not finished. On the other hand, in the Company, any modification tasks in the cabinet testing processes could occur at any time during the entire process. There was no specific order that had to be followed like tasks in mortgage determination, in tax claims or in health care and invoicing processes. For example, in (Rozinat et al. 2007) a 'process required' task cannot happen before a 'register' task or an 'archive' task cannot be executed before 'evaluate'. In the wafer scanner machine testing Rozinet et al. mentioned that there were specific ordering tasks (Kwanghoon & Clarence 2007; Mikolajczak & Chen 2005; van der Aalst, Weijters & Maruster 2004). One of the key aims of this research was to identify what ordering actually happened in the design process in the Company. There was no evidence from either the written documents, logs or from the interviews with the engineers, that they actually had a planned or specific design/test/build process. Most modifications and actions resulted from identified issues during the design, build and test processes The engineers were asked if there were specific processes and ordering in their work. They indicated that there probably was but they were "unaware of it".

Secondly, sample processes studied in the health care industry, public works department, wafer scanner manufacturing and in insurance claim processes contained 'OR split' and 'AND split' processes. 'OR split' is the stage of the process when one or the other task has been executed. 'AND split' is the stage of the process when more than one tasks have been executed at the same time. In the Company workflow there were no 'OR split' processes. Cabinet testing processes at the Company contained significant numbers of 'AND split' process (from three to five tasks processes contained in the entire event logs). There were some modification tasks that the engineers considered as ‘a last resort solution’ due to the physical characteristics of the commercial refrigerators. Some particular assembly parts in the cabinets were difficult to access. For example changing the rear duct was a last consideration. The rear duct was a piece of rectangular metal sheet die punched to form holes through which cooled air supplied to the products that were stored in the cabinet. It was located at the back of the cabinet and considered as one of the deepest locations in the assembly. To change the rear duct the engineers had to uninstall everything in the front part of the cabinet. This meant the testing process basically had to start all over again after everything was reinstalled. Therefore, often other solutions and tasks were undertaken to avoid this problem. This process used in the Company was not then a common repetitive set of tasks always done in the same order.

The idea for the application of heuristic process mining (HPM) in this research developed from Van Der Aalst et al. (2003). Heuristic process mining was derived from a more formal approach called the α-algorithm. This algorithm has been used in process mining in various applications (Weijters & Van der Aalst 2003). The intention was to gain understanding of the event in a process perspective which can help the researcher answer ‘How?’ question about the process. The algorithm will ascertain the causality of sequences and extent of the ordering of tasks in the process. It has been shown that the α-algorithm can reveal what is hidden in workflows (van der Aalst, Ton & Laura 2004; Weijters & Van der Aalst 2003).

There were assumptions that had to be made about the process in its application in their study. These assumptions were that only complete workflow logs and noise free workflow logs are useable. Complete in this sense means the actual tasks in the log records have been executed and have been recorded correctly without any omissions. Noise free logs were process logs where everything has been registered correctly and contain sufficient information (van der Aalst, Ton & Laura 2004). This approach then examined the heuristic order of tasks in workflow nets. Workflow net is a subset of Petri Net (Pnina, Maya & Yair 2008; Weijters & Van der Aalst 2003). The workflow net structure is simpler and requires a smaller set of construction. However, the expressiveness is high and can precisely represent the workflow (van der Aalst, Ton & Laura 2004).

In workflow nets, if any given task A happens then task B always happens immediately; this is likely to mean that task A has a dependency relationship with task B (Weijters & Van der Aalst 2003). The α-algorithm focuses on the four kinds of ordering relationships between task A and task B in a workflow log. These relationships can be seen in the workflow log (Weijters & Van der Aalst 2003). The relationships between tasks in workflow are one or other among these four types:

1. $A > B$ If and only if there is a trace line in W (workflow) in which event A and directly followed by event B.
2. $A \rightarrow B$ If and only if $A > B$ and not $B > A$ and this relationship is the so-called *dependency relationship* (*B* depends (directly) on *A*).
3. $A \# B$ If and only if not $A > B$ and not $B > A$ this relationship is the so-called *non-parallel* relation.
4. $A \| B$ If and only if both $A > B$ and $B > A$ is the so-called *parallel relation* (it indicates potential parallelism).

However, noise free and complete logs are difficult to find in reality. Sometimes system operators miss recording one or more steps during the process. Sometimes operators mistakenly record some steps more than they actually occurred. Noise and incompleteness in the log can affect the validity of an α-algorithm result. Heuristic mining techniques have been developed to be less sensitive to noise and incompleteness (Weijters & Van der Aalst 2003). However, complete and noise-free workflow is the ideal.

This research adopted the heuristic mining technique from van der Aalst, Ton & Laura 2004. There are three steps in the heuristic process mining. Firstly, dependency and frequency table construction is undertaken. Secondly, reduction of dependency and frequency graphs occurs and lastly workflow net from D/F graph is generated. This process was applied to the problem of reducing the make-span in the Company product development process.

6.3.2 Dependency and Frequency table construction (D/F Table)

First step: Generally workflow logs contain information about the process (Schimm 2004). The information mentioned is a set of events (Aubrey 2006;

Kwanghoon 2009; van der Aalst & Weijters 2004; Weijters & Van der Aalst 2003) which occur at the beginning of the process followed by subsequent events and it keeps continuing until the process is finished (van der Aalst et al. 2007; Weijters & Van der Aalst 2003). The notations in developing the dependency and frequency process are:

I. $\#A$ is the overall frequency of task A
II. $\#B < A$ is frequency of task A directly preceded by another task B
III. $\#A > B$ is relationship of task A directly followed by another task B
IV. $\$A \rightarrow^{L} B$ is a heuristic rule that use to construct local metric that identify the strength of the dependency relation between task A and another task B. Local metric IV can be defined as

$$\$A \rightarrow^{L} B = \frac{(\#A > B - \#B > A)}{(\#A > B + \#B > A + 1)}$$

The frequency of the order of task A and tasks B has to be counted and recorded. Then the algorithm is used to calculate D/F values. This results in a dependency metric between task A and task B. The value of dependency and frequency value (D/F) is between -1 to 1. The value of $\$A \rightarrow^{L} B$ approaching 1 means the relationship between two tasks is very strong and it is plausible that task A is the cause of task B. A sample of using this heuristic will be shown in a later section: Methodology and Analysis of Product development process at the Company. Frequencies of pairs of tasks have to be identified because the heuristic approach can show how certain the relation is between tasks A and task B (Weijters & Van der Aalst 2003). The frequency of an occurrence of events can be used as a factor to identify the certainness of phenomena.

Second step: reduction of the dependency and frequency graph. In this step the D/F values are placed in the workflow. The result is a representation of an existing workflow, complete with D/F values between tasks.

Third step: New workflow net generation. This is the process of generating the new workflow net in which only high D/F values between tasks are contained. The new workflow net can then reflect simpler processes and be more optimal.

6.4 Automating HPM

Much previous research has been concerned with application of algorithms, like the above, to mine data which is almost always in integer formats. This work has often been used to extract data on processes and build structures to demonstrate what is happening. Weijter and Van Der Aalst introduced *'Little Thumb'* software to demonstrate workflow mining processes (Weijters & Van der Aalst 2003). Examples in the business processes used in their demonstration process contained large amounts of instances of each task. The research showed that the software can handle processes with large instances. Initially in this research, the researcher thought that the application of this type of automated software might be applicable to the Company problem.

The research process for the Company started with an investigation of the Little Thumb software (Fig 6.1). *Little Thumb* was a tool used to create workflow models out of workflow logs by using the dependency and frequency values between tasks. The first version was developed in 1993 by researchers from Eindhoven University of Technology. *Little Thumb* provides graphical representation of the analysed workflow. Heuristic process mining technique has been embedded in this software. The software can analyse workflow logs and represent them as a 'Workflow Net' (van Dongen et al. 2005).

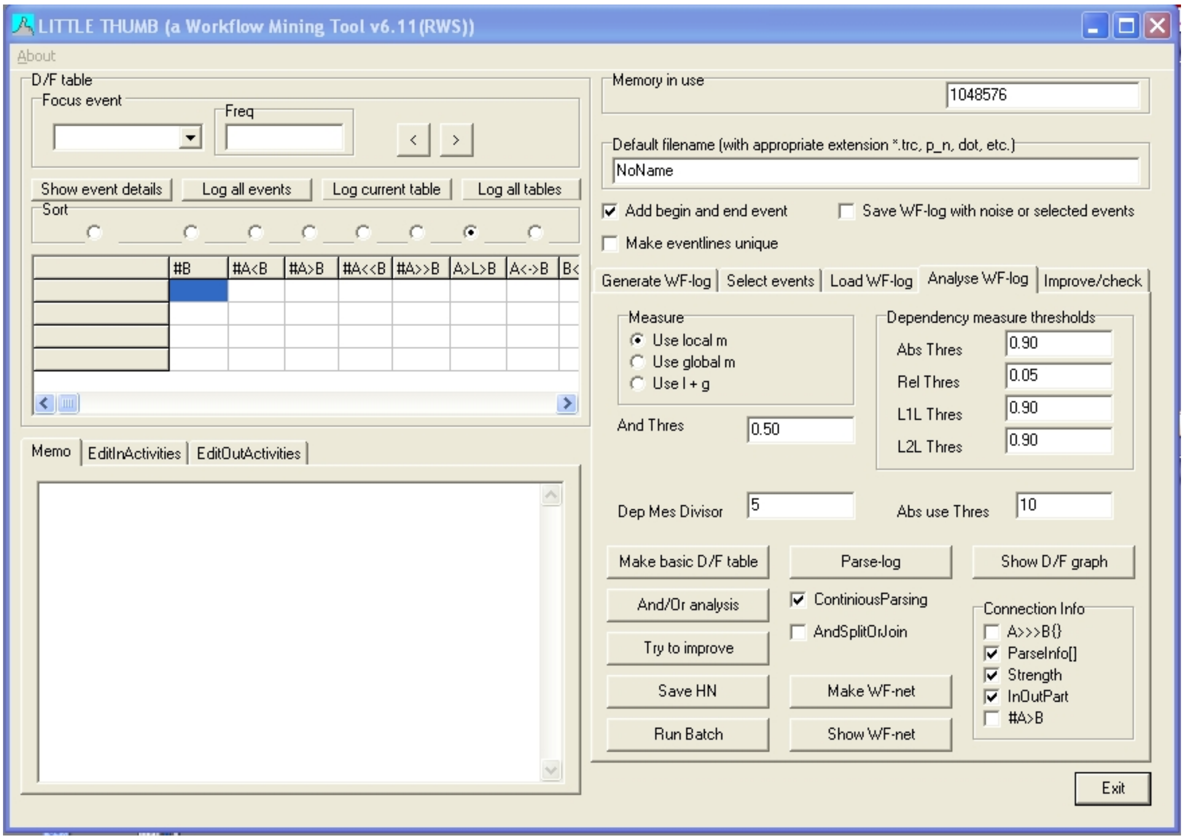


Figure 6.2 Little Thumb screen shot.

Figure 6.2 shows a sample of a *Little Thumb* screen shot. *Little Thumb* analysed workflow logs by importing log files from external sources. The external source in this case means other business process information systems that record event logs from business processes. The event log file formats recognised by *Little Thumb* include *.trc, .p_n and .dot*. The outcomes of the *Little Thumb* analysis were dependency and frequency values in the form of metrics. *Workflow nets* can then be re-constructed out of the D/F values that have been calculated. However, the Company event logs, had not been recorded by other business process information software. They were hand written on A3 paper and stored in drawers. However, the Company's event logs were much simpler than the samples shown in previous research. The researcher initially saw the potential of creating the Company event logs by using other software then using *Little Thumb* software to analyse those logs. Therefore, the researcher tried to apply the *Little Thumb* software in collaboration with the developers at Eindhoven University of Technology to deal with the incompatibility of the data sources at the Company. The software developers there suggested that there was newer software that has a plug-in which was developed from *Little Thumb*. The software is '*ProM*'. The *ProM* framework was also process mining software. It was a *plug-able* environment, which is flexible for a variety of input and output workflow formats (van der Aalst et al. 2003). One of the plug-ins in the framework was a '*Heuristics Miner*' (Fig 6.3) which has the same functionality as '*Little Thumb*'.

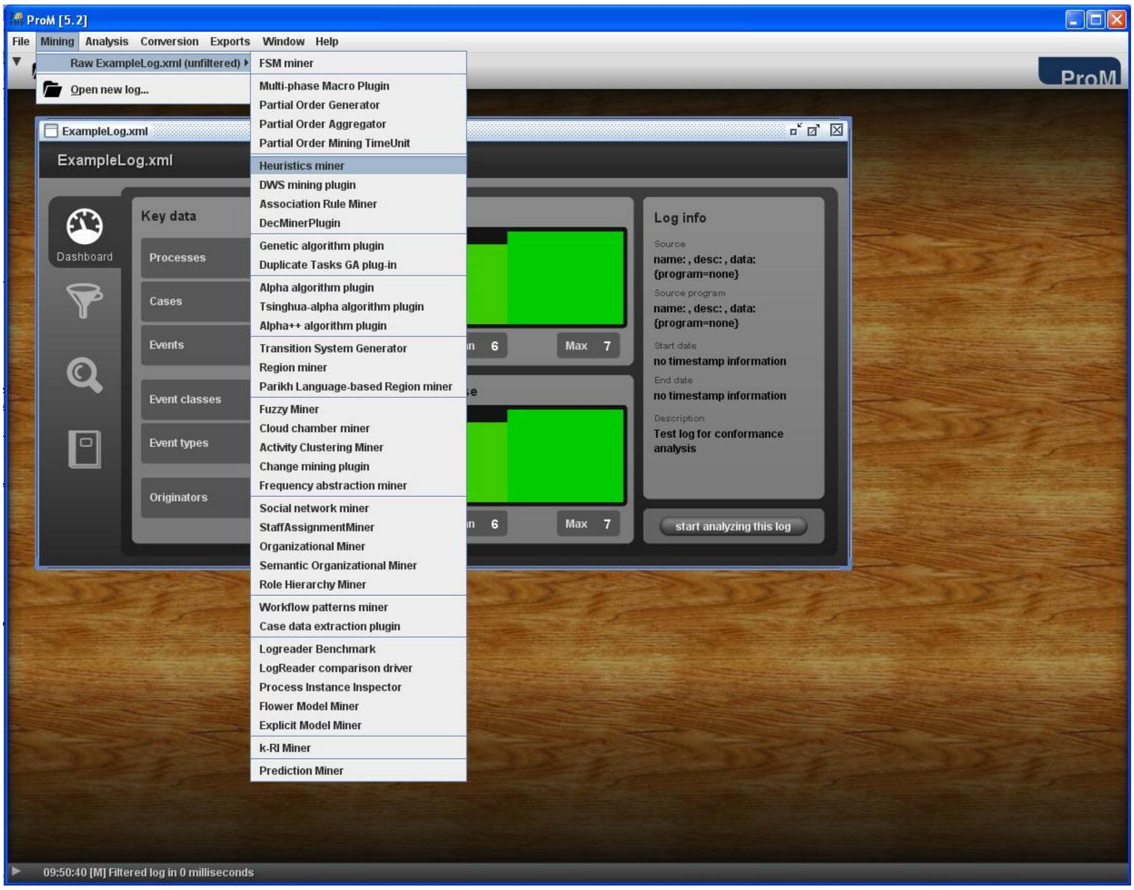


Figure 6.3 ProM framework screen shot.

Traditionally, to execute an efficient process, workflows have to be designed by business model experts before starting the process. In real life situations to improve process workflows, workflow analysis can be done in reverse. By collecting the existing workflow from event logs then the actual phenomena embedded in the practices can be discovered. The other reason for analysing the actual process workflow is to assess the validity of the result. This is because process workers can make actual processes deviate from the designed process model. The process mining software *ProM* had been developed using such an approach. *ProM* has been developed by the same group of researchers who developed Little Thumb. The goal of using *ProM* as a process mining software was to gain a good understand about how processes are executed from evidence, not for re-designing the process (Weijters & Van der Aalst 2003). *ProM* is XML-based and there was no event log creation process built in it. Event logs have to be created by using other software. This means only XML event logs can be used in *ProM*. *ProM's* Developers wanted to promote XML as a single language to reduce the implementation effort. However, common business process information systems in the market produce various event log file formats other than XML. For that reason, researchers need a tool that can convert various event log file formats into XML. The *ProM* developers have thought about this problem and developed *ProM* Import Framework to solve this problem.

ProM Import framework (Fig 6.4) is a workflow conversion software. The *ProM* import framework has 11 filters to convert event logs from 11 different software formats into XML file format. These 11 filters are MS Access database, Eastman, Subversion, CVS, Adept demonstrator, Test Driver, CPN Tools, Staffware, PeopleSoft, Apache2 and MXML Pipe. The software *ProM* enables the production of workflow management, enterprise resource planning system and Petri Net editing. The usage of *ProM* and *ProM* import were quite straight forward.

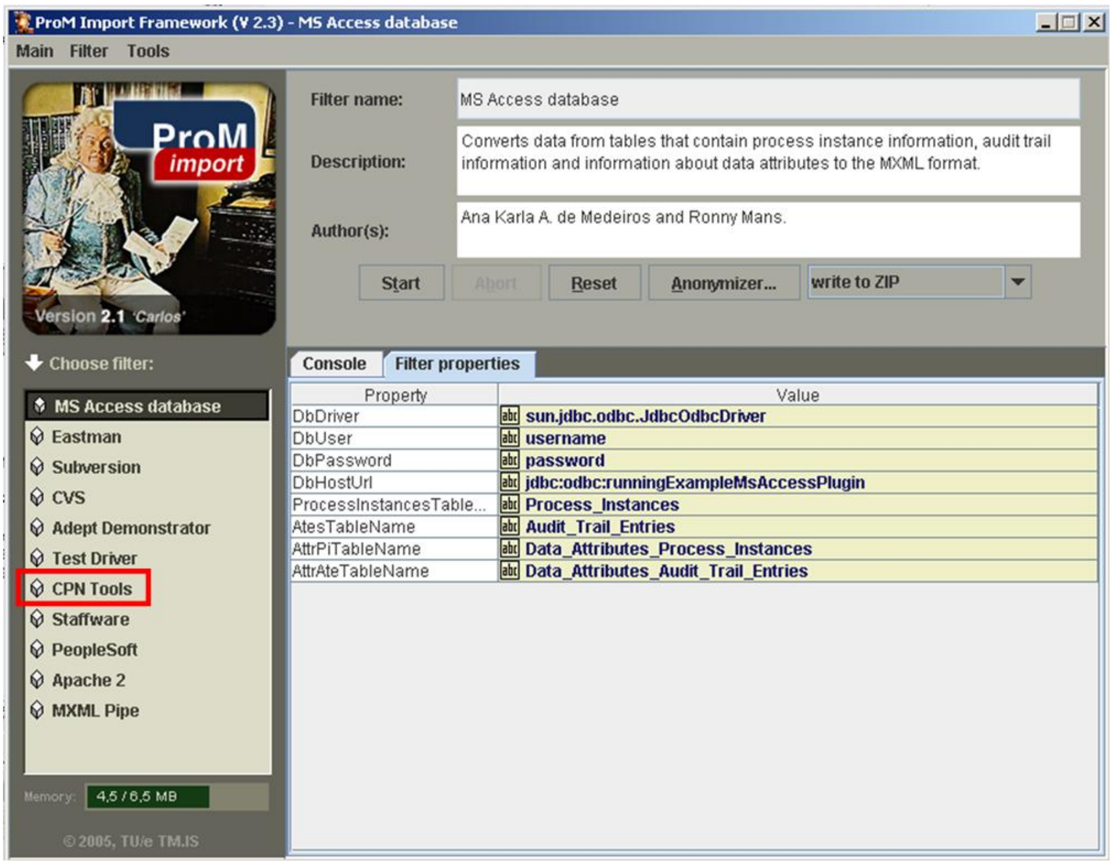


Figure 6.4 ProM import framework

The researcher also investigated the application of Petri Net editing software such as Petri Netz editor and CPN Tools[1] for the purpose of creating the Company workflow nets to enable analysis for make-span reduction modelling. *ProM* import has a filter that can convert CPN Tools files into XML files. CPN Tools have features that the researcher can use to create the Company workflow nets which can be converted to XML by using *ProM* import and then be analysed by using heuristic miner plug-in in *ProM*. Figure 6.4 shows the CPN Tools graphic user interface. The menu contains a toolbox used in creating workflow nets. CPN Tools have a powerful expression and can be used to create a coloured Petri net. The Company workflow logs are simpler that coloured Petri nets (Wen, Wang & Sun 2006). Therefore, using CPN Tools which have a high expression tool to create the Company workflow nets was considered feasible.

o [1] A CPN tool is a Coloured Petri Net constructing software. It contains features that enable construct ion of all elements of Coloured Petri Nets. These include net declaration, net inscription, arc expression and colour set of Petri Net.

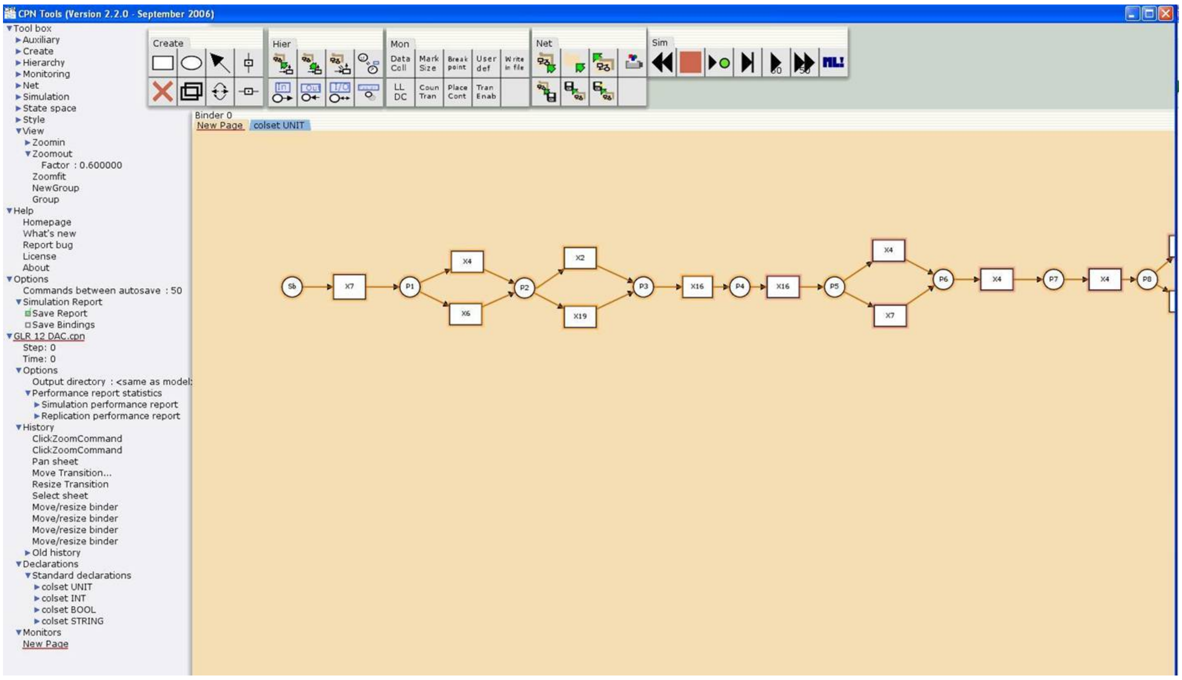


Figure 6.5 CPN Tools

Figure 6.5 shows the sample of CPN Tools. The next step in the analysis was to extract the Company's engineering design workflow information and knowledge from the product development knowledge-based system that was constructed in first half of the research (Chapter 5).

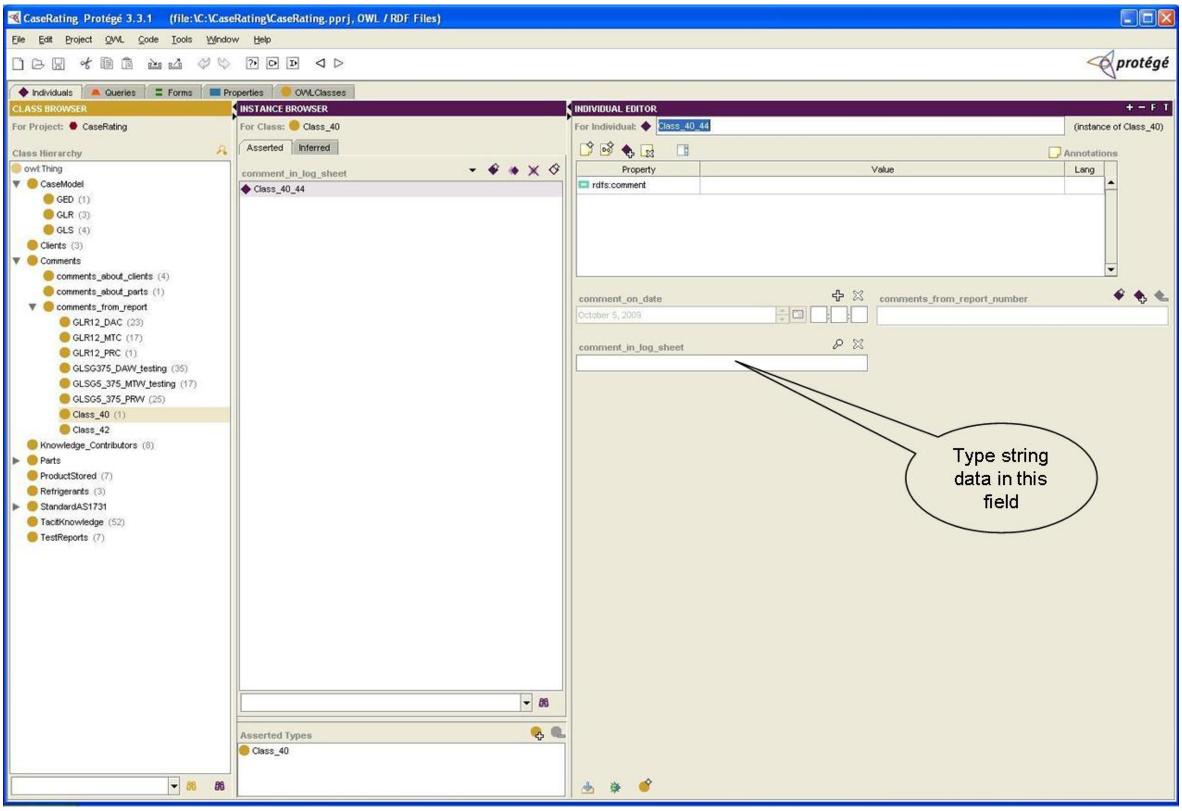


Figure 6.6 Product development knowledge-based system.

Based on previous applications of this software the researcher was confident that the Company workflow nets could be created from the information recorded in the testing log sheets that had been input into the knowledge-based system. Figure 6.6 shows the product development knowledge-based system where instances from testing log sheets had been transferred. The Company engineers also noted their product development processes in other papers. In the design process in the Company, after the cabinet was set up for testing in the laboratory all of the modifications that the engineers had made to the cabinet were noted on a piece of A3 paper which was attached on the white-board in the laboratory. The testing results and modifications were continually updated on the testing log sheets by two engineers with responsibility for the testing procedure. These logs should provide the information for the make-span analysis.

The workflow net software contains markers called *Places* and *Transitions*. These are derived from the event logs. In the Company case *Places* represent conditions of the test cabinet at an initial result and after the modifications have been made. *Transitions* represent modifications that have been made to the test cabinet. The

Places and *Transitions* in the models developed in this research were constructed in sequences derived from the initial result after the first 48 hours of testing. Figure 6.6 shows one of the workflow nets from one of the base testing reports in the Company. The workflow net consisted of *Transition* (rectangular symbol) represented here by tasks such as T1, T2 and T3. *Place* (circles symbol) represented pre and post conditions of process such as P1. This was a condition of the process before T1 had been executed and P2 was a condition of the process after T1 had been executed. *Arcs* (arrow symbol between Transition and Place) represented workflow relation (van der Aalst 1998, p. 17).

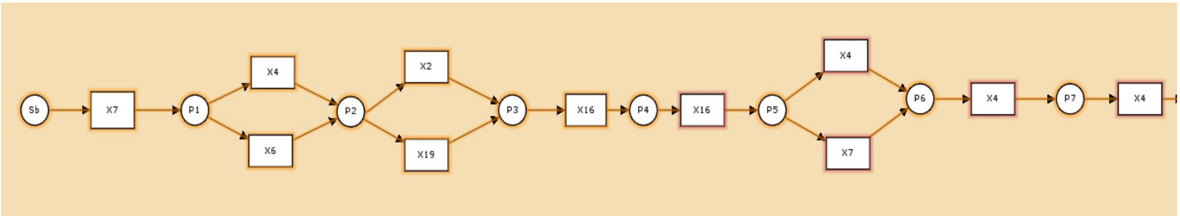


Figure 6.7 The Company workflow net.

Next, the Company workflow nets created by the CPN Tools in *.cpn* format were converted into XML format by using the *ProM* import framework software. The conversion results in the production of a Company workflow log in XML format. Then the author used the *ProM* framework to analyse the workflow nets. The result appears as shown in Figure 6.8

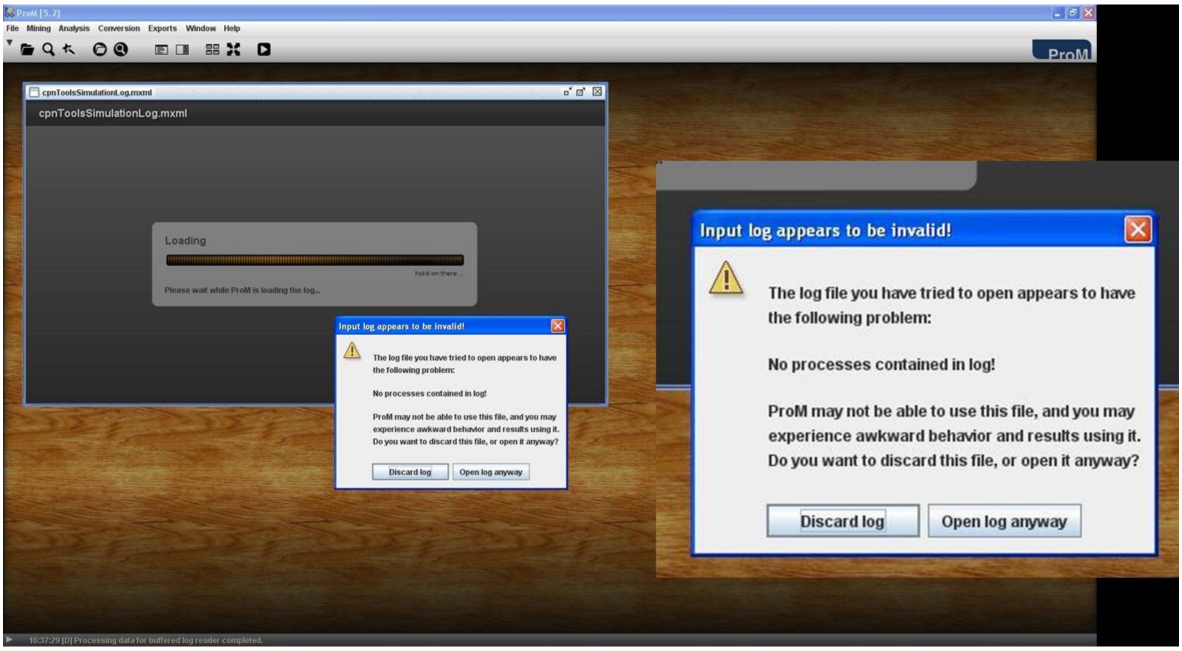


Figure 6.8 Error from first analysis

The first Company’s workflow net analysis showed the error message above. The researcher tried the analysis on many occasions and used various sets of data form the Company. The same error message reoccurred. The researcher then investigated the error with the CPN Tools developers who suggested that the Company workflow net is an empty file. The complete Petri Net has to contain all of the elements needed in the software. The elements mentioned were *places, transitions, arc, arch expression, inscription* and *colour set*. These elements fill up with values. Complete element Petri Nets enables Petri net firing rules that can simulate the process in the Petri net. However, in the Company testing process the logs contained only values of dates and tasks. Therefore, the Company workflow net could not be completed with all element values. This meant that the Company events logs could not be created as a Petri net using this automated analytical system. The *ProM* framework could not analyse the Company workflow net, resulting in error messages as shown in Figure 6.8. The empty Petri net files from the Company could not be analysed by any of the available software. The use of automated software as a means of investigation was not successful. The incompleteness of the data source resulted in investigation failure. Therefore, the process mining approach had to be changed. At this stage, the researcher had to make a choice to develop a recognition tool for the incomplete data in the Company files or seek an alternative research strategy to continue to address the strategic problem identified by the Company based on their lack of use of their collective knowledge. The researcher, in consultation with the Company executives, and his supervisors, determined that the latter was more important at this stage and the focus returned to use of the heuristic mining technique, applied to the Company event log, using a combination of the CPN software and manual calculations using the determined algorithm described in Section 6.3.1 above[2].

6.5 Analysis of Product development process at The Company – determining the make-span

6.5.1 Analysis Step 1: Information Consistency

Following the lack of success in applying the automated analytical system, the researcher needed to re-evaluate the logs based on the outcomes of the attempts to use that particular software. There was an issue raised during heuristic process mining study. The way the engineers recorded their modification notes was disorganized.

Figures 6.9 shows samples of cabinet testing log sheets. The samples showed that the Company logging process was not standardized. An analysis of the documentation showed clearly that the engineers had written about the same modification in more than one way. For example, changing the cabinet fan speeds were noted as ‘fans to 1200 rp’ and ‘changed fan speed to 1500 rpm’. Another example was that the modification task ‘suction pressure’, which was a frequent task that the engineers performed on the cabinets, was sometimes written as ‘suction pressure to 500 Kpa’ and also as ‘suction pressure adjusted to 500 Kpa’. The researcher asked the engineers how these two notes could be distinguished. They suggested that for the words written in this column they couldn’t distinguish the difference. Further details of suction pressure adjustments have to refer to the pressure column on the left hand side of the table. In a further example, defrost configuration had been noted as ‘changed defrost duration’, ‘extended defrost’ and ‘defrost shortened’. Another one of the modification tasks that had been noted

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o [2] The choice here was to continue with the analysis and that was the purpose of the research. An alternative solution would be to work on resolving the computing problem. An evaluation showed that this would have consumed considerable time and since the research was not a computing student, this was deemed unnecessary at this stage. However it does raise the potential for additional research at a later date.

differently was ‘cut out setting’. It had been written as ‘cut out lowered’, ‘cut out raised’ and ‘cut out altered’. These cabinet configuration settings notes had the same problem characteristics. There were many names referring to the same tasks. It was difficult to match up the tasks and sequences when one action has been referred to in numerous different ways. The utilised information form process logged data in the logs sheets had then to be reorganised to enable mining of the knowledge and information in the knowledge-based system to be made useful for an analysis of the work task processes.

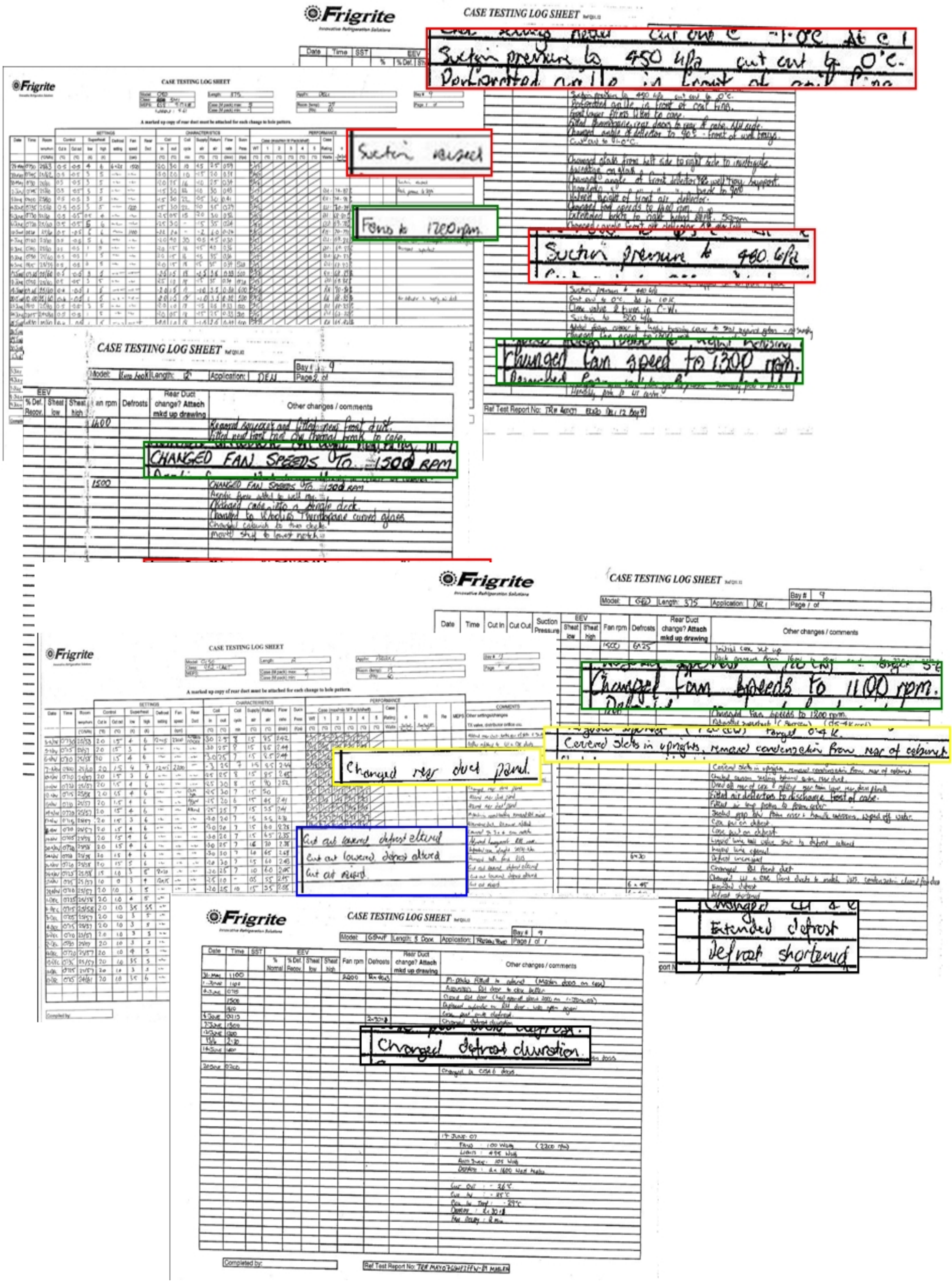

Figure 6.9 Samples of The Company cabinet testing log sheets.

Figure 6.6 shows the first version of the product development knowledge-based system. It was developed during the early stages of the construction of the system. In this version the engineers had to type in details about modifications and dates into the system in the same way as they wrote the notes on the paper. These pieces of string data were disorganised and difficult for reuse. Following this analysis, and after discussions with the engineers who were involved based on feedback about the first iteration of the system, another version of the knowledge-based system was developed. The engineers noted the following in their review of the first iteration:

- Each day-to-day modification was string data which the engineers had to type into the system.
- There was no element that could show the result from each modification.
- The engineers' information management inconsistency affected the result of query features. The engineers often used different terms to describe the same modification tasks. The result from the search feature did not cover all of the knowledge needed.
- There was some information regarding to Australian Standard AS 1731 missed out.
- Some parts of the standard were not retrievable for the questions that engineers asked.

In this new version a tasks pool idea had been implemented. The researcher reviewed all of the modification notes that the engineers had written in the log sheets. The researcher found that there were a number of modifications that the engineers often repeated. In the variety of modification notes, there were a number of modification tasks written differently, which could be classified as the same action. The researcher has listed and renamed all of the modification tasks in one place, which is the tasks pool. The engineers could then select the listed tasks instead of writing different terminology. The class: 'Modification notes' was created to store the instances of the renamed tasks. The data field; 'today's modification' was created in an individual editor. A 'Today's modification' objects property was created to link with ‘Comment from Report’ with the reports with the modification tasks.

The engineers could now select modification task instances for those they decided to use to modify the cabinets. However, the field: ‘comments in log sheet’ still remained in this version for storing fine details of the modifications that have been made to the relevant cabinet. The revised version of the knowledge-based system is shown in Figure 6.10.

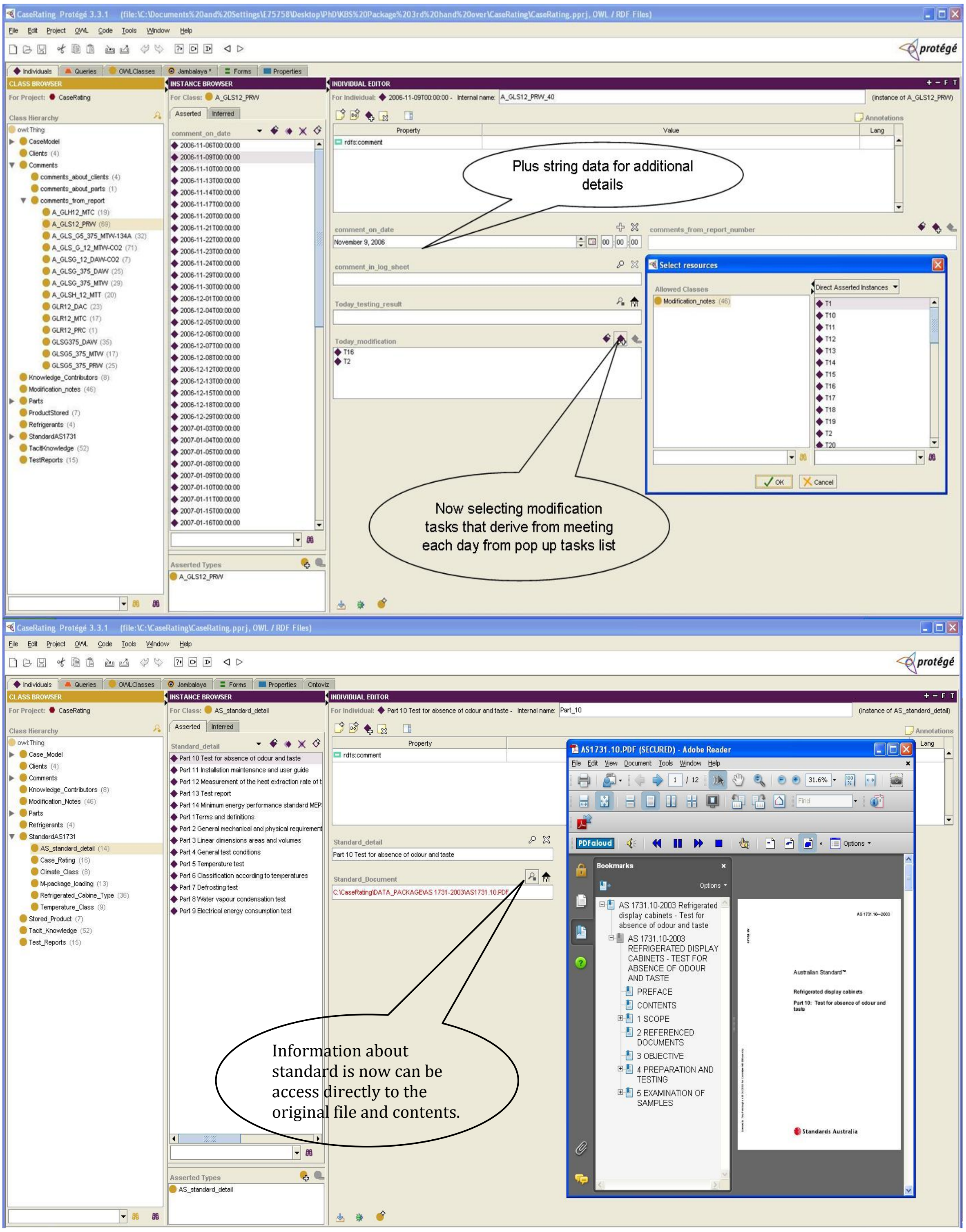

Figure 6.10 Revised versions of KBS

Figure 6.10 shows the system which now contained a new feature where instances related to the reorganised modification tasks could be selected. For example all of the modification tasks about cabinet ‘cut out configuration’, from any testing cabinet, had been grouped together and represented as an instance called 'Modify cut out'. All of the modification tasks instances were created and stored in the tasks pool. Instead of writing the modification notes unsystematically on the papers, engineers were able to record the modifications that they had made to the cabinet more accurately and consistently. Each of the tasks could be clicked on and the instance added to the class. Having the 'Modification Notes' class provided a single set of nomenclature and overcame the problem of alternative working which was one of the causes of the lack of success with the automated analysis systems outlined above. The lower screen shot in Figure 6.10 shows the modifications related to the standard. The system enabled users to search content and access the original standard.

Fig 6.11 shows all of the 'Modification Notes' class which contained the modification tasks that the engineers undertook in all of the testing reports for the 13 collected cabinets.

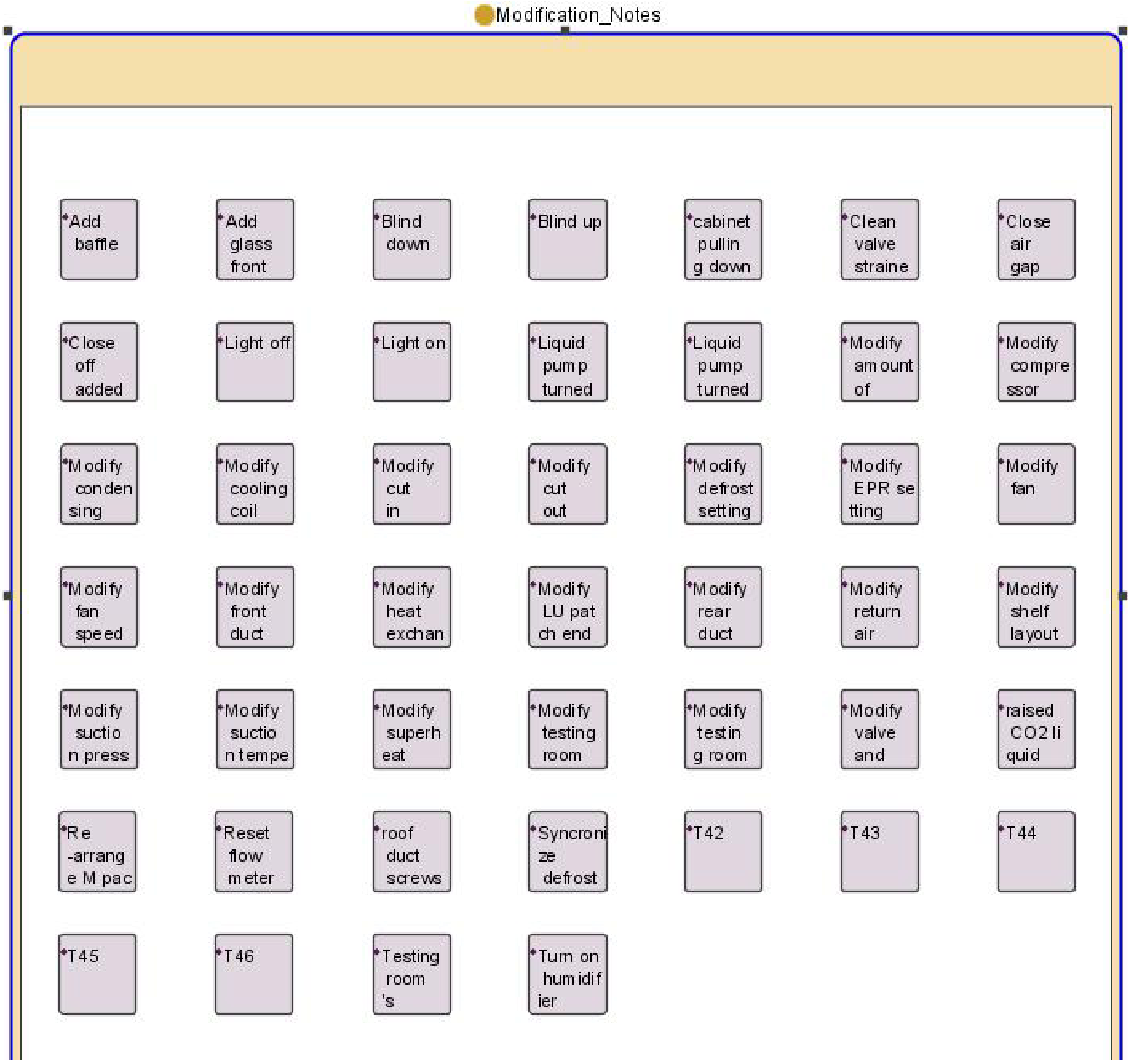

Figure 6.11 'Modification Notes' class.

Figure 6.12 shows event log from refrigeration case GLR12 DAC in the knowledge-based system. In 'CLASS BROWSER' there was a class name: 'Comments' which has three subclasses which are 'comments about clients', 'comments about parts' and 'comments from reports'. The subclass 'comments from reports' contains many subclasses which represent details about each specific cabinet case testing processes and results. The first subclass in the 'comments from report' is case GLR12 DAC. The subclass case GLR12 DAC contains instances related to this particular cabinet during the testing period. There are five individual pieces of information held in these instances: 'comment on date', 'comment in log sheet', 'Today's testing result' and 'Today's modification'

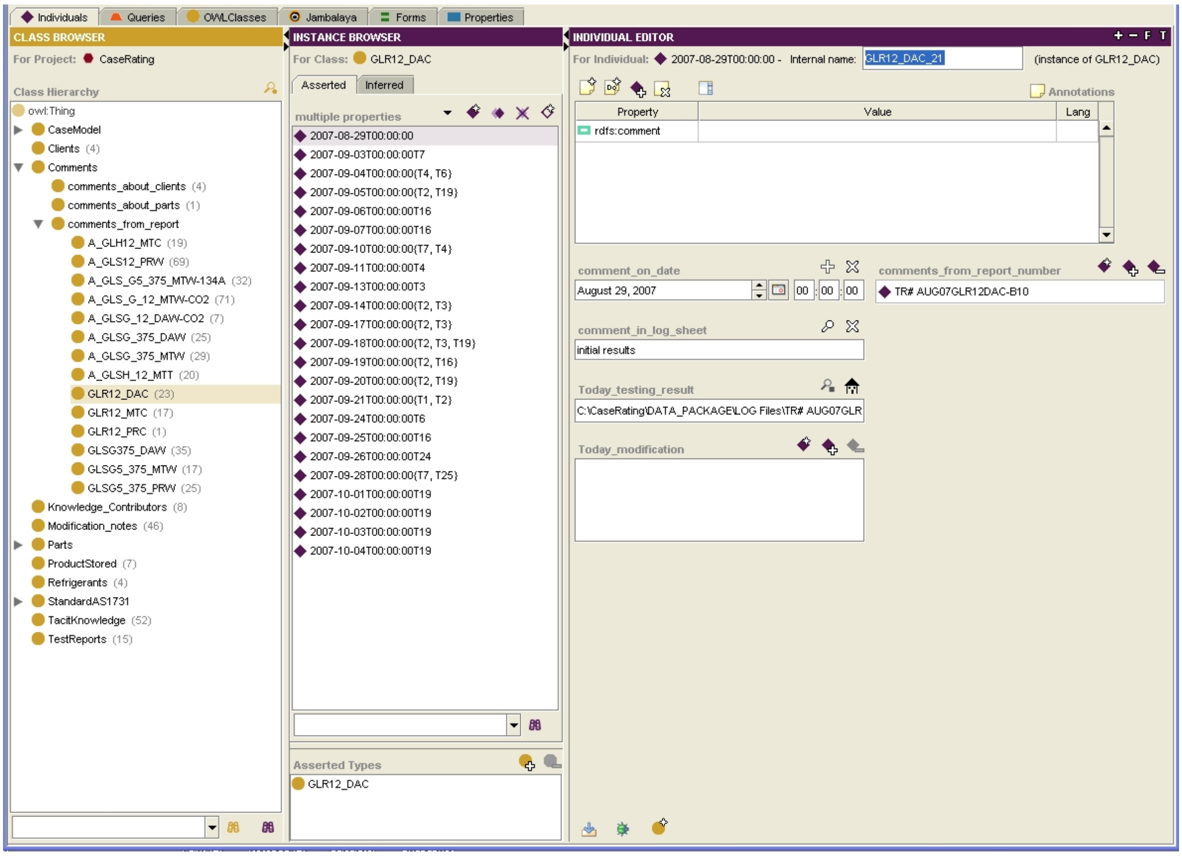

Figure 6.12 Case GLR12 DAC event log

Once the information contained in the reports and then in the knowledge-based system was verified as accurate by the adoption of the consistency in the Tasks Pool, the research was able to move into the second stage of the analysis – applying heuristic mining. In the Company workflows the number of cases and instances in each case are not large. This made mining the Company cabinet testing processes manually feasible. Applying the Company cabinet testing process mining started with extracting process information from the product development knowledge-based system. The modified Company product development knowledge-based system enabled the researcher to develop the Company cabinet testing workflow logs. The workflow logs contain enough information to apply the algorithm for heuristic process mining. The first sets of data collected from the engineers at the factory consisted of five cases of past prototype cabinets. The cases were GLR12 DAC, GLR12 MTC, GLR12 PRC[3], GLSG 375 DAW, GLSG 5 375 MTW and GLSG 5 375 PRW.

o [3] This case was eliminated because it contained only one task.

6.5.2 Analysis Step 2 mapping the workflows

The heuristic mining technique pays a great attention to tasks, task types and to the ordering of those tasks. The Company event logs contain information that matches the needs of the heuristic mining technique. The tasks are defined in the tasks Pool. The 'INSTANCE BROWSER' window (as shown in Fig. 6.12) in comments from the log sheets subclass shows the cabinet testing process from start to finish. The Company workflow comprised the events that occur in a series of one or more modification tasks that engineers made to a prototype cabinet from when the prototype cabinet comes up with initial results until the testing process was finished. 'Finish', in the engineers' view, meant that the cabinet performance met the National Standard in term of temperature and power consumption. As mentioned previously, the cabinet testing process actually started after the cabinet had been installed in the laboratory, and all measurement equipment had been attached to the cabinet and the cabinet was running. The workflow started with the date when the testing cabinet gave the initial results. These initial results determined what modification tasks the engineers would make to the cabinet.

To better understand the process involved and the extent of the information that can be extracted from the log sheets of the engineers, an example is presented below:

The cabinet GLR12 DAC has been set up and run in the laboratory until the initial results come out on 29th of August 2007. The engineers have not recorded the time period of installing the cabinet or when it was first running. It usually took about one to two days. The researcher ignored this cabinet setting stage because it has no effect on overall testing time consumption. Sometimes the engineers left the cabinet just working continuously on a first run for a few days for result stability to be enabled. In the next step, the engineers reviewed the initial results on the 3rd of September 2007. They then made decisions about what parts or setting configuration should be modified. On the 3rd of September 2007 the engineers decided to do Task 7 (T7) which was 'modify cabinet shelf layout.' These decisions about physical modifications were made collaboratively in the meeting room immediately at the start of the day and usually take one or two hours to get done after that morning meeting. Then the cabinet was left running for 24 hours. On the 4th of September the results from the previous day were reviewed and the engineers decided to make two modifications. The two modification tasks were T4 which is ‘modify amount of M package’ and T6 which is ‘modify valves or orifices.’ Then the cabinet was left running for another 24 hours. On 5th of September engineers decided to do task T2 which is ‘modify cut out temperature’ and T19 which is ‘modify rear duct.’ On 6th and 7th of September the task T6 was decided on. This task: ‘modify valves or an orifice’ has been made to the cabinet repeatedly. On 10th September 2007 modification T7 and T4 were made to the cabinet. There was then a two days gap due to the factory not being open on the weekend. On resuming work on 11th September T4 was repeated. On 13th of September 2007 the engineers decided to undertake task T3 which is ‘modify fan speed.’ On the 14th and 17th of September T2 and T3 were done consecutively. On the 18th of September 2007 T2 and T3 were done again but this time the engineers decided to include T19 into that day’s modifications. On the 19th of September the engineers re-did T2 modification. However, they also undertook T16 as well. On 20th of September T2 was still being done but they changed the other tasks back to T19. On 21st of September the engineers undertook both T1 and T2. Next, on 24th of September only a T6 modification was made to the cabinet with a T16 on 25th and a T24 on 26th accordingly. On 28th of September T7 and T25 which is “Re-arrange M packages” were done.

This extraction of the information in the knowledge-based system was one example of mining to determine what the workflow was and what each part of the workflow actually meant. That workflow could now be projected into a workflow net diagram. Workflow net is a “Petri net which models a workflow process definition” (Li, C, Reichert & Wombacher 2009; van der Aalst 1998, p. 8; Wen et al. 2009; Wil, Mathias & Guido 2003). It is a low level of a Petri net. Workflow net consists of T (task) responses to tasks that have been executed and P response conditions of any given stage in the workflow net. Workflow net also can specify routing of the case workflow processes. Conditions that determine routing of the case include the following and are based on other research work (Weijters & Van der Aalst 2003);

1. *Sequential condition* is the condition of workflow that one task has been executed and then is followed by next task.
2. *Parallel condition* is the condition of workflow when one task has been executed then followed by 2 tasks that have been executed at the same time. This means *AND-split* condition appears when the first task is executed. Then after 2 tasks have been executed at the same time an *AND-join* condition appears.
3. *Conditional condition* is when the first task has been executed then there is a choice of two or more tasks to choose from to perform. However only 1 task that needs to be chosen to perform. This means the *OR-split* condition appears after the first task has been executed. Then *OR-join* condition appears after the chosen task has been executed.

The Company's workflow net did not contain OR-split and OR-joint situations. This is because all of the modification that had been made to the testing cabinets derived from decisions made in the meetings. Modifications noted in the testing log were finalised. *AND-split* conditions were shown in the workflow net on the day that the engineers made more than one modification.

Figure 6.13 shows the workflow net of cabinet GLR12 DAC. This workflow net was extracted from event logs in product development knowledge-based system. It can be seen that at the very beginning of the testing process the initial results are shown in the Sb circle. Then T7 was completed on the cabinet. Next the engineers reviewed results P1. This review was an assessment of the outcomes that affected the cabinet built from task T7.

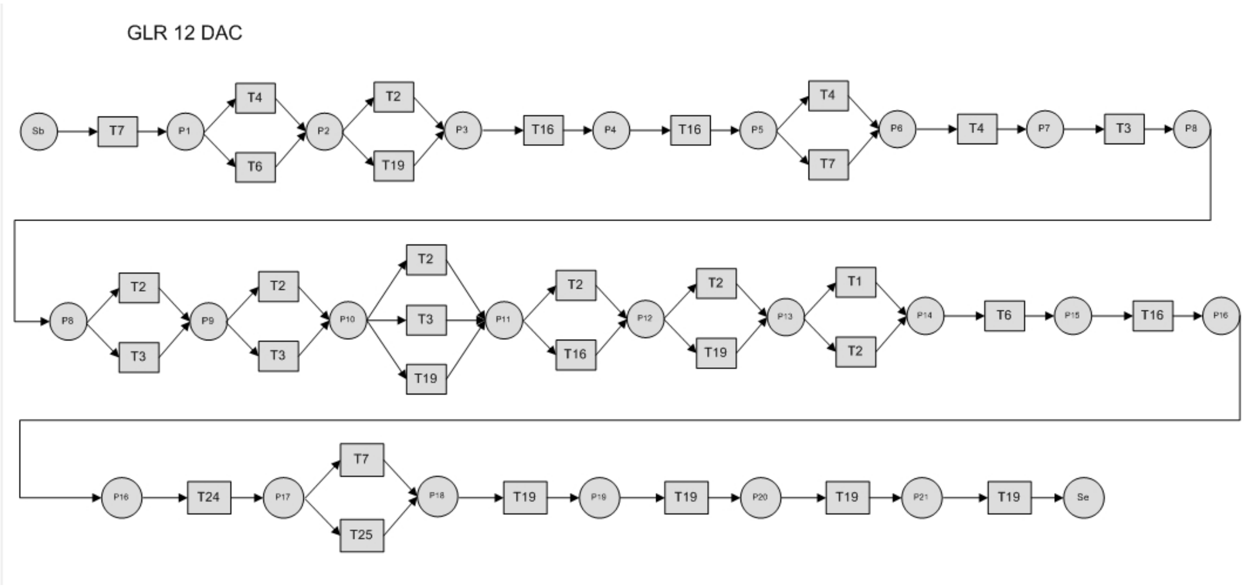

Figure 6.13 Case GLR12 DAC's workflow net

P1 in the workflow net showed an *AND-split* condition in the process where the engineers performed two modifications to the cabinet. An *AND-joint* condition appears at P2 which was where the cabinet condition changed after T4 and T6 were done to the cabinet. The workflow net diagram represented information about the testing process until it was finished at the Se circle.

Next, the researcher applied the same method to extract the required information from four other cabinet cases from the second version of the knowledge-based system. The cabinet testing report collected form the engineers included examples of two dairy cabinets, two meat cabinets and one produce cabinet. The results of the workflow mapping from cabinets GLR12 MTC, GLSG 375 DAW, GLSG 5 375 MTW and GLSG 5 375 PRW are shown In Figs 6.14 to 6.17.

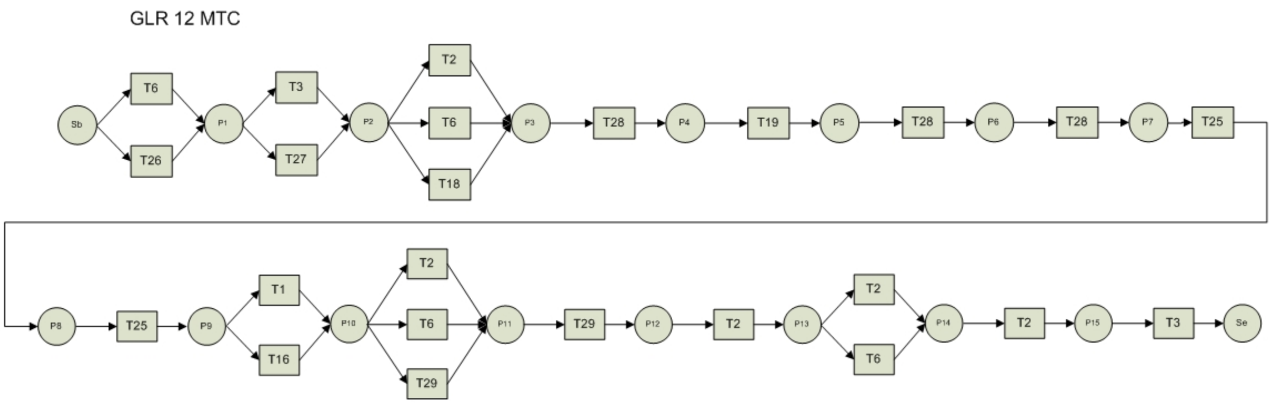

Figure 6.14 GLR12 MTC workflow net

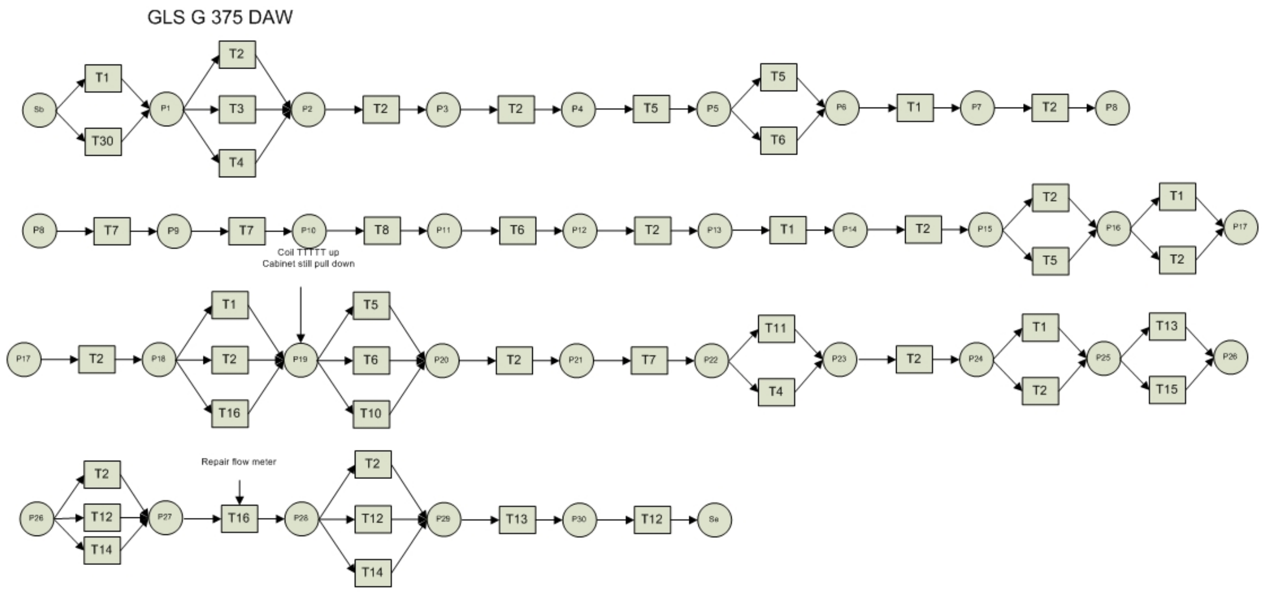

Figure 6.15 GLSG 375 DAW workflow net

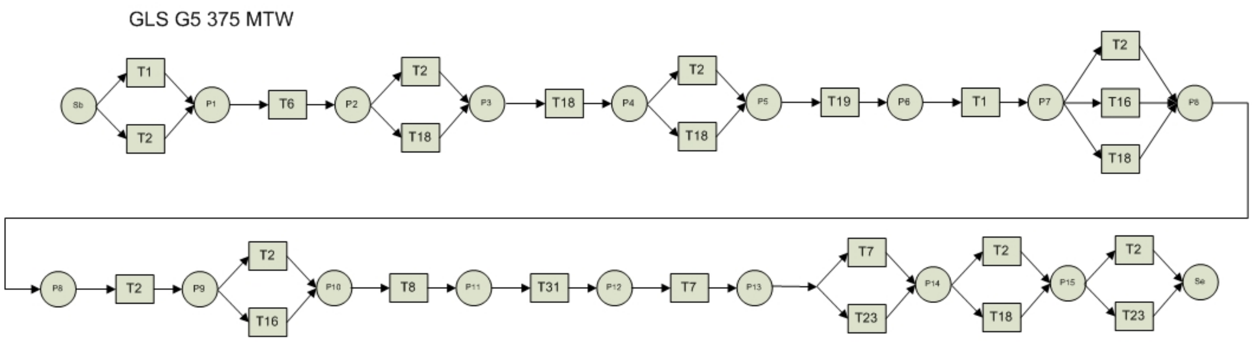

Figure 6.16 GLSG 5 375 MTW workflow net

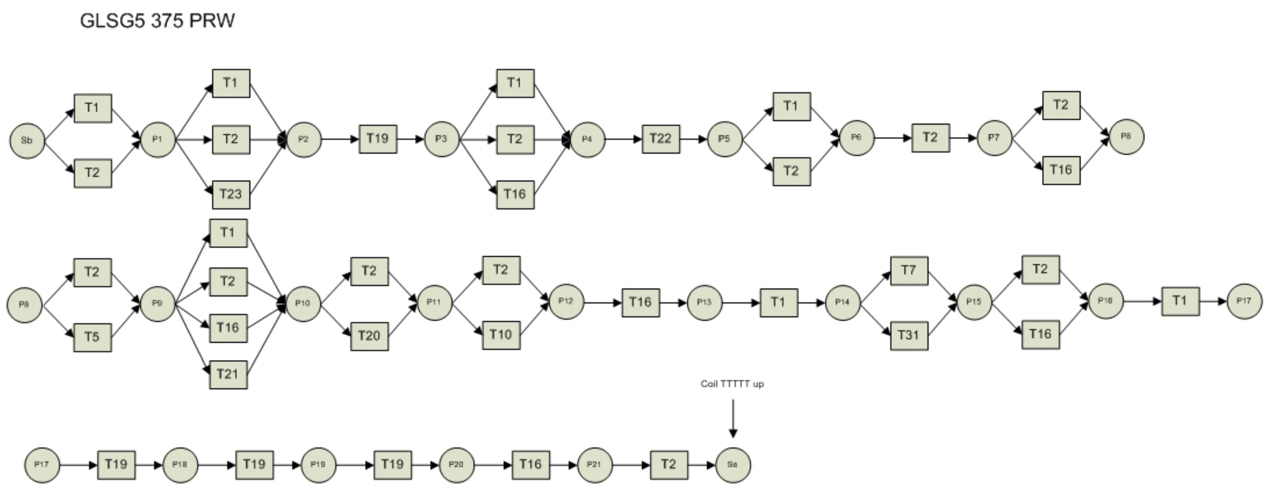

Figure 6.17 GLSG 5 375 PRW workflow net

The workflow net diagrams were now consistent. They showed different patterns in workflow, different degrees of complexity and covered different time periods. The adoption of heuristic mining algorithm enabled the researcher to determine the relationships inherent in these models by examining and relating both dependency and frequency of tasks and their order.

6.5.3 Analysis Step 3 – Dependency and Frequency analysis

6.5.3.1 Round 1 Analysis

Developing dependency and frequency tables in this analysis follows the method proposed by (Wen et al. 2009). The notation used in this process relates to the ordering of tasks A and B where A and B can be any pair of tasks used in the design/production process. Along the line of workflow, the ordering of task A and B are counted for any given pair of tasks. The dependency and frequency table construction process results from counting the existence of a pair of tasks in the workflow. In the application of the algorithm, described above in section 6.3.2. As noted there, that $A > B$ is iff there is a trace line in W (workflow) in which event A is directly followed by event B. For example in the GLR12 DAC workflow (Figure 6.18), the first modification task done to the cabinet was T7 which was now determined as task A or TA. The following modification tasks that have been done to the cabinet are T4 and T6 both then were tasks B or TB. This means T7 > T4 was counted once and T7>T6 was counted once also. The next pair of tasks was complex. TA now shifts to T4 and TB were T2 and T19. Another TA at this P1 condition was T6 and T6 was followed by both T2 and T19. This means T4>T2, T4>T19, T6>T2 and T6>T19 were all counted at one instance each. Next an *AND-joint* condition appear in the workflow and TA>TB were both T2>T16 and T19>T16. Next in the process T16 was followed by T16 (T16>T16) which called a short loop. At P5 and an *AND-split* happens again. This time the pair of tasks were T16>T4 and T16>T7. Next at P6 an *AND-joint* instance appeared again with T4>T4 which also a short loop and T7>T4. The counting process was repeating until the end of the workflow at Se. As can be seen, T19>T19 was repeated three times. As part of the analysis all of the relationships B>A were also counted.

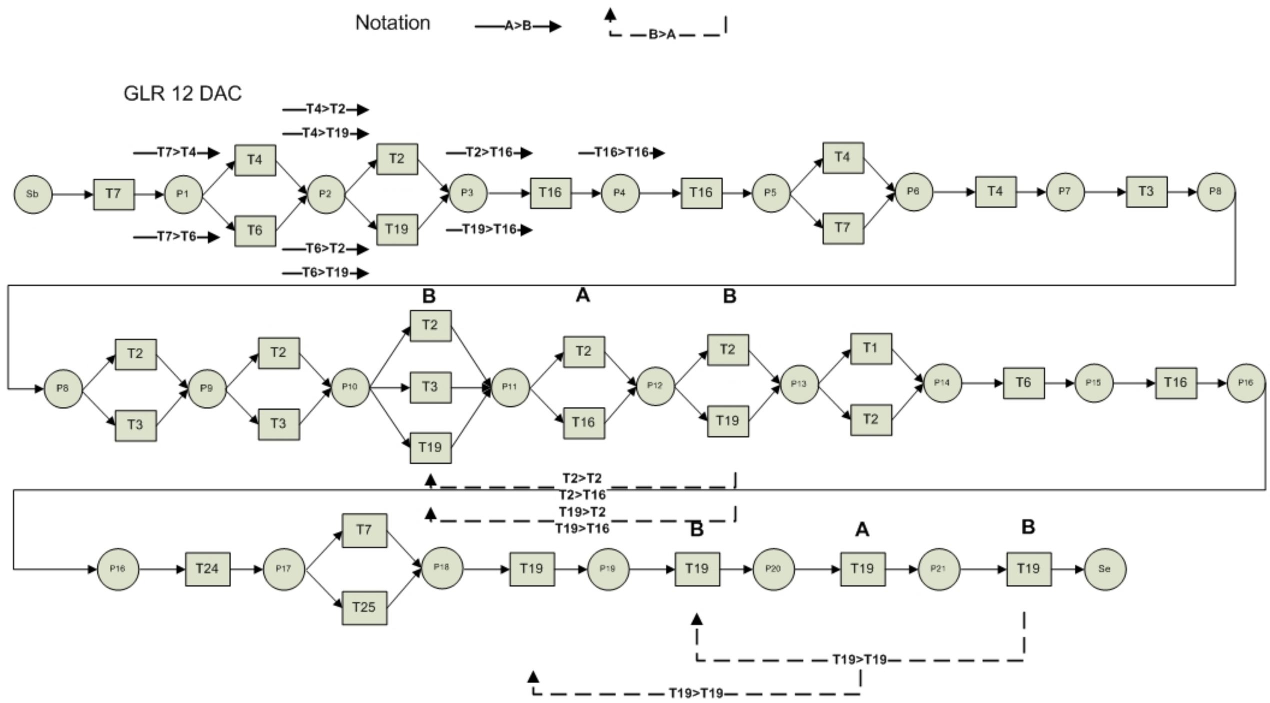

Figure 6.18 Counting tasks relationship in case GLR12 DAC

Figure 6.18 shows how can tasks relationship were determined in both A>B and B>A. For example at P11 and P12 heuristic process mining determine the ordering of the tasks in the workflow at A which are T2 and T16 and followed by B which were T2 and T19. The workflow shows that T2 and T19 which acted as B also have been executed before tasks A which were T2 and T16. This can be counted as T2>T2, T2>T16, T19>T2 and T19>T16 for one count each. The last four step of the workflow showed another B>A example which was T19>T19. The outcome of tasks relationship A>B and B>A counting process was shown as a dependency and frequency matrix in Table 6.1. Wen et al (2009) did a similar process by counting the tasks relationship. However, they used the term ‘tasks ordering’. Furthermore, Wen et al. separated the tasks relationship matrices into following the process direction and in reverse (Rozinat et al. 2007; Dustdar, Hoffmann & van der Aalst 2005; Gu, Chang & Yi 2008; Mans et al. 2009; Medeiros & Günther 2005; Rozinat et al. 2009; van der Aalst et al. 2007; van der Aalst & Weijters 2004; Wen et al. 2009).

Table 6.1 shows cabinet GLR12 DAC dependency and frequency matrix the notation S represents A>B and P represents B>A relationships instead of separate tasks relationship into two matrixes. For example the engineers did T19 then did T2. This happened twice, while in reverse, it happened once.

Table 6.1 GLR12 DAC dependency and frequency matrix

GLR12 DAC																														
A B	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20	T21	T22	T23	T24	T25	T26	T27	T28	T29	T30
T1						s																								
T2	s	sssss pppp	sspp			s										ssp			sspp											
T3		ssssp p	ssspp													s			s											
T4		s	s	s															s											
T5																														
T6		s														s			s											
T7				ss		s													s											
T8																														
T9																														
T10																														
T11																														
T12																														
T13																														
T14																														
T15																														
T16		s		s			s									s			s					s						
T17																														
T18																														
T19	s	ssp														ssp			ssspp											
T20																														
T21																														
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T24							s																		s					
T25																			s											
T26																														
T27																														
T28																														
T29																														
T30																														

This trial analysis demonstrated the proposed methodology enables extraction of relationship data and the applicability of the algorithm. However, data from one mining process was not enough. The researcher then repeated the counting process of tasks relationships A>B and B>A in another four cabinet testing cases. The results were then combined in one dependency and frequency matrix. In total there were 31 modification tasks extracted from the five sample testing logs. The results are shown in Table 6.2.

Table 6.2 Dependency and frequency matrix of 5 cabinet cases

		#A I	#A S	#A	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20	T21	T22	T23	T24	T25	T26	T27	T28	T29	T30	T31
T1	Modify defrost setting	5	33	38	s	I,s,s,s,s,s,s,s,s,s,s,P,P,P,P	s	s	s	c,c,c,c,c,	s			s			s		s	s		s	I,s,s	s		s	s						c,c		s
T2	Modify cut out temperature	11	64	75	I,s,s,s,s,s,s,s,P	I,s,s,s,s,s,s,s,s,s,s,s,s,s c,c,c,c,c,c,c,c,c,c,P,P,P,P P,P,P,P,P,P,P,P,P,P,P,P	I,c,c,c,P		I,s,s,s,	c,c,c,c,c,	I,I,s, s,	s		c,c			c,c		s	c,c,c,c c,c,c,c P,P		s	c,c,c,c,c, P,	s	s	s	c,c,P					c,c	c,c		
T3	Modify fan speed	1	16	17		c,c,c,c,c,c,c,P,	c,c,c,P,			c,c,P,										s		c,c	s												
T4	Modify amount of M package	1	10	11		c,c,c,c,c,c,	I,s	s															s												
T5	Modify cooling coil	1	6	7	s,c,	c,c,P,P,P,			s	s										P					s										
T6	Modify valve and orifice	3	16	19	s	I,s,s,s,s,P,P,P,	c,c													I,s		s									c,c	c,c	c,c		
T7	Modify shelf layout	5	14	19		c,c		c,c,c		s	I,s, s,	I,s			s					s		s	s				s								
T8	Modify testing room RH	2	2	4						I,s																									I,s
T9	EMPTY			0																															
T10	Add glass front		2	2		c,P														s															
T11	Modify LU patch end		1	1		s																													
T12	Blind down		2	2													s			s															
T13	Blind up	1	4	5		c,P										I,s,c,P		s																	
T14	Light off		2	2													s			s															
T15	Light on			0		P										O		s																	
T16	Modify suction pressure	6	27	33	I,s,s	I,s,s,s,s,s,s,s,P,P,P		s	c,c	c,c	c,c	s		s		OP		c,P		I			OP	s		s		I,s					c,c		
T17				0																															
T18	Modify superheat setting	2	9	11		c,c,c, P																c,c,P	I,s				c,P					c,c			
T19	Modify rear duct	9	18	27	I,s,s,s,P	c,c,c,P,P,P														I c,c,c,c,			I,I,I,c,c,c, c,c, P P P P P P									I,s,c,P,P			
T20	condensing pressure raised		2	2		c,P								s																					
T21	compressor changed lowered		2	2		c,P																		s											
T22	roof duct screws loosened	1	2	3	c,P	c,P																													
T23	Modify suction temperature		3	3		s																s	s												
T24	Add baffle to back of shelf	1	2	3							s																		s						
T25	Re-arrange M packages (brought product forward as shelves)	2	7	9	c,c															s	s		s						I,s,s						
T26	Modify front duct (honeycomb to 4 mm. FPG from 3 mm. FPG)		4	4			c,c																								c,c				
T27	Modify testing room condition		6	6		c,c				c,c,P												c,c													
T28	Modify EPR setting	2	6	8																			c,c						I,s,s			I,s,s			
T29	Testing room's condition change	1	3	4		I,s,P,																											c,c		
T30	cabinet pulling down		3	3		s	s	s																											
T31	Close off added to SL3, shelf#4	1	3	4		s					I,s									s															

To complete a dependency and frequency analysis in the application of the algorithm, it was necessary to apply the heuristic algorithm to the values of A>B and B>A in the matrix. The heuristic algorithm was defined previously as:

$$\$A \rightarrow^{L} B = \frac{(\# A > B - \# B > A)}{(\# A > B + \# B > A + 1)}$$

For example, in the dependency and frequency value of tasks T7 and T2 derived from the value in the matrix, T7>T2 happened twice while the opposite did not occur. The dependency and frequency value was therefore:

$$\$A \rightarrow^{L} B = \frac{(2 - 0)}{(2 + 0 + 1)} = 0.666$$

In the next example the relationship between T3 and T2, T3>T2 happened seven times while T2>T3 occurred once. The dependency and frequency value was therefore:

$$\$A \rightarrow^{L} B = \frac{(1 - 1)}{(7 + 1 + 1)} = 0.66$$

In the example of T5 and T6, in 5 cases T5 was followed by T6 only once and T6>T5 never happened. The dependency and frequency value was therefore:

$$\$A \rightarrow^{L} B = \frac{(1 - 0)}{(1 + 0 + 1)} = 0.50$$

The researcher developed a computational form to calculate all relationships and all of the dependency and frequency values which are shown in Table 6.3. The Table is constructed with the initial task A on the top row. First column shows tasks B which follow from task A in order. The second, third and fourth columns show the frequency of task A followed by task B, task B followed by task A and the value of dependency and frequency consecutively. Not all tasks and its follower tasks appeared in the testing log sheet. Only the following tasks have measured D/F values. This is because the engineers have never done certain tasks after certain other tasks. The tasks that have D/F value are T1, T2, T3, T4, T5, T6, T7, T13, T16, T18, T19, T26, T27 and T28. The others were excluded because these pairs of tasks appeared as A>B only once and did not occur as B>A in the whole process.

For example, T7 followed by T11 happened once and T11 never happened before T7. There are examples when the number of A>B occurred the same number of times as B>A, then D/F value will equal zero.

$$\$A \rightarrow^{L} B = \frac{(1-1)}{(1+1+1)} = 0.00$$

Table 6.3 highlights the high dependency and frequency values. For example the dependency between T4 to T2, T1 to T6 and T2 to T6 show values which are higher than 0.6. The value of 0.6 was determined by finding the mean of all D/F values, excluding 0. This assumption of 0.6 and its validity were the subject of evaluation by the engineers throughout the process and is discussed in detail later in this chapter in section 6.5.3.

Table 6.3 Dependency and frequency values of modification tasks in 5 test cases.

B	#A>B	#B<A	$A-->B Local
A= T1			
T2	10	3	0.5
T6	5	0	0.833333333
T19	2	0	0.666666667
A = T2			
T1	8	1	0.7
T2	26	16	0.23255814
T3	4	1	0.5
T5	4	0	0.8
T6	5	0	0.833333333
T7	2	0	0.666666667
T16	8	2	0.545454545
T19	5	1	0.571428571
T23	2	1	0.25
A = T3			
T2	7	1	0.666666667
T3	3	1	0.4
T6	2	1	0.25
T18	2	0	0.666666667
A = T4			
T2	7	0	0.875
T3	1	0	0.5
T4	1	0	0.5
A = T5			
T1	2	0	0.666666667
T2	2	3	-0.166666667
T5	1	0	0.5
T6	1	0	0.5
T16	0	1	-0.5
A = T6			
T1	1	0	0.5
T2	5	3	0.222222222
T3	2		0.666666667
T16	1		0.5
T18	1		0.5
T27	2		0.666666667
T28	2		0.666666667
T29	2		0.666666667
A = T7			
T2	2	0	0.666666667
T4	3	0	0.75
T6	1		0.5
T7	2		0.666666667
T8	1		0.5
T10,T16,T18,	1		0.5

B	#A>B	#B<A	$A-->B Local
A=T13			
T2	1	1	0
T12	2	1	0.25
T14	1	0	0.5
A=T16			
T1	2		0.666666667
T2	8	3	0.416666667
T4	1		0.5
T5	2		0.666666667
T6	2		0.666666667
T7	2		0.666666667
T8	1		0.5
T10	1		0.5
T12	1	1	0
T14	1	1	0
T19	1	1	0
T24	1		0.5
T29	2		0.666666667
A=T18			
T2	3	1	0.4
T18	2	1	0.25
T19	1		0.5
T23	1	1	0
T28	2		0.666666667
A=T19			
T1	4	1	0.5
T2	3	3	0
T16	4		0.8
T19	5	3	0.222222222
T28	2	1	0.25
A=T27			
T2	2		0.666666667
T1	2		0.666666667
T6	2	1	0.25
T18	2		0.666666667
A=T26			
T3	2		0.666666667
T27	2		0.666666667
A=T28			
T19	2		0.666666667
T28	2		0.666666667
T25	2		0.666666667

Table 6.3 highlights a number of pairs of tasks which have high D/F values. For example T1 followed by T6 has the highest D/F value at 0.83. T1 is ‘modify defrost’ setting and T6 is ‘modify valves and orifice’. From the five cases the engineers did modify the defrost setting and they did modify valves and orifice five times, while the engineers never did modify valves and orifice before modifying defrost setting. This shows that the task ‘modify defrost setting’ is the cause/initiator of the task ‘modify valves and orifice’. The other pair of tasks with the same D/F value (0.83) were T2 and T6.

The next step in the analysis requires constructing the D/F graph with dependency and frequency values. The five cases of workflow nets used in this example application from the Company are shown in Figs 6.19 – 6.23:

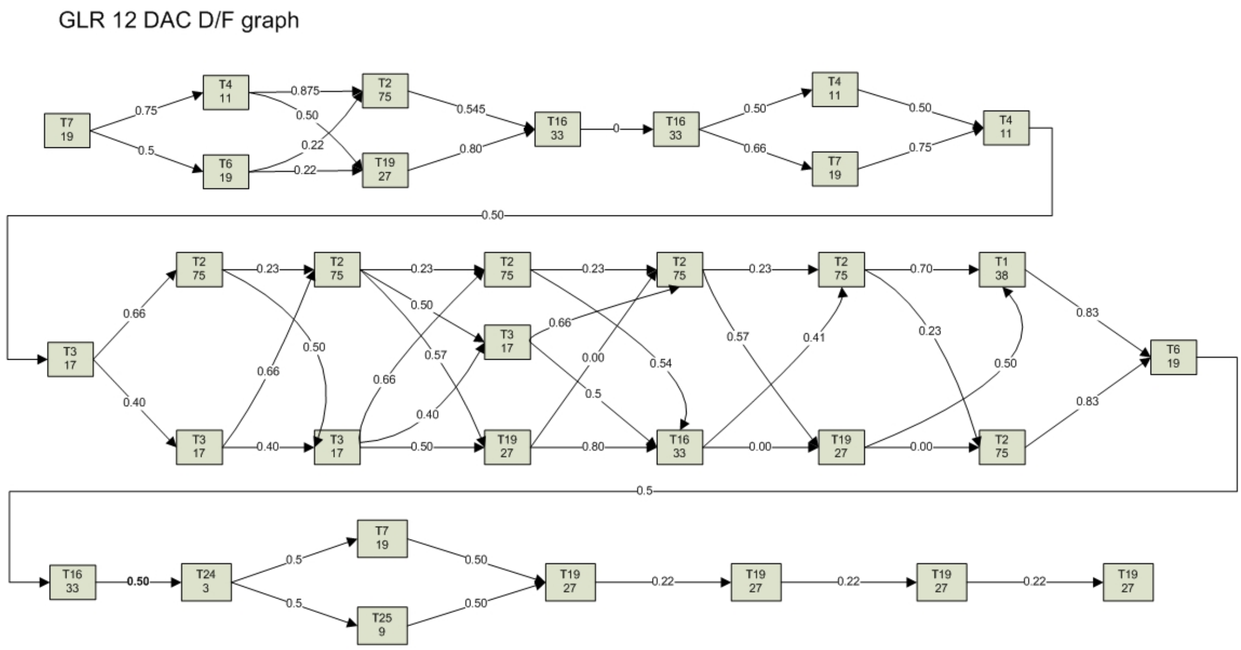


Figure 6.19 GLR 12 DAC D/F graph

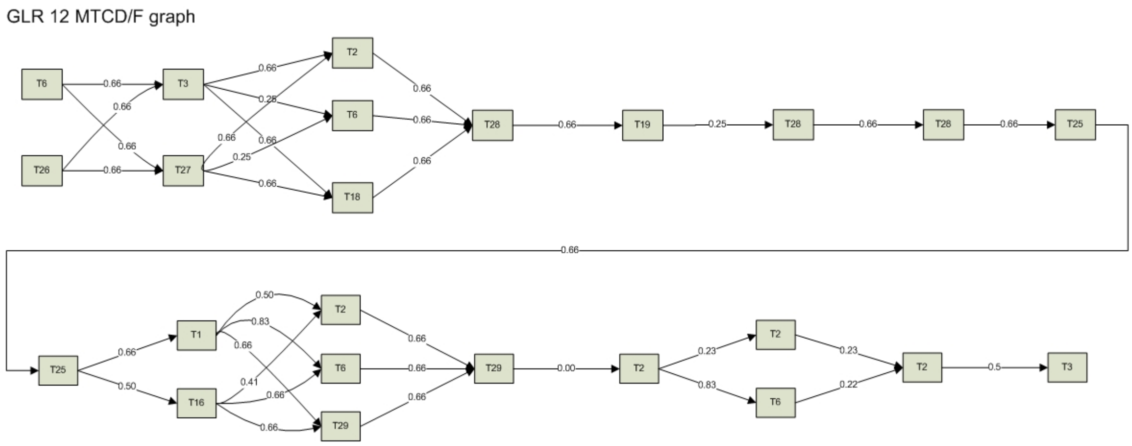


Figure 6.20 GLR 12 MTC D/F graph

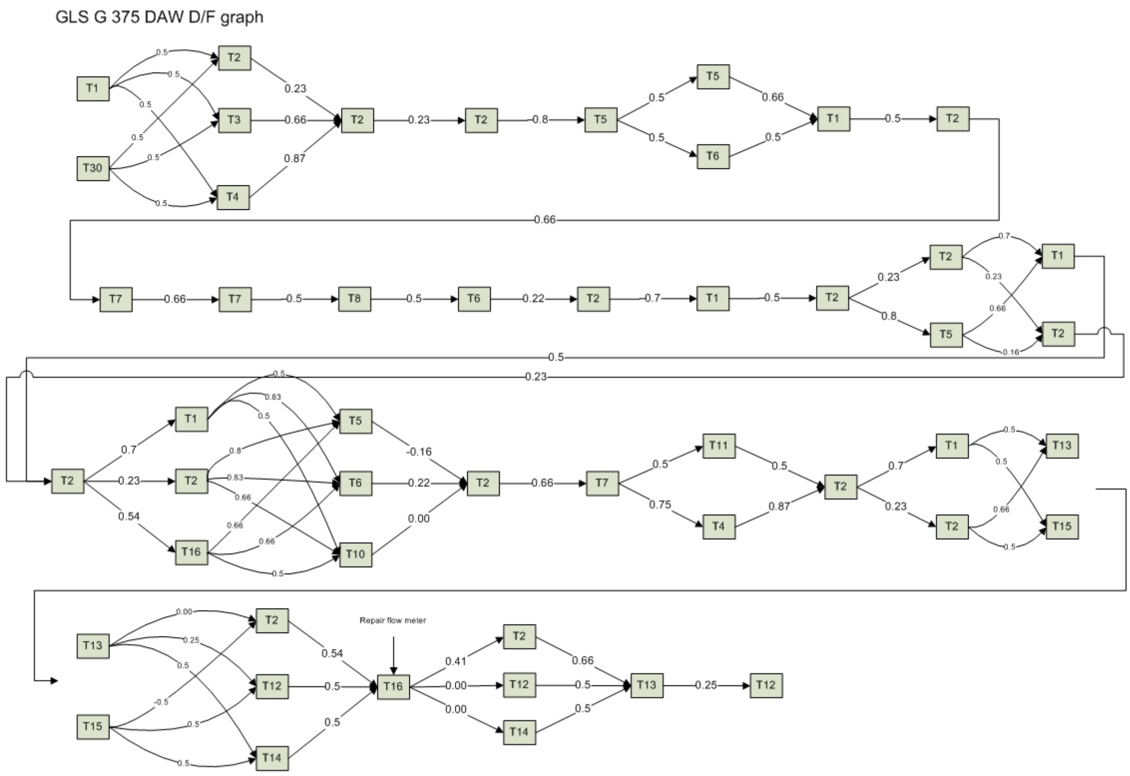


Figure 6.21 GLS G 375 D/F graph

GLS G5 375 MTW D/F graph

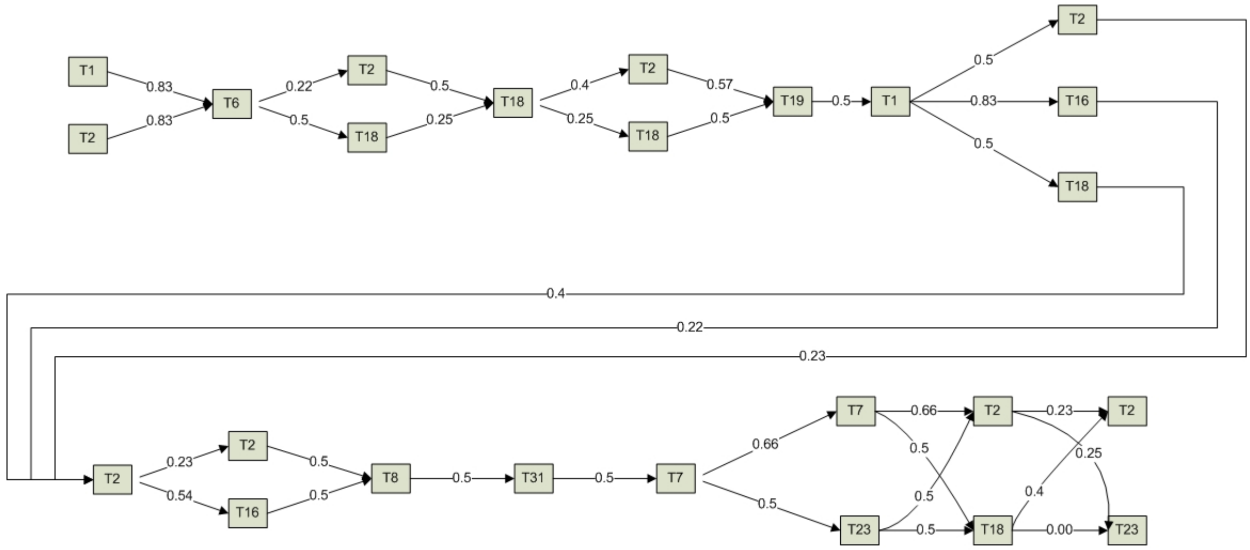


Figure 6.22 GLS G5 375 MTW D/F graph

GLSG5 375 PRW D/F graph

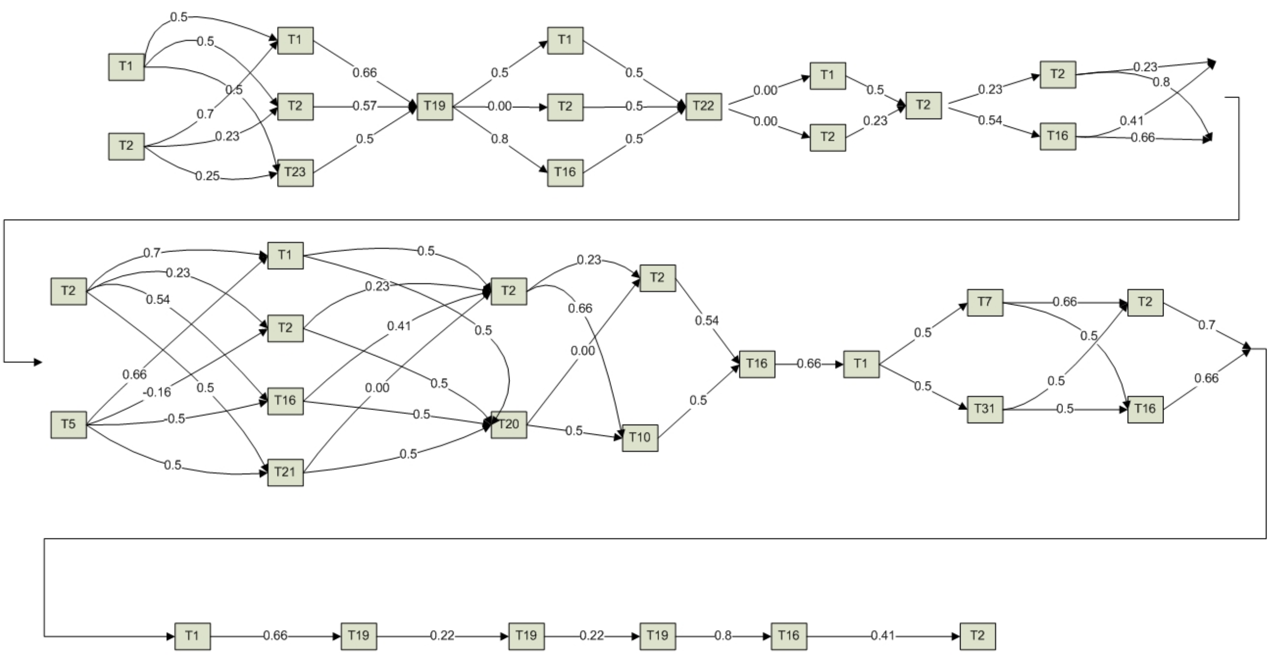


Figure 6.23 GLS G5 375 PRW D/F graph

At this stage the result of dependency and frequency values were not quite sound. The number of instances in the five cases was only 115. The dependency and frequency high and low values were not clearly distinguished enough. Previous research using this method has shown that the more data that was added, the more accurate the analysis becomes. Additional data collection for further workflow analysis was thus needed. Therefore, the researcher added a further eight testing reports to the analysis. Each new case contained larger amounts of instances. This additional data when analysed strengthened the modification tasks dependency value.

6.5.3.2 Round 2 Analysis

The eight additional sets of testing reports for eight other cabinets were verified with the engineers. There were five additional meat cabinets, one produce and two dairy cabinets. This covers all of the workflow instances for the Company. The numbers of instances in the additional eight cases was 272. In this round the numbers of instances from the first five cases and the additional eight cases have been combined for dependency and frequency values evaluation. The total numbers of instances becomes 389. Starting with case GLH12 MTC, this cabinet was tested for two months and eight days. The event log contained 19 instances as shown in Figure 6.24. The process involved is complex and is described below.

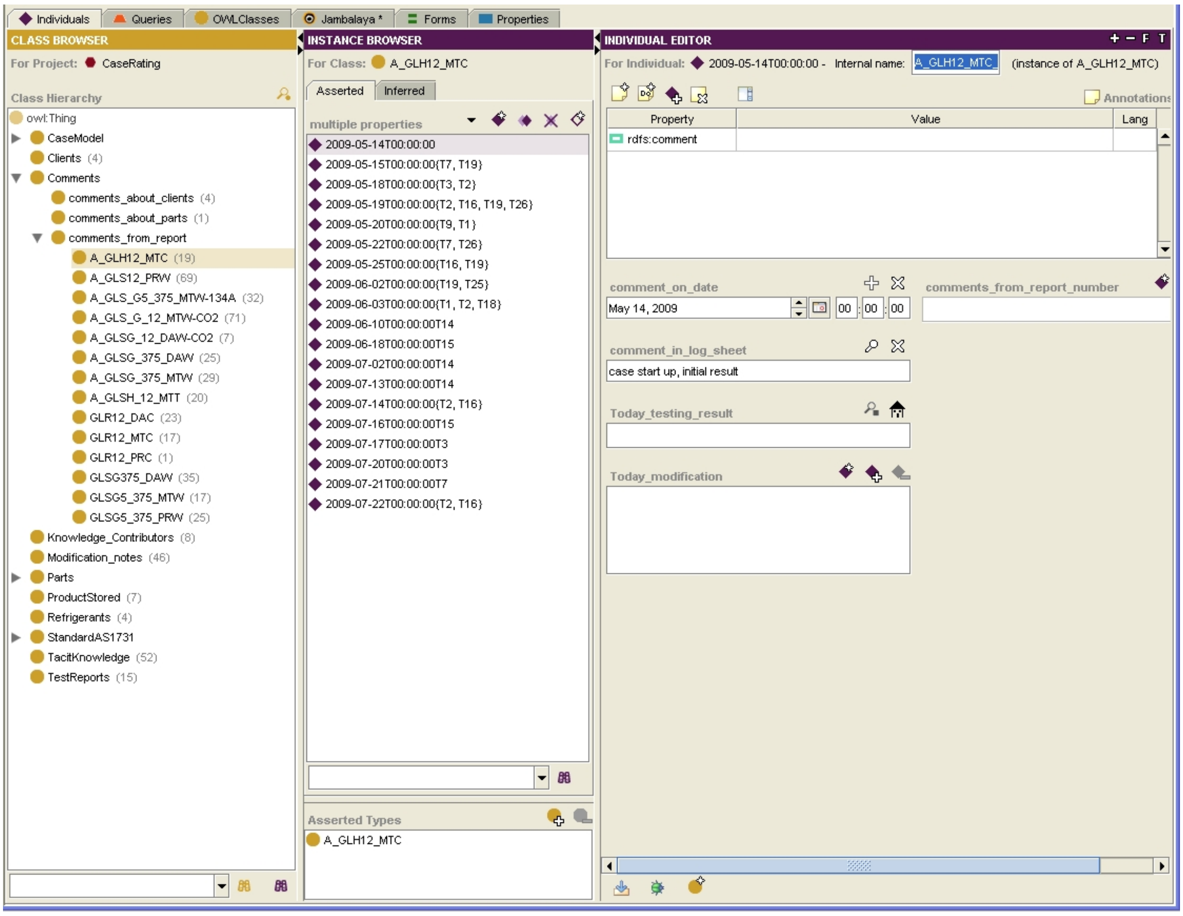


Figure 6.24 Event log of the cabinet case GLH12 MTC

Case A_GLH12_MTC event logs start on 14th of May 2009. The engineers then reviewed the initial result from the date mentioned and decided that they will do task 7 and task 19. Then the engineers let the cabinet run continuously. On occasions they let the cabinets run 24 hours or longer to let the modifications that they have made take effect. In this particular case 15th of May 2009 was a Friday therefore the case was left running over the weekend. Next the engineers decided to do T3 and T2 on Monday 18th of May. The next day 19th of May the engineers decided to do 4 tasks on the same day which are T2, T16, T9 and T26. On 20th of May T1 and T9 modifications were made to the case. On the 22nd, 25th of May and 2nd of June 2 modification tasks were again made to the case. These tasks were T7 and T26, T16 and T19 and T19 and T25 accordingly. On 3rd of June the engineers have made T1, T2, T18 modifications to the case. The case was then left running in the laboratory for 6 days and then change T4 was made to the case on the 10th of June. On 18th of June the engineers made change T15 to the case. The case was left running again until the 2nd of July when change T14 was made to the case and repeated on the13th of July. On the 14th of July changes T2 and T16 were made to the case. On the 16th of July the engineers made T15 modification to the case. On 17th and 20th of July T3 modification were made to the case. Then on 21st of July change T7 was made. On 22nd of July the engineers made T2 and T16 modifications and the testing process was finished.

This observed case is used to illustrate the D/F diagram as shown in Figure 6.25

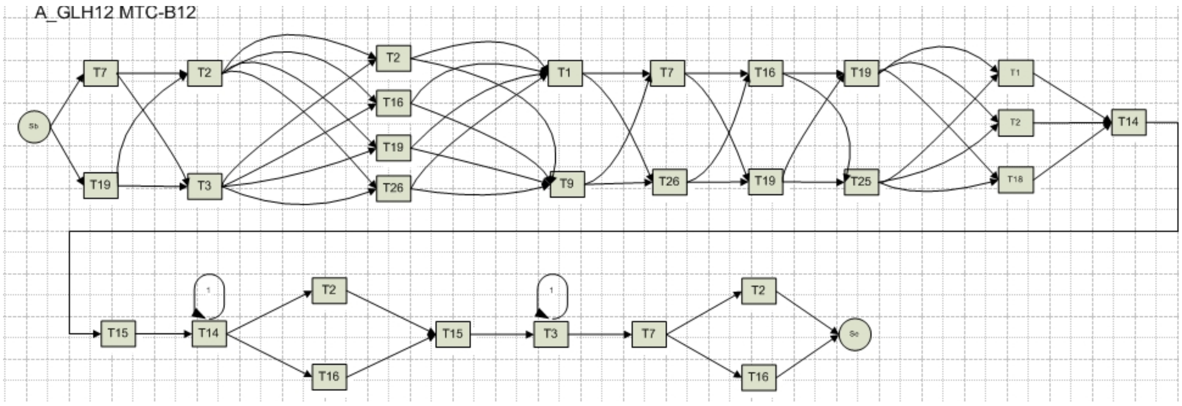


Figure 6.25 Workflow net of case GLH12 MTC.

Then the process of constructing D/F graphs out of the testing logs was repeated for the remaining seven additional testing logs. The outcomes are workflow nets for each case shown in Figs 6.26 to 6.32 below.

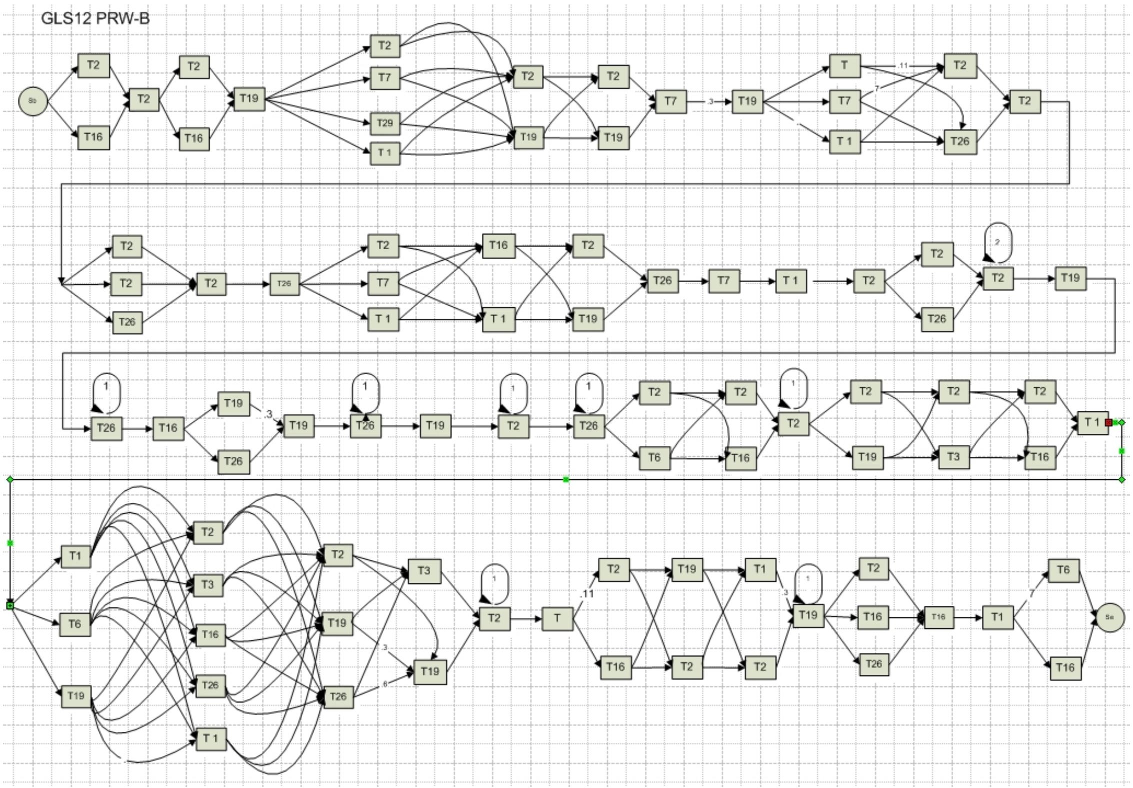


Figure 6.26 Workflow net of case GLR 12 PRW

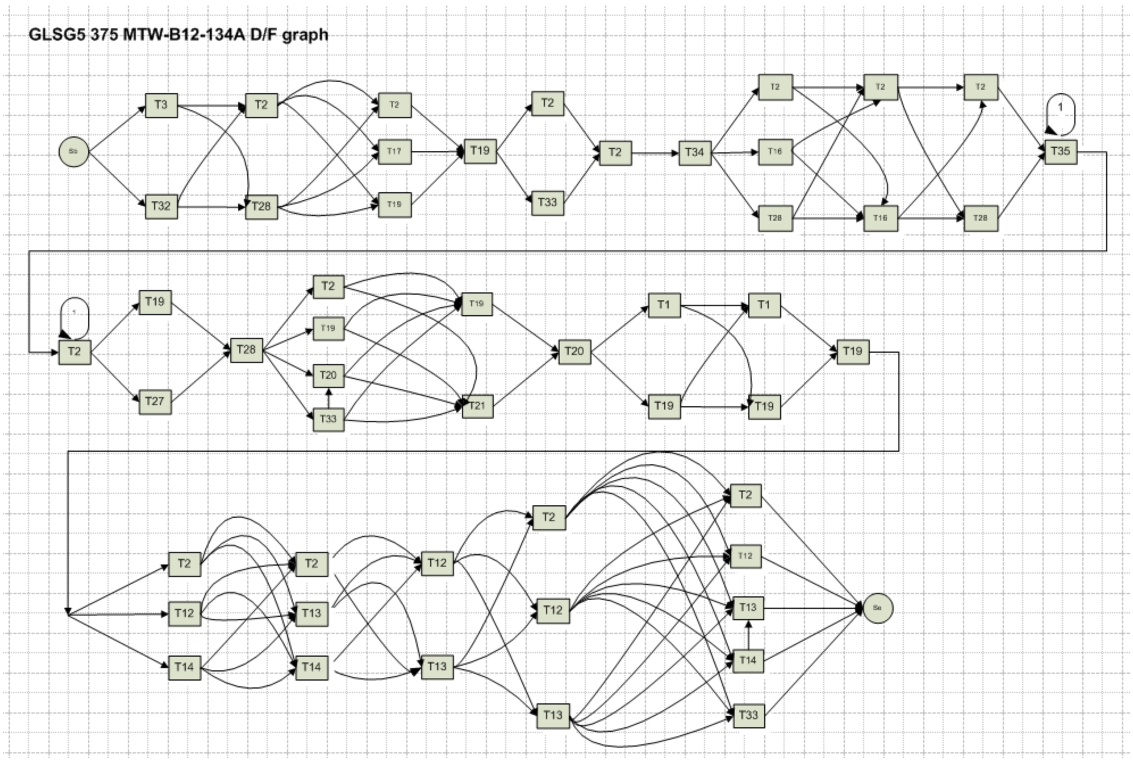


Figure 6.27 Workflow net of case GLS G5 375 MTW B12 134A

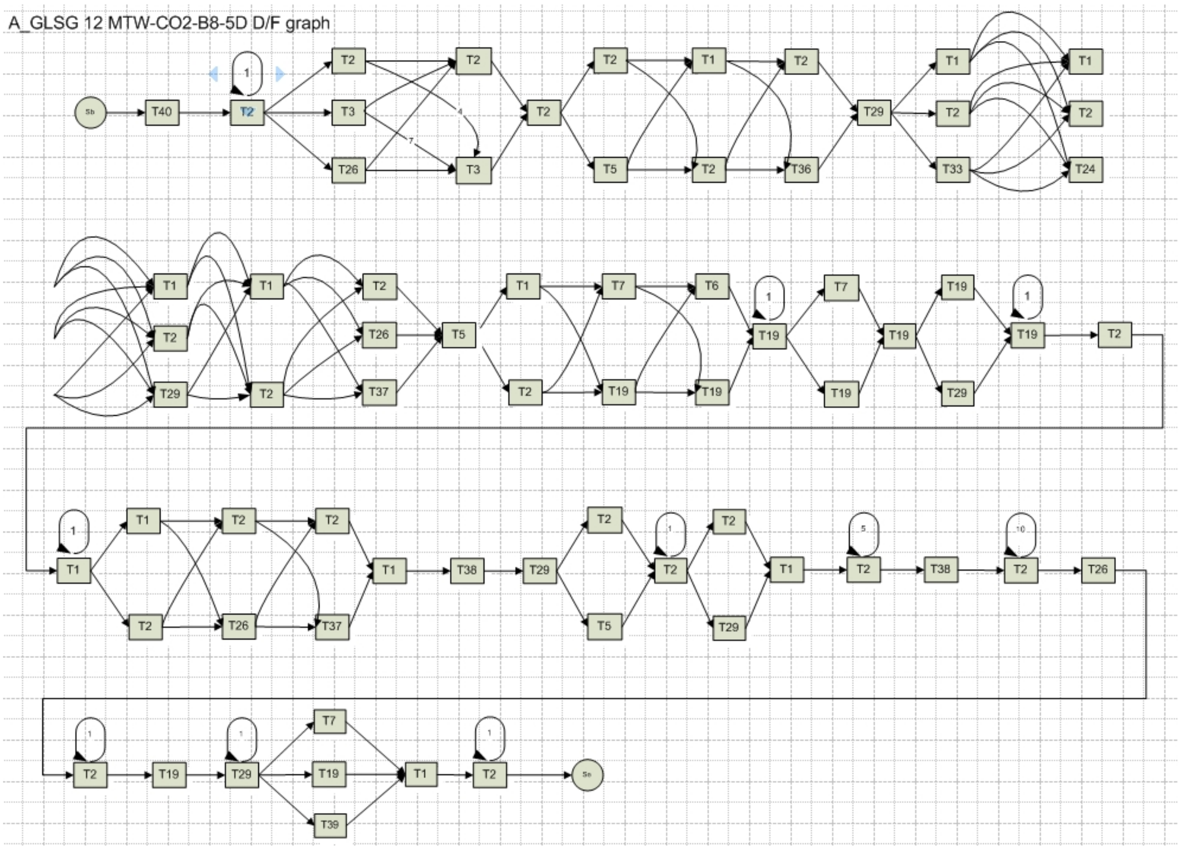


Figure 6.28 Workflow net of case GLS G 12 MTW

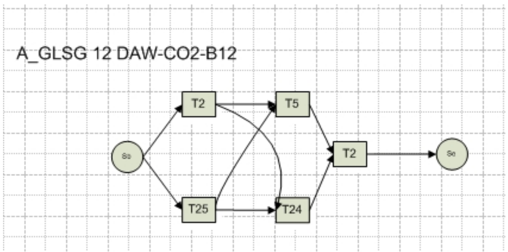


Figure 6.29 Workflow net of case GLS G 12 DAW

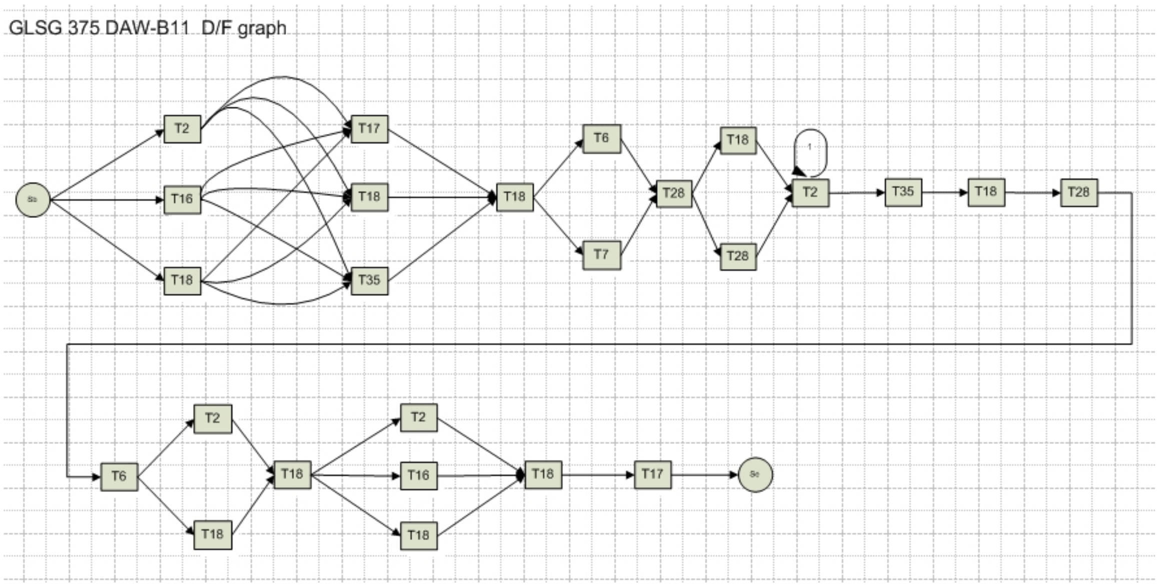


Figure 6.30 Workflow net of case GLS G 375 DAW

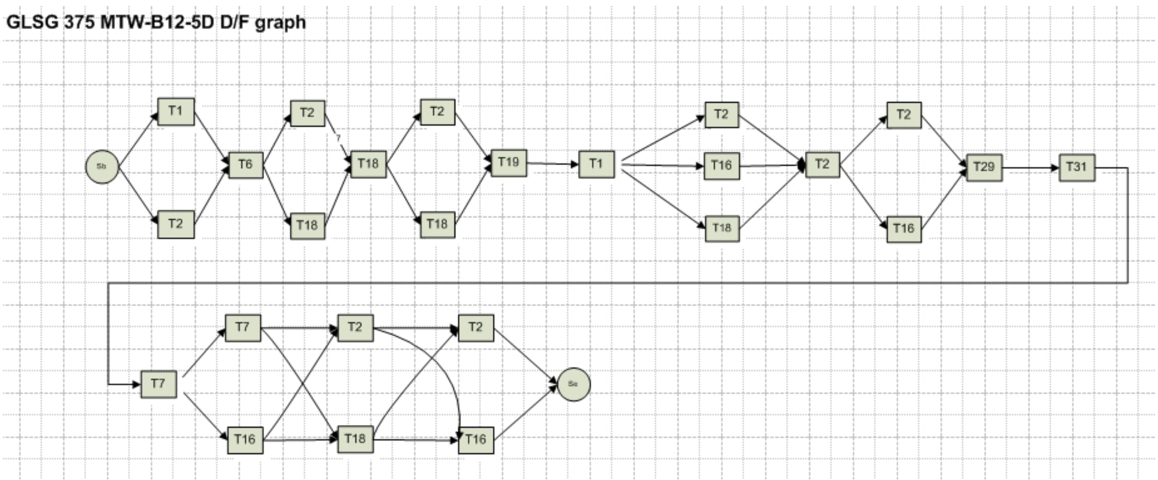


Figure 6.31 Workflow net of case GLSG 375 MTW

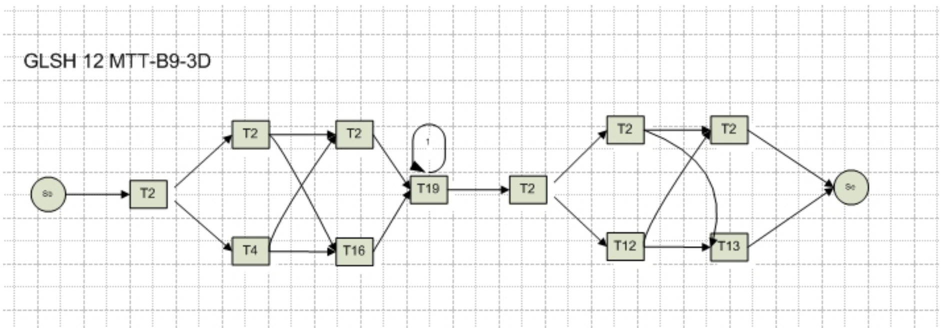


Figure 6.32 Workflow net of case GLS H 12 MTT

Again following the procedures used in the analysis of the first five examples, the next step is construction of the dependency and frequency matrix. However, this time the frequencies of pairs of tasks included the frequencies of all 13 cases. The outcome from this process is shown in Table 6.4.

Table 6.4 Dependency and frequency metric of 13 cases

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20	T21	T22	T23	T24	T25	T26	T27	T28	T29	T30	T31	T32	T33	T34	T35	T36	T37	T38	T39	T40	T41
T1	sssssssp pp	sssssssssssssssssssP PPppppp	ss	s	s	sssssss	sss			s			s	s	s	ssssp		ss	ssssssppp	s		s	s	s		ssssp			ss		s					s	s	s			s p
T2	sssssssss sssssssP pp	sssssssssssssssssss sssssssssssssssssss sssssssssssssssssss sssssssssssssssssss ssssssssPPPPPPPpPp PPPPPPPpppppppppp PPPPPPPPPPPPPPPPPP pppppppppppp	ssssssssPp	s	ssssssss	ssssss	ssss	s	s	ss		sss pp	ssssssp	sss	ss	ssssss ssssss ssssPp Ppp	ss	sssssp	ssssssssss ssssssssss sssPppp	s	ss	s	ssP	ss	ss	ssssssss ssp	s	sssp	sssss s				s	s	sss	s	ss	s			ss
T3		sssssssssssssPpp	sssssP			ssP	s									sss		ss	sss						s	ss		s													
T4		sssssssssp	s	s												s			s																						
T5	ssss	sssssssssPPPpppp			s	s										Ps					s					s		p													
T6	s	sssssssssPPPp	sss													sss		sss	s p							s	ss	sss	ss												sp
T7	s	ssssss		sss		ss	sss	s			s					sssss		ss	sssssppp				s			s		s													ss
T8						s																									s										
T9							s																			sp															
T10		sP														s																									
T11		s																																							
T12		ssssspp										ssp	ssssspp	ss		s																	s								
T13		sssPp										sssssPpp	ssspp	ss																			s								
T14		ss										sp	sss	ss	s	ss																									
T15		P	s									S		ssp																											
T16	ssss	sssssssssssssssPPpP pp		s	ss	ss	ss	s	s	s		SP		sP	s	ss	s	sssp	sSsssssPp	s		s		s	ss	ssp		s	sss						s						s
T17																		sp	s																						
T18		ssssssss Ppp				s	s							s		ssp	ss	sssssssss pPpp	ss				sP					sss							s						
T19	sssssssss sP	sssssssssssssssPPpP ppp	ssssp		s	s	ssssp		s			s		s		ssssss		s	ssssssssss ssssssssss sss PPpppppp pPp	sp	s				ss	sssss		sssP	sss				s								sssp
T20	s	sP								s									ss		s																				
T21		sP																		ssp																					
T22	sP	sP																																							
T23		s																s	s																						
T24	sp	ssp					s																		s				s												
T25	ssss	s sspp			ss											s	s	s	s					s	sss																
T26	s	ssssssssppppp	sss sp		s	s	ss		s							sss			sss ssp							ssss	ss										s				s
T27		ss				ssP												ss										s													
T28		ssss				s										s	s	s	ssss	s					ss			sss					s		s						
T29	sssp	sssssPp			s		s												ssspp										sss		s		s						s		
T30		s	s	s																																					
T31		s					ss									s																									
T32		s																										s													
T33	s	ss																	s		s			s																	l
T34		sp														s												s													
T35		s																ssp																	s						
T36																						l							s												
T37	s				s																																				
T38		sp																											s												
T39	s																																								
T40		s																																							
T41	s	sssssp				s										s			sssspp							ss															s

In Table 6.4 the number of modification tasks used by the engineers increased from 31 to 41. This is due to the expansion of the data source. The frequencies of pairs of tasks also change and as a result the dependency and frequency value also change. For example, in the first five cases the dependency value of T7>T2 = 0.66, T3>T2 = 0.66 and T5>T6 = 0.50. When data from the eight additional cases was included the dependency and frequency of pair of tasks changed. The new dependency and frequency value for that relationship improved to:

$$\$A \rightarrow^{L} B = \frac{(7 - 0)}{(7 + 0 + 1)} = 0.875$$

For the relationship between T3 and T2, the dependency and frequency value changed from 0.66 to:

$$\$A \rightarrow^{L} B = \frac{(13 - 3)}{(13 + 3 + 1)} = 0.588$$

For exemplar pair process T5 and T6, after including another eight cases the frequency number of T5>T6 did not change and T6>T5 also did not occur. Therefore, the dependency and frequency value remained the same

$$\$A \rightarrow^{L} B = \frac{(1 - 0)}{(1 + 0 + 1)} = 0.50$$

All new dependency and frequency values are shown in Table 6.5

Table 6.5 Dependency and frequency values of all 13 cases.

B	#A>B	#B<A	$A-->B Local
T1	7	3	0.363636364
T2	20	8	0.413793103
T3	2		0.666666667
T6	7		0.875
T7	3		0.75
T16	4	1	0.5
T18	2		0.666666667
T19	6	3	0.3
T26	4	1	0.5
T29	2		0.666666667
A = T2			
T1	16	3	0.65
T2	92	58	0.225165563
T3	8	2	0.545454545
T5	8		0.888888889
T6	6		0.857142857
T7	4		0.8
T12	3	2	0.166666667
T13	6	1	0.625
T14	3		0.75
T16	18	5	0.541666667
T18	5	1	0.571428571
T19	23	4	0.678571429
T21	2		0.666666667
T23	2	1	0.25
T24	2		0.666666667
T25	2		0.666666667
T26	10	1	0.75
T28	3	1	0.4
T29	6		0.857142857
T35	3		0.75
T41	2		0.666666667
A = T3			
T2	13	3	0.588235294
T3	5	1	0.571428571
T16	3		0.75
T18	2		0.666666667
T19	3		0.75
T26	2		0.666666667
A = T4			
T2	8	1	0.7
A = T5			
T1	4		0.8
T2	9	7	0.117647059
A = T6			
T2	9	4	0.357142857
T3	3		0.75
T16	3		0.75
T18	3		0.75
T19	1	1	0
T27	2		0.666666667
T28	3		0.75
T29	2		0.666666667

B	#A>B	#B<A	$A-->B Local
A = T7			
T2	7		0.875
T4	3		0.75
T6	2		0.666666667
T7	3		0.75
T16	5		0.833333333
T18	2		0.666666667
T19	6	3	0.3
T41	2		0.666666667
A = T12			
T2	4	2	0.285714286
T12	2	1	0.25
T13	5	2	0.375
T14	2		0.666666667
A = T13			
T2	3	2	0.166666667
T12	5	3	0.222222222
T13	3	2	0.166666667
T14	2		0.666666667
A = T14			
T2	2		0.666666667
T12	1	1	0
T13	3		0.75
T14	2		0.666666667
T16	2		0.666666667
A = T15			
T14	2	1	0.25
A = T16			
T1	4		0.8
T2	16	6	0.434782609
T5	2		0.666666667
T6	2		0.666666667
T7	3		0.75
T16	2		0.666666667
T18	3	1	0.4
T19	7	2	0.5
T25	2		0.666666667
T26	2	1	0.25
T29	3		0.75
A = T18			
T2	8	3	0.416666667
T16	2	1	0.25
T17	2		0.666666667
T18	9	4	0.357142857
T23	1	1	0
T28	3		0.75

B	#A>B	#B<A	$A-->B Local
A = T19			
T1	10	1	0.75
T2	16	7	0.375
T3	4	1	0.5
T7	4	1	0.5
T16	6		0.857142857
T19	23	11	0.342857143
T25	2		0.666666667
T26	5		0.833333333
T28	3	1	0.4
T29	3		0.75
T41	3	1	0.4
A = T20			
T19	2		0.666666667
A = T21			
T2	1	1	0
T20	2	1	0.25
A = T23			
T2	1		0.5
T18	1		0.5
T19	1		0.5
A = T24			
T1	1	1	0
T2	2	1	0.25
T7	1		0.5
T25	1		0.5
T29	1		0.5
A = T25			
T1	4		0.8
T2	3	2	0.166666667
T5	2		0.666666667
T16	1		0.5
T17	1		0.5
T18	1		0.5
T19	1		0.5
T24	1		0.5
T25	3		0.75
A = T26			
T1	1		0.5
T2	8	5	0.214285714
T3	4	1	0.5
T5	1		0.5
T6	1		0.5
T7	1		0.5
T9	1		0.5
T16	3		0.75
T19	5	1	0.571428571
T26	4		0.8
T27	2		0.666666667

B	#A>B	#B<A	$A-->B Local
A = T27			
T2	2		0.666666667
T6	2	1	0.25
T18	2		0.666666667
T28	1		0.5
A = T28			
T2	4		0.8
T6	1		0.5
T16	1		0.5
T17	1		0.5
T18	1		0.5
T19	4		0.8
T20	1		0.5
T25	2		0.666666667
T28	3		0.75
A = T29			
T1	3	1	0.4
T2	5	2	0.375
T5	1		0.5
T7	1		0.5
T19	3	2	0.166666667
T29	3		0.75
T31	1		0.5
T33	1		0.5
T39	1		0.5
A = T31			
T7	2		0.666666667
A = T33			
T2	2		0.666666667
A = T34			
T2	2	1	0.25
A = 35			
T2	1		0.5
T18	2	1	0.25
A = T41			
T2	5	1	0.571428571
T16	1		0.5
T19	4	2	0.285714286
T26	2		0.666666667
T41	1		0.5

Mapping all of the data produces a new set of the Company's product development D/F graphs for the 13 cases. These are shown in Figs 6.33 to 6.45 below:

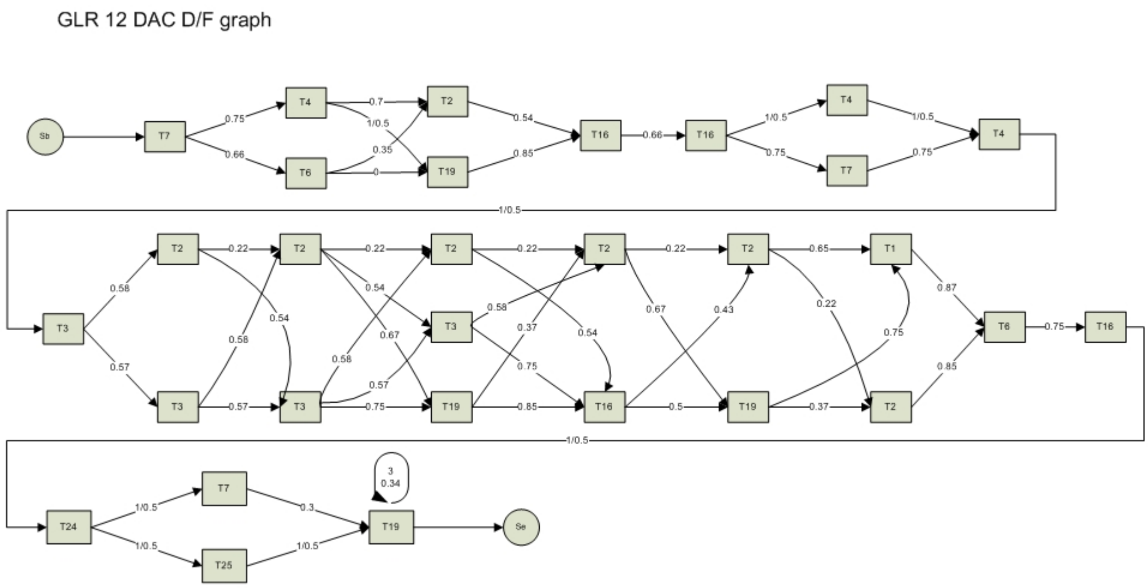


Figure 6.33 GLR 12 DAC D/F graph with new D/F values

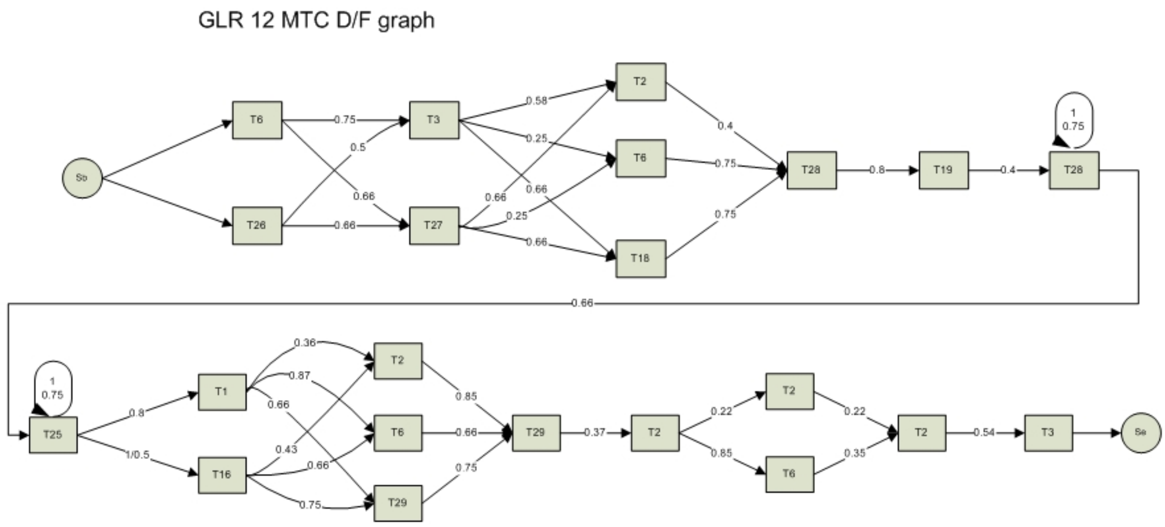


Figure 6.34 GLR 12 MTC D/F graph with new D/F values

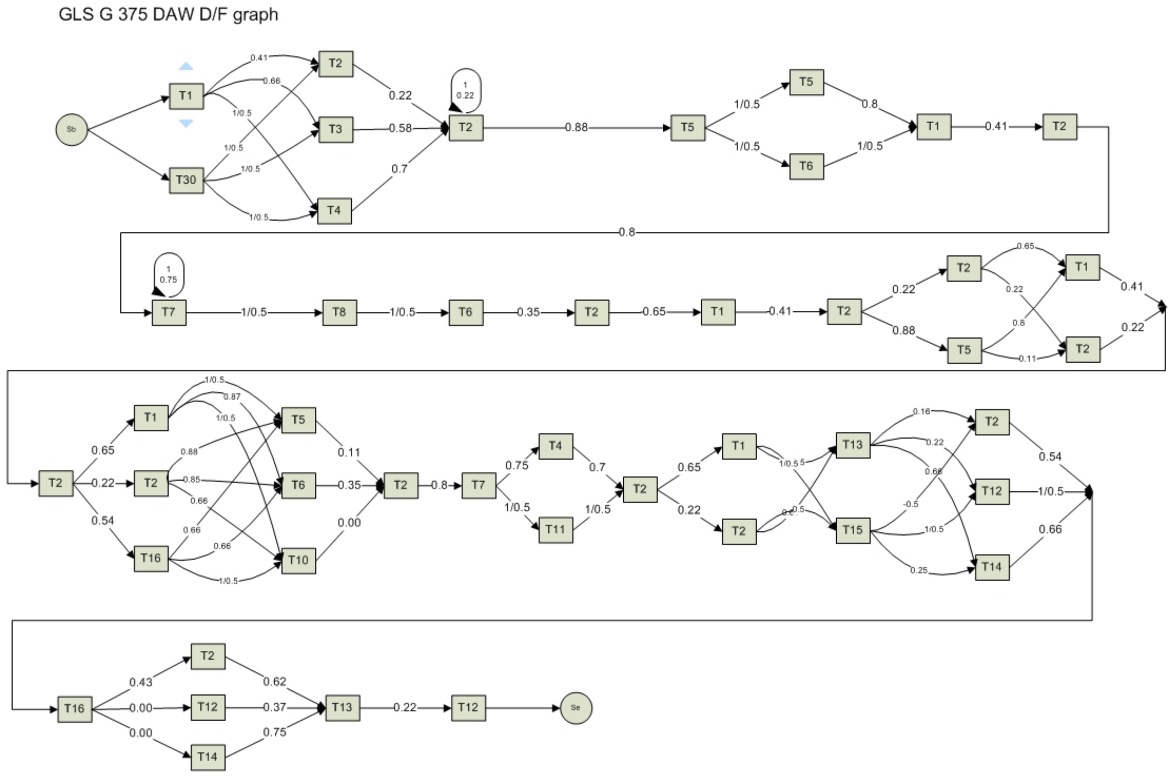


Figure 6.35 GLS G 375 DAW D/F graph with new D/F values

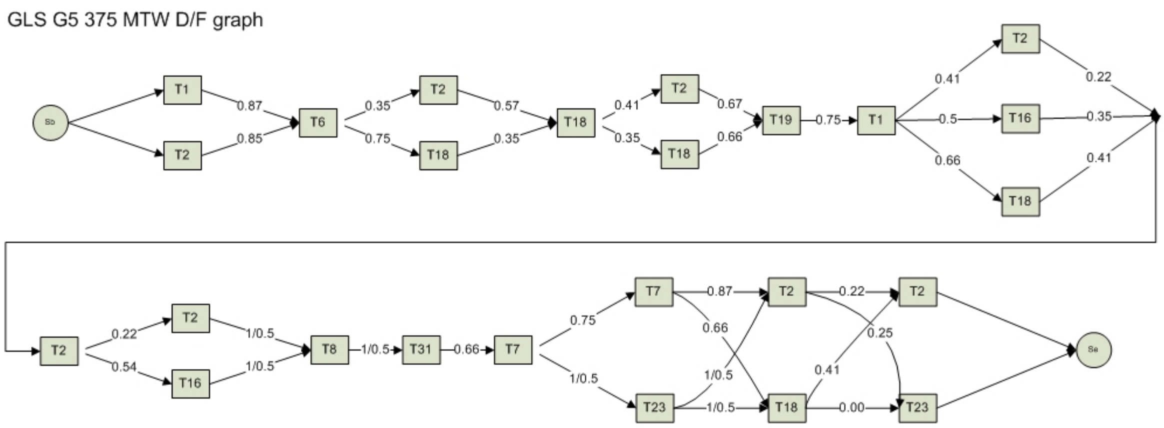


Figure 6.36 GLS G5 375 MTW D/F graph with new D/F values

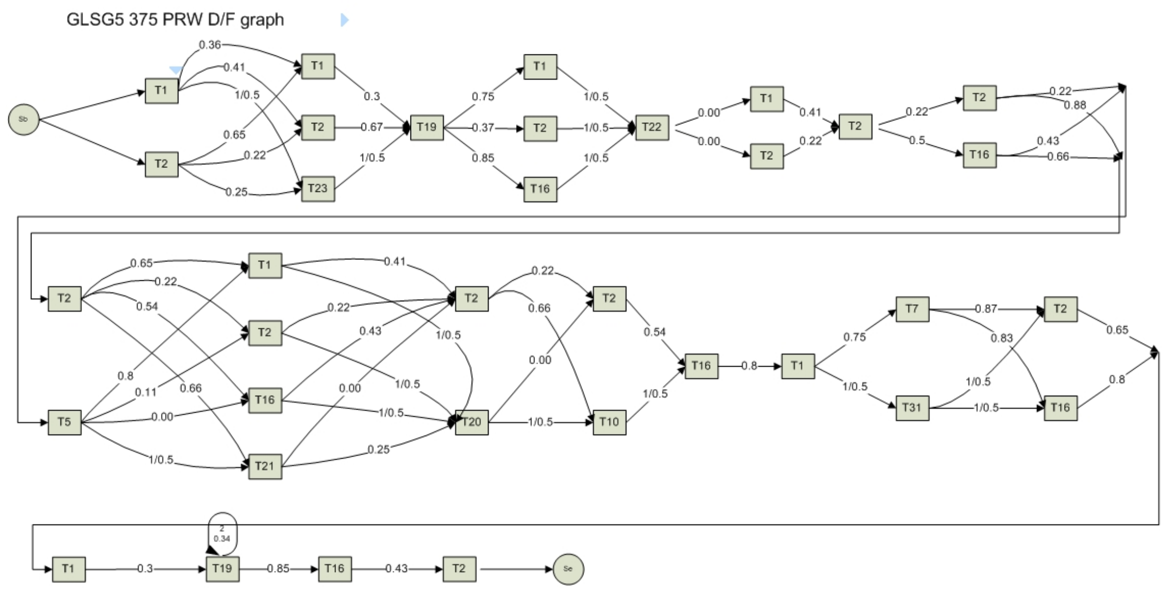


Figure 6.37 GLSG5 375 PRW D/F graph with new D/F values

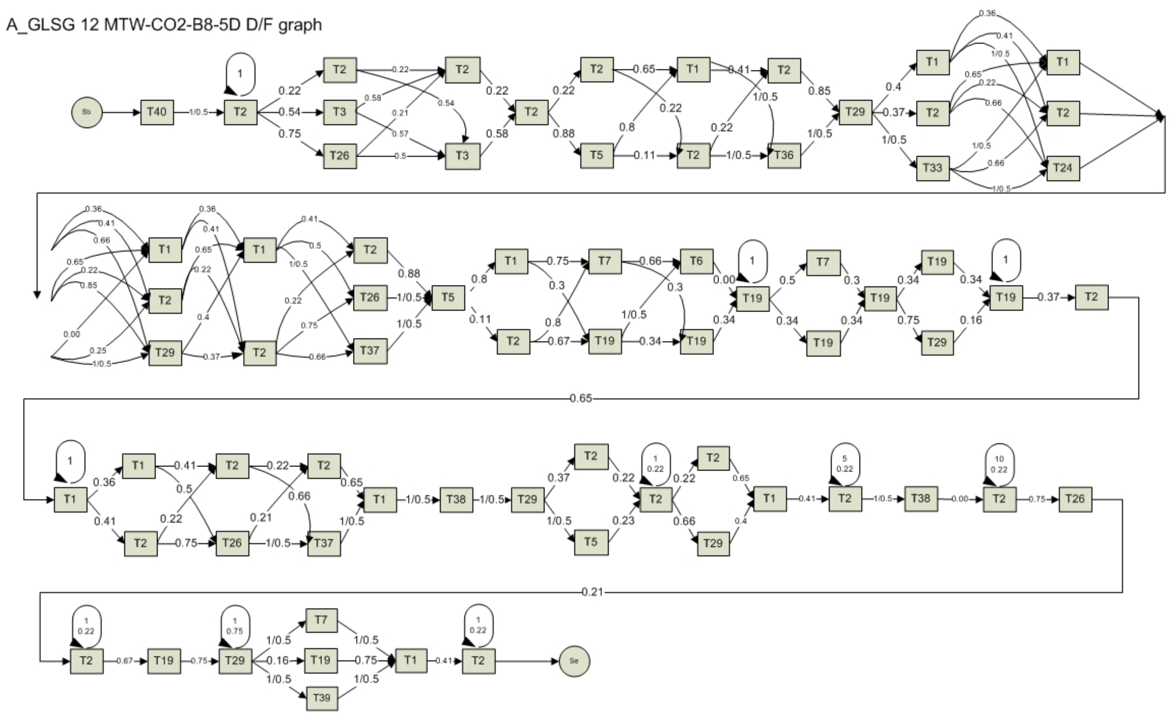


Figure 6.38 GLSG 12 MTW-CO2-B8-5D D/F graph with new D/F values

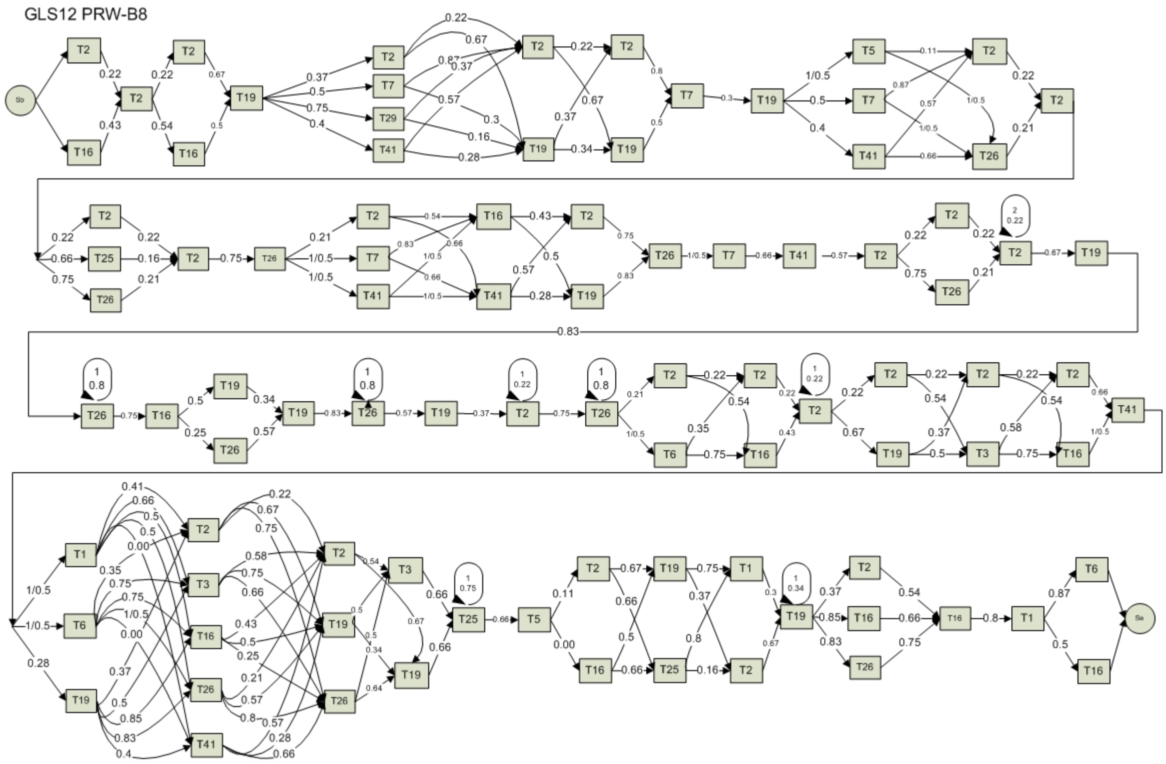


Figure 6.39 GLS12 PRW-B8 with new D/F values

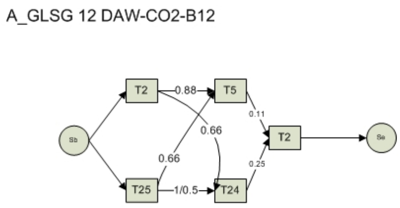


Figure 6.40 GLSG12 DAW-CO2-B12 with new D/F values

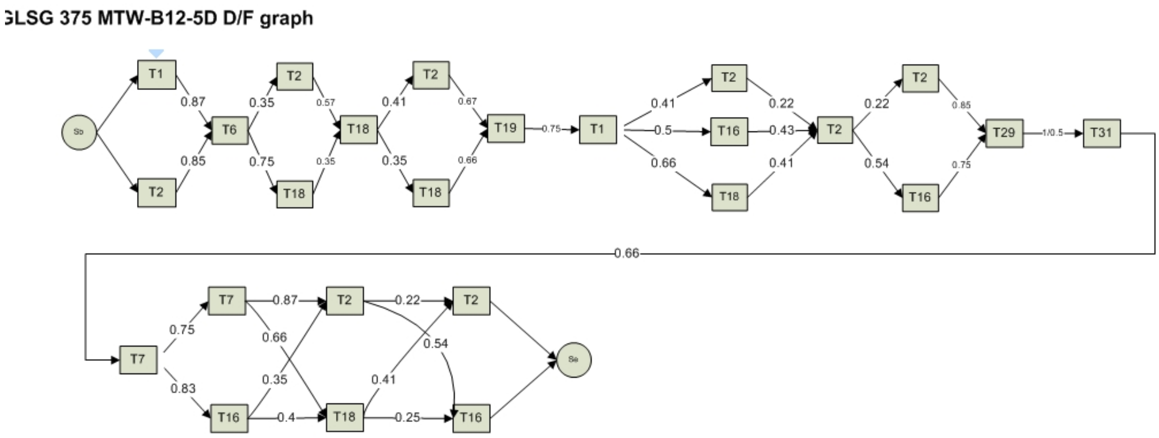


Figure 6.41 GLSG 375 MTW-B12-5D D/F graph with new D/F values

GLSG 375 DAW-B11 D/F graph

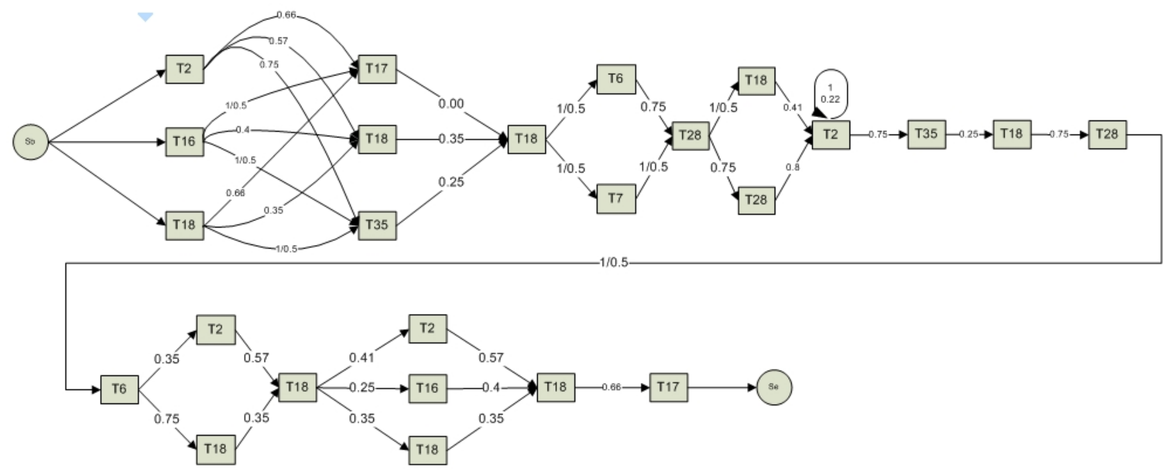


Figure 6.42 GLSG 375 DAW-B11 D/F graph with new D/F values

GLSH 12 MTT-B9-3D

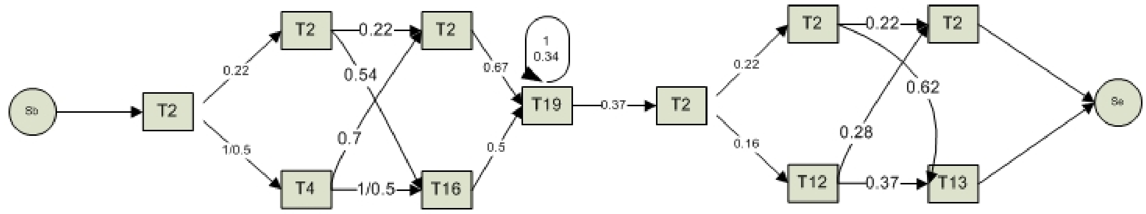


Figure 6.43 GLSH 12 MTT-B9-3D with new D/F values

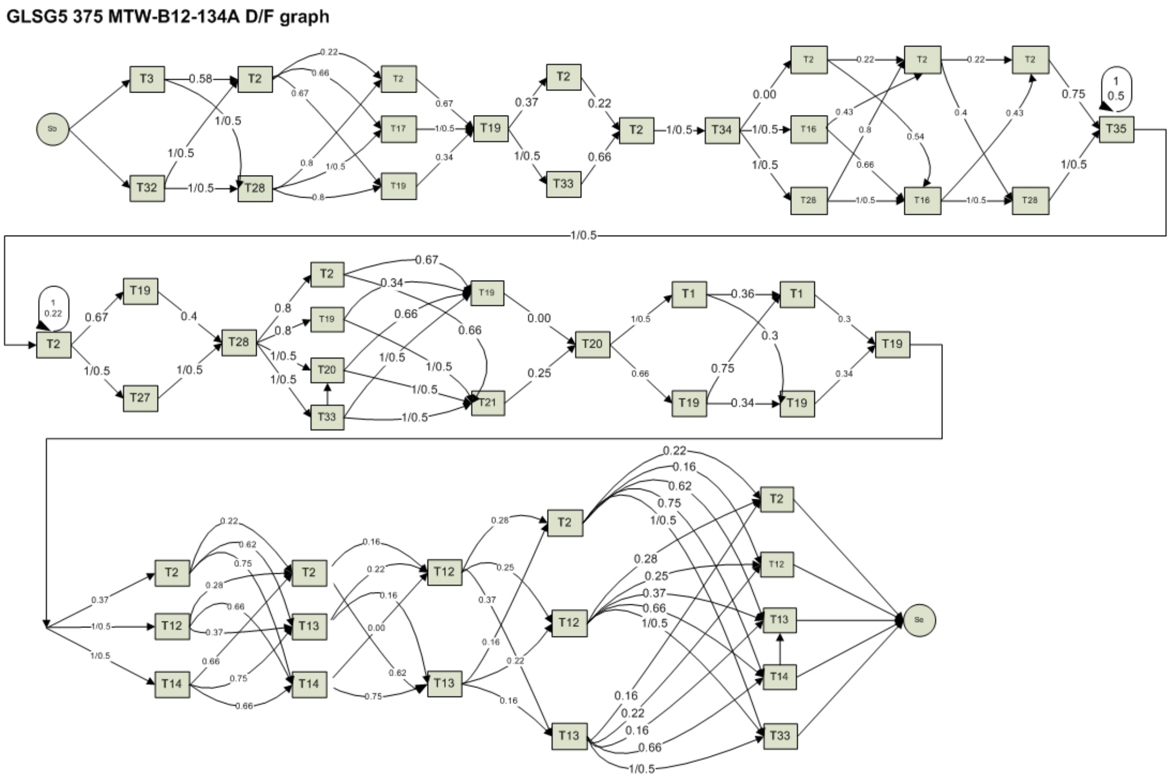


Figure 6.44 GLSG5 375 MTW-B12-134A D/F graph with new D/F values

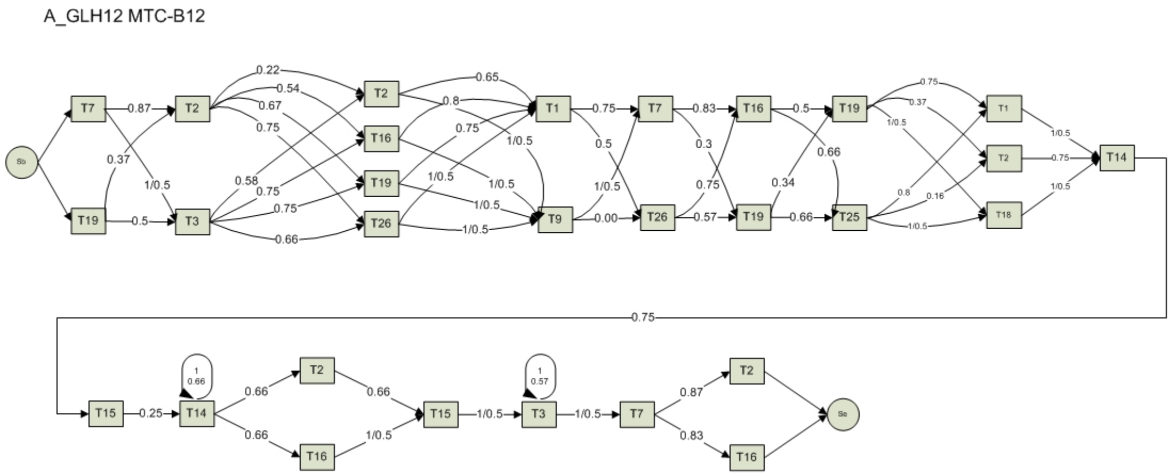


Figure 6.45 GLH12 MTC-B12 with new D/F values

The major result from expanding the amount of cases and instances in the application of the process mining was improvement in both dependency and frequency values for many of the paired relationships. These are highlighted in Table 6.6.

Table 6.6 D/F values comparison

Pair of Tasks	D/F values 5 cases	D/F values 13 cases
T3>T2	0.66	0.57
T5>T6	0.50	0.50
T7>T2	0.66	0.87
T4>T2	0.87	0.7
T6>T2	0.22	0.35
T16>T1	0.66	0.8
T16>T2	0.41	0.43
T19>T1	0.80	0.85

To reiterate, the D/F values show the degree of the relationship between task A and task B. A higher value means that task A is plausible to be a cause of task B. For example in this case T2>T5 D/F value equal 0.88 therefore, after the engineers undertake T2, which is to ‘modify cut out temperature’ they will make modification T5 which is to ‘modify cooling coils’. The assumption can be made that, if any pair of that D/F value of TA>TB is low, TB was less relevant to the process and engineers might not have to do this task. This technique can help engineers to eliminate a number of tasks.

The next step in this analysis was to use the dependency and frequency analysis data and apply that to deriving a reduction in workflow process. This process started with redrawing workflow nets. However, only workflow D/F values higher that 0.6 were considered. As explained above, 0.6 was the approximation of the mean of all of the D/F values and this was chosen as a cut off point for effective relationships.

The efficacy of this value was tested with the engineers who agreed that the value was a sensible approximation for cut off. They noted this value reflects their reality.

A detailed evaluation of this value determination is given in the Evaluation Chapter (Ch 7).

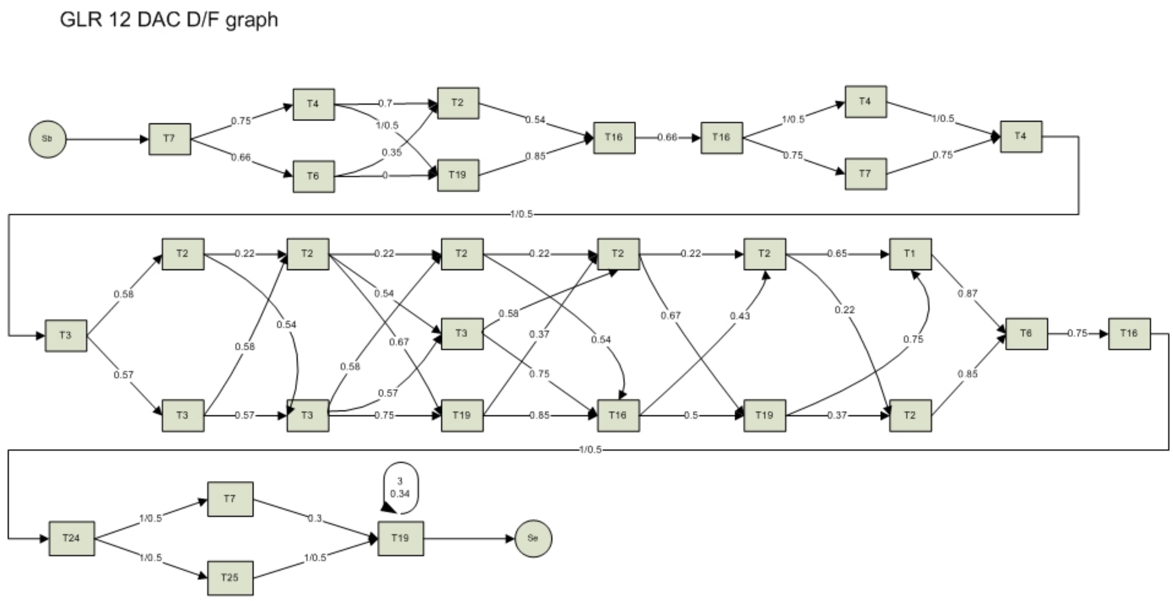


Figure 6.46 Workflow of the case GLR 12 DAC before induction process

6.5.4 Workflow induction process

Case GLR 12 DAC is used to demonstrate the workflow reduction process. Figure 6.33 shows cabinet GLR 12 DAC D/F graph. The steps used in the analysis for one cabinet are described in detail in the following box.

1. The testing process started with modification T7 then an *AND-split* into T4 with D/F value 0.75 and into T6 with a D/F value of 0.66. Therefore, it was proposed that the reduced workflow will start with T7 then connect to T4 and then T6. This is because the D/F values of both pair are higher than 0.6. This first step is shown in Figure 6.47 at the red circle with number 1 on top.
2. The next set of tasks were:
   - T4 an *AND-split* to T2 with a D/F value of 0.7,
   - T4 to T19 with D/F value of 0.5,
   - T6 an *AND-split* to T2 with a D/F value of 0.35 and
   - T6 to T19 with D/F value of 0.0.

   This suggested in the proposed modelling that only the T4 connection to T2 was include in the reduced workflow model because it's D/F value is higher than 0.6. This second step is shown in Figure 6.47 with red circle with number 2 on top.

3. Next in the process was an, *AND-joint:*
    - T2 to T16 which has a D/F value of 0.54.
    - T19 to T16 which has a D/F value 0.85.

   Therefore, only T19 to T16 was included in the reduced workflow because the D/F value is higher than 0.6. This third stage is shown in Figure 6.47 at the red circle with number 3 on top.
4. Next in the process T16 to T16 has a 0.66 D/F value. However, it was considered as a short loop and not included in inducted workflow because it is the repetition of the same task did not contribute to the D/F value based on the algorithm.
5. Next set of tasks were:
    - T16 *AND-split* to T4 with D/F values 0.5
    - T16 *AND-split* to T7 with D/F values 0.75

   Only T16 remained connected to T17 as included in the reduced workflow because it has D/F value higher than 0.6. This step is shown in Figure 6.47 at the red circle with number 5 on top.
6. Following this point an *AND-joint*:
    - T4 to T4 has a D/F value of 0.5
    - T7 to T4 has D/F value of 0.75.

   T4 to T4 is not included in the inducted workflow as it is a repetition of the same task and did not contribute to the D/F value based on the algorithm. Only T7 to T4 is included in inducted workflow because it has D/F value higher than 0.6. This step is shown in Figure 6.47 at the red circle with number 6 on top. As T7 to T4 is already exist in the inducted workflow therefore the researcher use R1 to show that this T7 to T4 was repeated one time.
7. Next set of tasks was T4 to T3 with D/F value 0.5. There for it is not included in inducted workflow. The next set of tasks is *AND-split:*
    - T3 to T2 with D/F value 0.58
    - T3 to T3 with D/F value 0.57
    - Then *AND-split* from T2 to T2 D/F value 0.22
    - T2 to T3 D/F value0.54
    - T3 to T2 D/F value 0.58

- T3 to T3 D/F value 0.57

All of the D/F value in this step is lower than 0.6 therefore were excluded in the reduced workflow model.

8. The next set of modification tasks were:
   - *AND-split* from two to three tasks. T2 to T2 with D/F value 0.22
   - T2 to T3 with D/F value 0.54
   - T2 to T19 with D/F value 0.67
   - T3 to T2 with D/F value 0.58
   - T3 to T3 with D/F value 0.57
   - T3 to T19 with D/F value 0.75

   Therefore only T2 to T19 and T3 to T19 were included in the reduced workflow because the D/F value is higher than 0.6. This step is shown in Figure 6.47 at the red circle with number 8 on top.
9. The next set of tasks were:
   - *AND-split* from three tasks to two tasks T2 to T2 with D/F value 0.22
   - T2 to T16 with D/F value 0.54
   - T3 to T2 with D/F value 0.58
   - T3 to T16 with D/F value 0.75
   - T19 to T2 with D/F value 0.37
   - T19 to T16 with D/F value 0.85

   Therefore, only T3 to T16 and T19 to T16 were included in inducted workflow Figure 6.47 because the D/F value is higher than 0.6. This step is shown in Figure 6.47 at the red circle with number 9 on top.
10. Next set of tasks were:
    - T2 to T2 with D/F value 0.22
    - T2 to T19 with D/F value 0.67
    - T16 to T2 with D/F value 0.43
    - T16 to T19 with D/F value 0.5

    Therefore, only T2 to T19 was included in inducted workflow Figure 6.47 because the D/F value is higher than 0.6. This step is shown in Figure 6.47 at the red circle with number 8 on top. However, this is the repetition therefore, the researcher used R1 to indicated.

11. In the next set tasks were:
    - T2 to T2 with D/F value 0.22
    - T19 to T1 with D/F value 0.75
    - T19 to T2 with D/F value 0.37
    - T1 to T6 with D/F value 0.87
    - T2 to T6 with D/F value 0.85

    Therefore, only T19 to T1, T1 to T6 and T2 to T6 were included in inducted workflow Figure 6.47 because the D/F value is higher than 0.6. This step is shown in Figure 6.47 at the red circle with number 11 on top.
12. The next set of tasks were:
    - T6 to T16 with D/F value 0.75
    - T16 to T24 with D/F value 0.5
    - *AND-split* from T24 to T7 with D/F value 0.5
    - T24 to T25 with D/F value 0.5

    Therefore, only T6 to T16 was included in inducted workflow Figure 6.47 because the D/F value is higher than 0.6. This step is shown in Figure 6.47 at the red circle with number 12 on top.
13. In the last set tasks were:
    - *AND-joint* T7 to T19 with D/F value 0.3
    - T25 to T19 with D/F value 0.5
    - Then the GLR 12 DAC testing process finished.

    Therefore, there is no process to add to inducted workflow.

The new reduced workflow model for case GLR 12 DAC, based on the assumptions above, is shown in Figure 6.36. It is significantly less complex and lengthy than the original in Fig 6.33 above.

GLR 12 DAC induct workflow

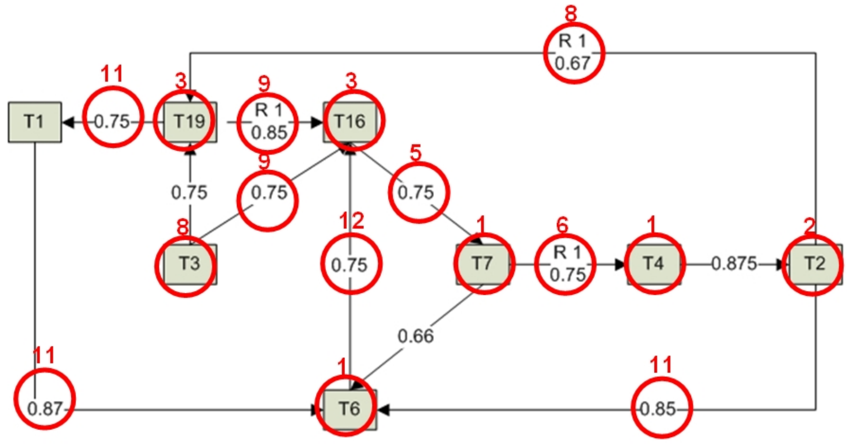


Figure 6.47 The inducted workflow model for case GLR 12 DAC

The reduced workflow diagram (Fig 6.47) shows that the pairing of T7 to T4 and T2 to T19 in the case GLR 12 DAC have been repeated once. The researcher then applied the same detailed logic to another example in the workflow net process, in this instance to case GLR 12 MTC.

This time workflow of the cabinet GLR 12 MTC (as shown in Figure 6.34) was added into the reduced workflow Figure 6.47. The process is complicated. As an example, the steps used in the analysis for one cabinet are described in detail in the following box.

1. After the cabinet GLR 12 MTC was installed and operated for the first time, the engineers made modifications tasks T6 and T26 to the cabinet. This *AND-split* was not included in the inducted workflow (Figure 6.48) because an initial result was an outcome of the cabinet installation and the first operation. It was not consequent of previous modifications.
2. The next sets of instances were *AND-split* processes. These included:
   - T6 to T3 with a D/F value 0.75,
   - T6 to T27 with a D/F value 0.66, and
   - T26 to T3 with a D/F value 0.5 and T26 to T27 with a D/F value 0.66.

   Therefore, only T6 to T3 (D/F value 0.75), T6 to T27 (D/F value 0.66) and T26 to T27 (D/F value 0.66) were included in the inducted workflow Figure 6.47 because the D/F value is higher than 0.6.

   However, there were no T26 and T27 tasks in the first reduced workflow

(Figure 6.48), therefore, T26 and T27 blocks were newly added because there were no T26 and T27 performed in cabinet GLR 12 DAC.

This second step is shown in Figure 6.48 by the red circle with number 2 on top.

3. The next sets of process instances were *AND-splits* from two to three tasks. They begin with:
   - T3 to T2 (D/F value 0.58),
   - T3 to T6 (D/F value 0.25),
   - T3 to T18 (D/F value 0.66),
   - T27 to T2 (D/F value 0.66),
   - T27 to T6 (D/F value 0.25) and
   - T27 to T18 (D/F value 0.66).

   Therefore T3 to T18, T27 to T2 and T27 to T18 were added into the inducted workflow because the D/F value is higher than 0.6. As there was no T18 in the first inducted workflow (Figure 6.47) it was newly added. This third step is shown in Figure 6.48 by a red circle with number 3 on top.
4. The next *AND-joint* reduced the number of tasks from three to one, The tasks reduced were:
   - T2 to T28 (D/F value 0.4),
   - T6 to T28 (D/F value 0.75) and
   - T18 to T28 (D/F value 0.75).

   Therefore, T6 to T28 and T18 to T28 and T28 block were included in the inducted workflow because the D/F value is higher than 0.6. This fourth step is shown in Figure 6.48 by the red circle with number 4 on top.
5. The next sets of tasks T28 to T19, T19 to T28 with D/F values of 0.8 and 0.4 respectively were examined. Only T28 to T19 was included in the inducted workflow because the D/F value is higher than 0.6. This fifth step is shown in Figure 6.48 by the red circle with the number 5 on top. Then the engineers repeated task T28 once with a D/F value 0.75. However, even though it had a high value at 0.75, it was considered as a short loop and not included in inducted workflow because it is the repetition of the same task did not contribute to the D/F value based on the algorithm

6. Next the task set T28 to T25 with a D/F value 0.66 was included in the inducted workflow because the D/F values were above the mean average of the all D/F value in the 13 collected testing process samples. This sixth step is shown in Figure 6.48 by the red circle with number 6 on top.
7. The next task was another short loop of task T25 which was excluded from the inducted workflow. This is because the short loop is the repetition of the same task which did not contribute to the D/F value based on the algorithm. Next, an *AND-split* from a single task T25 to two tasks T1, with a D/F value 0.8, and T16, with a D/F value 0.5, was analysed. Therefore, only T25 to T1 was included in the inducted workflow because the D/F value is higher than 0.6. This seventh step is shown in Figure 6.48 by a red circle with the number 7 on top.
8. In the next stage of the analysis an *AND-split* from two to three tasks was examined. These were:
    - T1 to T2 (D/F value 0.36),
    - T1 to T6 (D/F value 0.87),
    - T1 to T29 (D/F value 0.66),
    - T16 to T2 (D/F value 0.43),
    - T16 to T6 (D/F value 0.66) and
    - T6 to T29 (D/F value 0.75).

    Therefore T1 to T6, T1 to T29, T16 to T6 and T16 to T29 were included in the inducted workflow because the D/F value is higher than 0.6.
    This eighth step is shown in Figure 6.47 by the red circle with the number 8 on top.
9. In the next stage, an *AND-joint* set of tasks reducing from three tasks to a single task was examined. These were:
    - T2 to T29 (D/F value 0.85),
    - T6 to T29 (D/F value 0.66) and
    - T29 to T29 (D/F value 0.75).

    However, only T2 to T29 and T6 to T29 were included in the inducted workflow because T29 to T29 is a short loop which is the repetition of the same task which did not contribute to the D/F value
    This ninth step is shown in Figure 6.47 by the red circle with number 9 on

top.

10 The next sets of instances were T29 to T2 (D/F value 0.37), an *AND-split* T2 to T2 (D/F value 0.22), T2 to T6 (D/F value 0.85). Therefore, only T2 to T6 was included in the inducted workflow because the D/F value is higher than 0.6.

This tenth step is shown in Figure 6.47 by the red circle with the number 10 on top.

11 The final set of instances were *an AND-joint* T2 to T2 (D/F value 0.22), T6 to T2 (D/F value 0.35) and T2 to T3 (D/F value 0.54). Therefore, they were not included in the inducted workflow because the D/F value is higher than 0.6.

Then the analysis of the workflow of cabinet GLR 12 MTC testing process was finished. The outcomes from step 1 to step 11 were the inducted workflow models for both GLR 12 DAC and GLR 12 MTC, as shown in Figure 6.48.

The researcher then used the D/F values for links in each example and built a complex model which reflected all links between tasks of values greater than 0.6. How this was done can be explained in this way: in GLR 12 MTC there is a relationship between T6 to T3 at 0.75; in the inducted form of GLR 12 DAC there is no relationship between T6 and T3. Therefore the researcher added this link to a cumulative model from T6 to T3 and then repeated this process through all links in the model for GLR 12 MTC resulting in the more complex model shown in Fig 6.48.

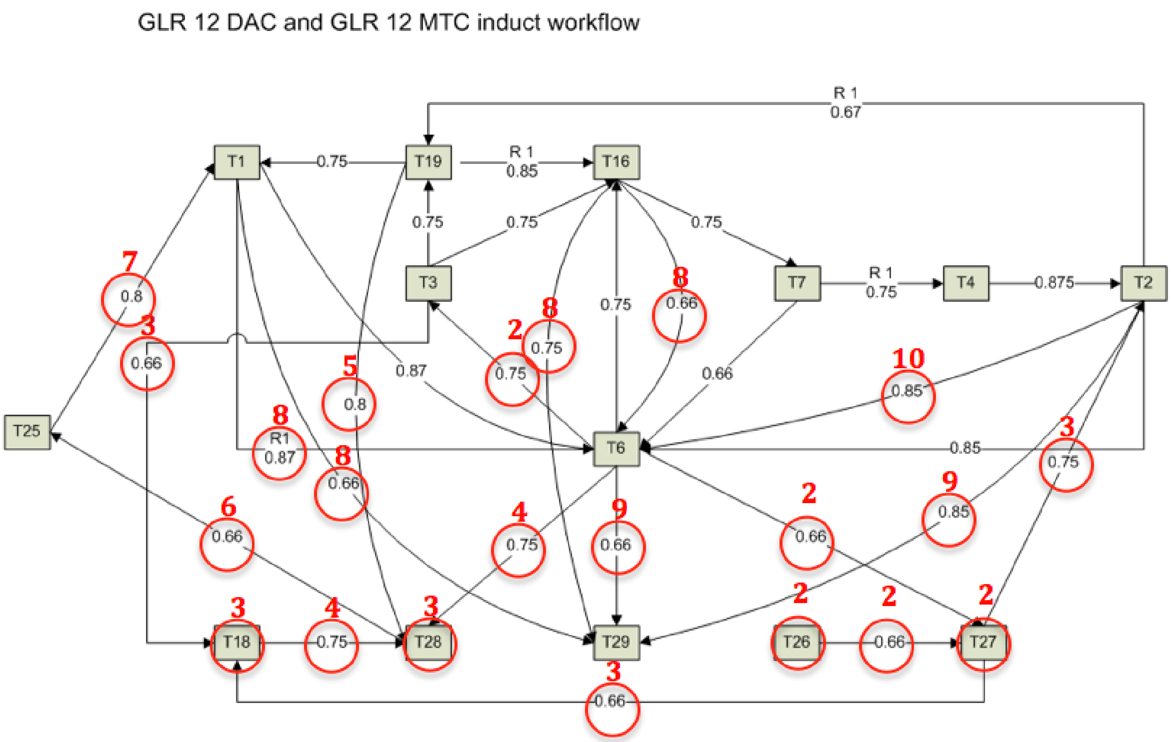


Figure 6.48 Inducted workflow models of both GLR 12 DAC and GLR 12 MTC.

The reduced workflow contained only pair of tasks with D/F value higher than 0.6. Next step was to repeat this workflow reduction process with the other 12 workflows nets by expanding the result from the first two cases of reduction workflow modelling. This resulted in the collective model shown in Fig 6.48 which depicts all of pairs of tasks with high D/F values.

all cases

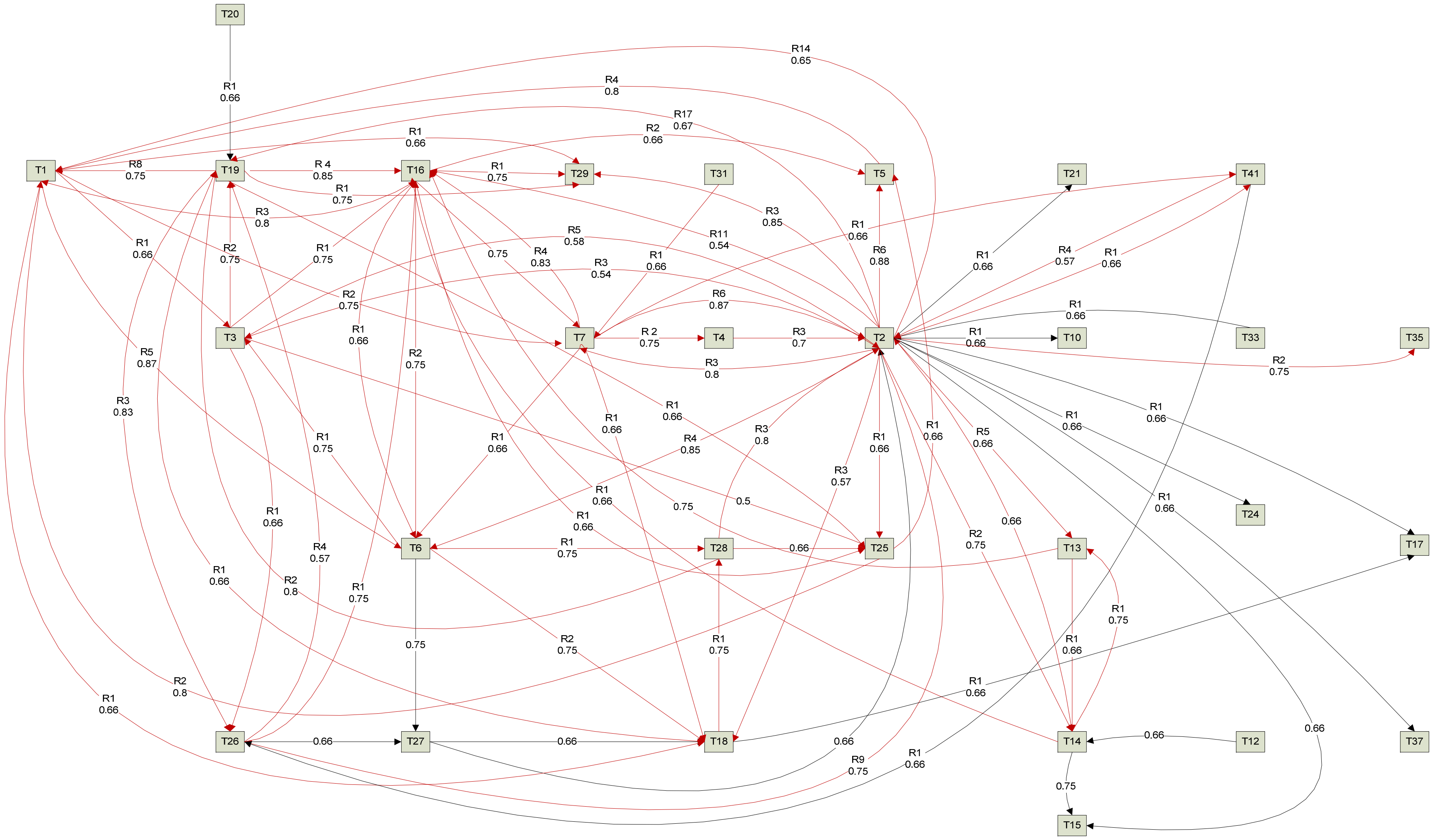


Figure 6.49 Inducted workflow of 13 cases

The consideration value set was set as 0.60. It can be seen that there are numbers of nodes that have a high density of task connections, for example: T1, T19, T16, T29, T5, T41, T3, T7, T4, T2, T6, T28, T25, T13, T26, T18 and T14. These high-density nodes show specific relationships to some other tasks in the modification process and the patterns are significant. Therefore, the researcher rearranged these tasks in a matrix form as shown in Table 6.7.

Table 6.7 High Density Task Matrix.

	T1	T2	T3	T4	T5	T6	T7	T13	T14	T16	T18	T19	T25	T26	T28	T29	T31	T35	T41
T1			R1 0.66			R5 0.87	R2 0.75				R1 0.66					R1 0.66			
T2	R14 0.65		R3 0.54		R6 0.88	R4 0.85	R3 0.8	R5 0.66	R2 0.75	R11 0.54	R3 0.57	R17 0.67	R1 0.66	R9 0.75		R3 0.85		R2 0.75	R1 0.66
T3		R5 0.58								R1 0.75		R2 0.75	0.5	R1 0.66					
T4		R3 0.7																	
T5	R4 0.8																		
T6			R1 0.75							R2 0.75	R2 0.75				R1 0.75				
T7		R6 0.87		R2 0.75		R1 0.66				R4 0.83	R1 0.66								R1 0.66
T13									R1 0.66	0.75									
T14		0.66						R1 0.75		R1 0.66									
T16	R3 0.8				R2 0.66	R1 0.66	0.75						R1 0.66			R1 0.75			
T18												R1 0.66			R1 0.75				
T19	R8 0.75									R4 0.85			R1 0.66	R3 0.83		R1 0.75			
T25	R2 0.8				R1 0.66														
T26										R1 0.75		R4 0.57							
T28		R3 0.8										R2 0.8	0.66						
T29																			
T31							R1 0.66												
T35																			
T41		R4 0.5																	

The matrix shows the numbers of instance of tasks A in row from T1, T2, T3, T4, T5, T6, T7, T13, T14, T15, T18, T19, T25, T26, T28, T28, T31, T35 and T41 relative to the next instance. The matrix columns show the number of instance of task B relative to Task A. In the matrix the red colour squares contain a pair of tasks with high D/F value and Cream Square contains moderate D/F value. At this stage the researcher noted that the key nodes marked in red above all had values higher than 0.7 and so the researcher changed the level of consideration of significant D/F values from 0.6 to 0.7. This is because after iterative discussion with some of the engineers, they commented that the method and the D/F values were sensible.

6.6 Discussion

The analysis of the design and build process for the 13 exemplar products made and sold by the Company across all of its range showed that there were, in total, 41 modification tasks that were performed by the design engineers. Some of the Company workflow instances were procedural. These tasks were static and required to meet the Standards referred to earlier in the thesis. Most of them have sequences that they have to follow. However, the ordering of the instances is dynamic. These tasks could be executed at any time in the process without sequential restriction. Practically the engineers performed modification task A and then they had 41 modification choices to select from for task B, including repeating task A again. If we considered only one single modification task per procedure the possibility to choose task B and further would be 41! This is equal to 3.34^{49} process instances. This means there were far too many tasks to choose from in the process to modify the design of a new or re-engineered refrigerated cabinet. This did not include multiple modification tasks that often occurred in one day and happened many times during the whole process. The engineers noted that in their practice the maximum number of the multiple modifications per day was five tasks. The number of the process instances was even bigger. However, the engineers argued that they knew by experience that if they did task A, they knew what task B will be. However, they could not describe that. Further evidence lies in the mapped workflow nets illustrated in this chapter. There were a large number of different processes task A and task B that may, or may not, follow each other. This resulted in the testing logs showing that what they had been doing was unsystematic. One of the outcomes of the development of the knowledge-based system described in Chapters 4 and 5, was that there would be a systematic process to follow with its adoption, increasing the value of its implementation.

The possible solutions to these issues can be found in the models developed in this chapter, based on the heuristic mining algorithm used. This process defined the dependency relationships between Task A and B in any sequence. The assumption made was that if the value was high, then Task A would cause Task B to be adopted. The higher D/F value meant the more significant the dependency of the modification relationship. On the other hand, if the D/F value between tasks A and B was low, it was plausible that A has got little to do with B. This meant that if the new testing process, based on the modelling undertaken, contained only relatively high D/F values, the engineers did not have to waste their time performing tasks that were not related, or did not contribute any effect to the end product of designing and testing the various cabinets. The new cabinet testing process contained the highest D/F value throughout the process. This can be assumed as the best possible candidate process which reflected the shortest possible design and testing time.

An example of the new possible design/testing process showed that the engineers often started the testing process with task 2: ‘modify cut out temperature’. Data from the collective model derived from the analysis (Fig 6.47, Table 6.7) showed that if the engineers started the cabinet design/testing process with T2, the next best task B is T5 because it has the highest D/F value. Then T5 is now task A, and therefore the best next task B is T1 with the highest D/F value together with T5. T1 is now task A and the next task B is T6 with a D/F value 0.87 and this is repeated five times. T6 is now task A and the next task B is either T16 or T18 because they have the same value. For example, if task T16 is selected as the next task in this process, T16 is now task A. Therefore T1 becomes the following modification task. T1 has been done already at the third step of the new testing process. Therefore, the new testing process is now complete. Selecting T18 as task B on the sixth step of the process, T18 now becomes task A and task B becomes T28; T28 is now task A and the next task B becomes T2. Up to this stage the task T2 is now repeated as it has been done in the first step of the process. Therefore, the new testing process is ended. These two best possible solutions derived are shown in Figure 6.50 below.

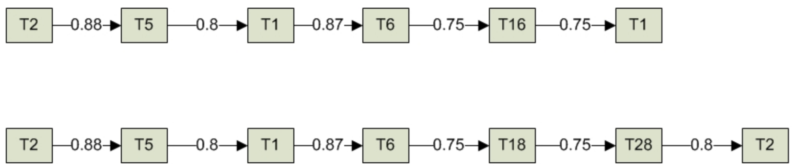


Figure 6.50 Examples of best possible solutions.

Using this same logic, there are other possible solutions that can be extracted from the D/F matrix, depending on the model being developed and the product purpose of the model. For instance changing the starting step in the process to other task will give different results from the first 2 examples (Fig 6.51). Such variation is necessary as the start point will vary by model but the dependency relationship should not change so the start point will then determine the following sequence of tasks.

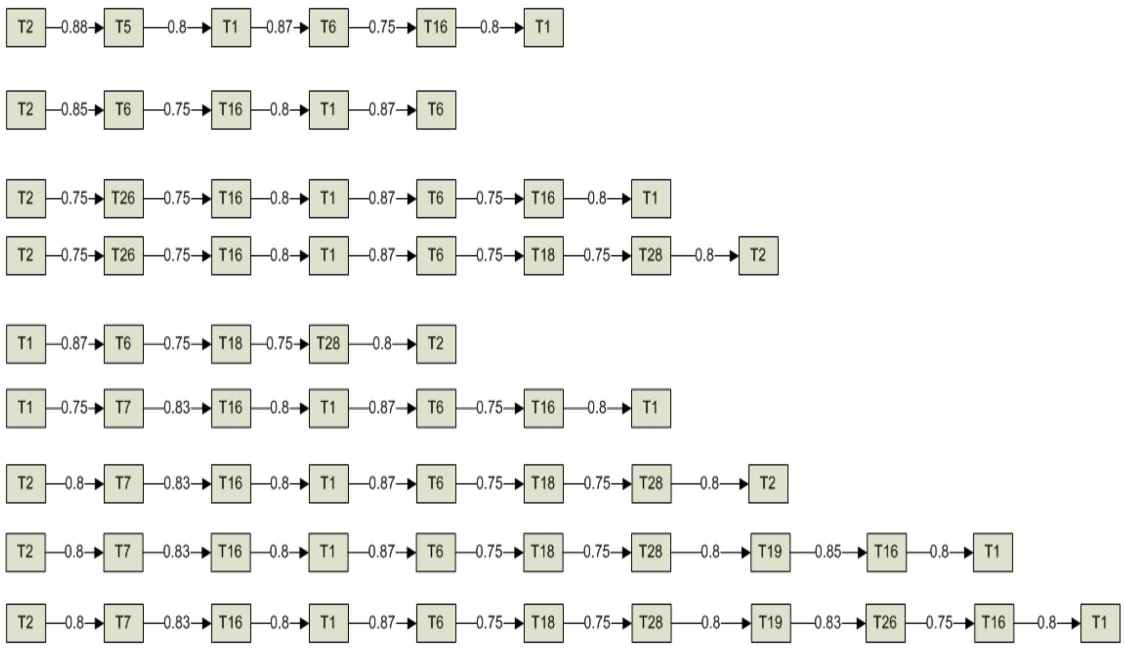


Figure 6.51 Examples of other possible solutions for new design/testing process.

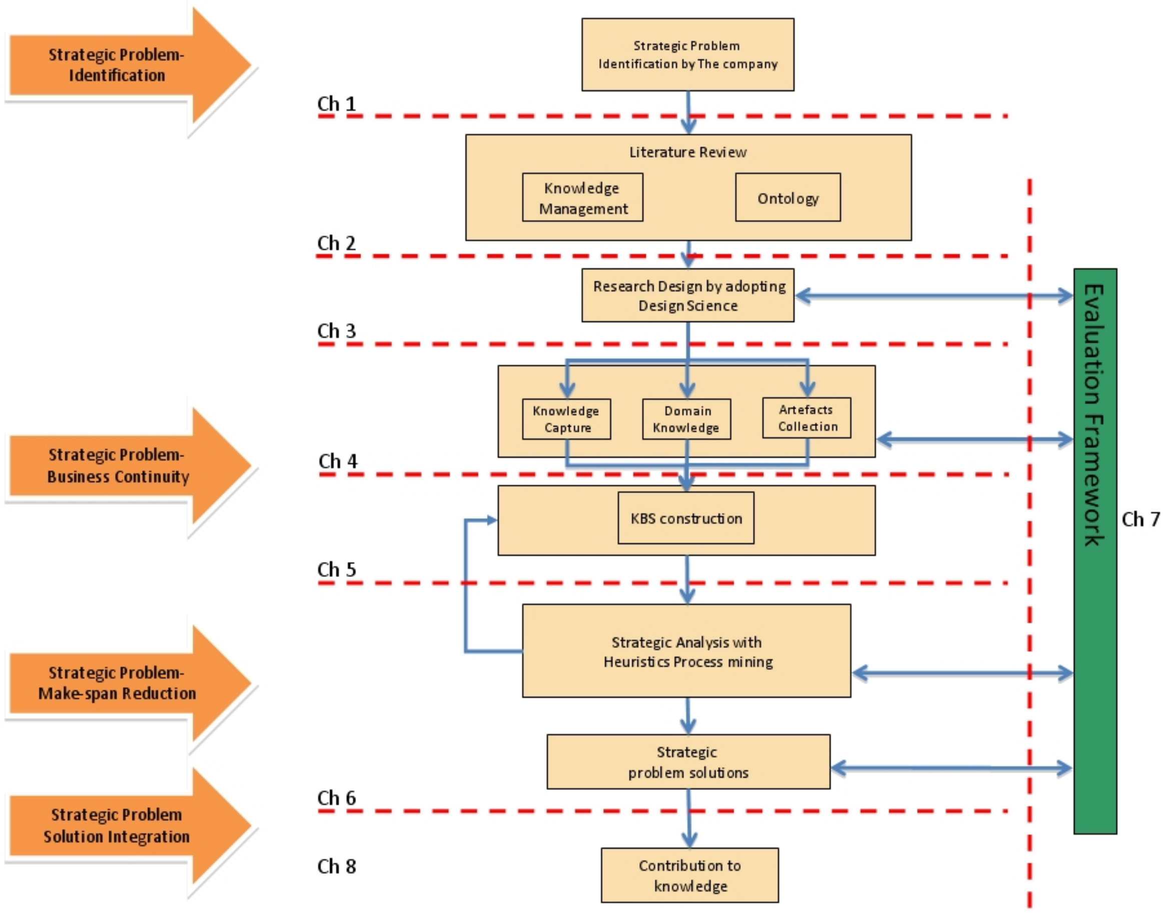
This analysis of the Company workflow nets based on application of a heuristic mining process showed the potential solutions available to resolve the Company make-span problem by eliminating irrelevant tasks that the engineers perform. The analysis eliminated 22 out of 41 tasks that had little dependency relationships in the design/testing process. The analysis also showed that the numbers of relevant tasks that could be selected were therefore limited. For example, in the D/F matrix it showed that if the engineers performed T1 they would have only two tasks, which are T6 and T7, to choose from. Another example, T2 had seven relevant tasks B, which were T5, T6, T7, T14, T26, T29 and T35. This helped the engineers to make decisions more easily in their product development meetings. Instead of having the choice of another 41 tasks to perform, the D/F matrix developed here limited the number of tasks for them. The relevance and applicability of this analysis is reported as part of the evaluation in Chapter 7.

6.7 Conclusion

Chapter 5 showed that the knowledge-based system can store knowledge, not only for knowledge sharing, capture and re-use, but, as this chapter has shown, it can also be used to extract specific knowledge for analytical purposes. In this chapter, the researcher has extracted the information and knowledge stored in the testing process log artefacts in the knowledge-based system and mapped them into process workflows. The mapped workflow were further analysed through the application of Heuristic Process Mining as a method to produce production processes that better optimize the testing, building and design processes of the engineers and enable shortened make-spans for each product. HPM is the process of finding the relationships of tasks in the workflow based on ordering. HPM allowed the researcher to identify dependency and frequency values between tasks in the workflows and then eliminate tasks with insignificant dependency and frequency. The application of the results means the engineers would only perform cabinet testing processes that contained relevant tasks. However the real results of the outcomes of the HPM analysis lay in its utility and applicability in the Company.

The analysis shows that the Company's make-span process can be reduced through an analysis of the tasks involved, identifying those tasks which are redundant or less significant to the actual process. The essential data for this analysis required the knowledge deposited and organised in the Company knowledge management system. The analysis identified a knowledge gap which needed to be addressed to resolve the strategy gap. The evaluation required to make this analysis is reported in the next chapter.

Chapter 7 Evaluation – Effectiveness and Efficacy



7.1 Introduction

Throughout the development process of the two artefacts in this research, the researcher undertook a continuous and iterative evaluation process. This was done to ensure that these artefacts, the knowledge management system and the solutions for make-span reduction, met the strategic needs of the Company. Both the usefulness of the knowledge-based system and the efficacy of the results of the heuristic process mining result needed to be checked at regular intervals in the research. However, the group of the engineers involved in this research was relatively small (at times seven and then reducing to three at the end) with the CEO and COO in addition. Therefore, traditional quantitative evaluative methods were not applicable to assess the validity of the thesis results. The population was far too small for any survey. Early in the research, the researcher had developed an evaluation framework (Chapter 3.5), which provided a comprehensive approach to cover all aspects of evaluation and efficacy in this research.

Using Design Science research methodology (Hevner et al. 2004), a knowledge-based system was developed to solve this business continuity problem in this research. The components of the KBS were gathered from

1. Theoretical knowledge;
2. Domain knowledge;
3. Organizational need; and
4. Personal creativity.

The purpose of the evaluation process was to ensure that the KBS worked, was useful and resolved the business continuity problem. Stacie et al. (2010) have proposed a set of artefact evaluation criteria (Stacie, Deepak & John 2010). The criteria include that the artefact is plausible, effective, feasible, predictable and reliable. These criteria and the others frequently used in previous research have been used in the KBS evaluation process using the evaluation framework. The complete evaluation is shown later in this chapter.

During the final stages of the evaluation process, the researcher received news from one of the engineers that the Company was closing down. That engineer informed the researcher that the company had encountered financial problems created in part by the influx of cheap untested products from overseas. This led the Company to go into administration and the company eventually discontinued business on the 28th of January 2011. This discontinuance of the business has directly impacted on the outcomes of this research. Initially the research plan was to apply best possible models to a real parallel cabinet testing process. The purpose was to test the simplified cabinet testing process during an exemplar design/build/test process. The engineers mentioned that they could set up a replica prototype cabinet for this testing purpose. This method of effectiveness evaluation would have provided the most accurate result for evaluation of the outcomes for reducing make-spans. Due to the Company’s unexpected anticipated closure, the researcher proposed another method of evaluating the results of the HPM analysis by adopting the consensus group evaluation technique.

One technique used by researchers in order to find the answer to possible controversial subjects is the consensus method (Fink et al. 1984). The consensus method has been used to resolve problems related to knowledge from domain experts, a process very applicable in this case where the domain experts were a key part of the solution to the strategic issues of the company. The consensus method techniques most widely used are the Delphi technique and nominal group method. Delphi technique is use to develop the opinions of the specific topic involved by using multiple round questionnaires or interviews to gain information from domain experts (Fink et al. 1984; Hsu & Sandford 2007). The Delphi technique has been used to acquire the most reliable opinions of specific issues from domain experts. The views of the experts are essential in the process (Becker & Roberts 2009; Thangaratinam & Redman 2005). The process includes a multiple round of questionnaires and control feedback from experts. The size of the evaluation panel can vary from 4 to 3000. One disadvantage of the Delphi technique is that it has no scientific measurement to back up results and to ensure that correct answers to the problems are actually found (Bader, McDonald & Selby 2011; Fick et al. 2003; Paes & Wee 2008; Wilde, Ford & McMeeken 2007). However, the results obtained from experts can be used as an alternative on issues that have no definite substantiation. The Delphi technique has been applied in medical research where the researchers were trying to find answers to questions that are very new and not well understood.

In the nominal group technique, the researcher has multiple meetings with domain experts. The purpose of the meetings is to gather qualitative information and assess possible solutions to solve the problem involved. Sometimes the meetings are used to actually reach a consensus solution to a problem. The nominal group technique aims to gain qualitative information and facilitate group decision-making from experts who are most associated with the problem (Anderson & Ford 1994; Becker & Roberts 2009; Potter, Gordon & Hamer 2004; Ritchie 1985; Treffers-Daller 2005). The process starts with freely asked questions which push the experts to come up with a list of ideas about the problem. Then a structured discussion, based on the ideas from the experts, is carried out. The discussions are assessed and used to develop consensus on the problem issues. The variety of research which has used this technique includes social services, industry, education, energy conservation, government organizations, pharmaceutical care and the health care industry (Stephenson, Michaelsen & Franklin 1982; Treffers-Daller 2005; Tully & Cantrill 2002). However, some researchers have found that this technique has a disadvantage in that it generally gives less frequent and stable consensus than the Delphi technique (Fink et al. 1984).

The other technique often used to gain agreement about conclusions in a certain context in the problem-solving group is to use the group consensus technique (Becker & Roberts 2009; Priem, Harrison & Muir 1995; Torra et al. 2005). Group consensus uses the group to seek decisions to implement new strategy (Dong et al. 2010; Dooley, Fryxell & J 2000; Tan, BCY, Teo & Wei 1995). The consensus group technique gains information from experts, stakeholders and practitioners in the field when they get together either geographically in conferences or virtually via email or videoconferences (Lamontagne et al. 2010; Martz & Shepherd 2004). The information that the experts share includes current practice and their knowledge. List (2001) suggested that consensus group technique is the combination of focus groups, public meetings, search conferences, nominal group method, Delphi method, repository grids and meeting facilitation techniques (List 2001, p. 278). Group consensus is used to seek opinions and the method fits well with action research (List 2001, p. 279). This research has adopted group consensus method for the evaluation.

Figure 7.1 illustrates the evaluation process used. It shows that the process of design, build and evaluation was an iterative one which resulted in constant change until a consensus was reached.

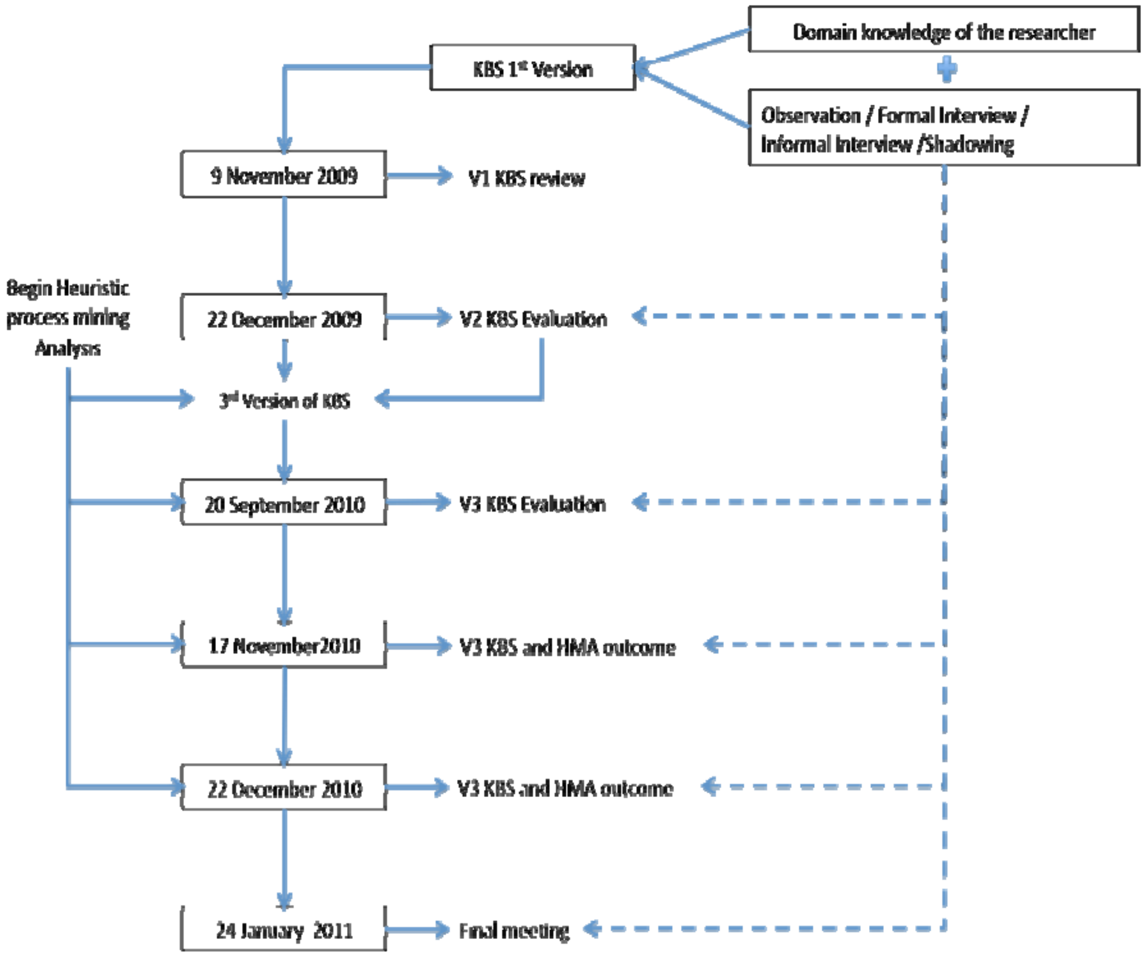


Figure 7.1 Process of Evaluation

The following discussion highlights the major outcomes of the discussions that developed in these formal meetings throughout the research. Each shows the nature of the feedback and the actions taken in the continued development of both artefacts. The summaries highlight both disagreement and also consensus. The details highlighted here were also supplemented by information collected in the shadowing, observation and interview processes described in Chapters 3 and 4. Collectively they provide substantiation that the outcomes of the research, the KBS and the modelled HPM solutions, are both effective and valid, and have successfully offered a solution set to the two strategic issues that were the initial motivation for this research.

7.2 Evaluation of the Knowledge Based System

The following notes of meetings are used here to illustrate the evaluation process that the researcher used throughout the research. The Design Science approach, incorporating action research, used in this research needed iterative build - evaluation – change - actions to ensure the original KBS met its objectives. Following the descriptions of the meetings the outcomes are applied to the evaluation framework.

12 November 2009 (3 months into the research)

In this first meeting the engineers confirmed the nature of the design and build process. This was important as the researcher had by this stage developed the first version of the KBS. Engineer S1 mentioned that the product development process can be started in two ways. First the company initiated the products specifications and then presented them to the client. Secondly, the clients requested the product's specifications 'then we build it for them'. The gathering of the requirements from the engineers varied from looking at the previous products' specifications to looking at the competitors' products in the market. The engineers then initiated a design and built their prototype, either from something similar to their competitors, or from something totally different. However, no matter how different the new product was going to be, the engineers always referred to the previous model that they had manufactured in the company. The engineers then built the prototype. They then iteratively altered the prototype until it passed the required tests to meet the National Standard. Furthermore the engineers noted that the specific details required, such as the cabinet's cooling capacity, airflow, fan set up or cooling coil size, were based on calculations made by Engineers S2 and S3, both of whom had domain knowledge experience. Engineers S1, S4 and S5, with 2 others, then applied the calculations and tested the cabinets on a daily basis making small and sometimes large modifications and then re-tested the models.

The engineers also confirmed that they often reviewed the initial testing results, checking that the prototype cabinet was running correctly with reference to the required specifications. For example, the cooling coil had to be working, having regard to the operating scheme or temperature of the discharge. Return air output had to meet the calculations of Engineers S2 and S3. At this point, after a review of the initial results, the engineers noted that they knew what needed to be done, based purely on their experience. The cabinets that the engineers developed were often similar to the products that they had previously manufactured. The engineers also confirmed that testing targets were always set before the testing process starts. The shortest testing process that the engineers used was one week, but this was rare. It was almost always much longer. The cabinet that did not pass this testing process could not be sold.

This first meeting showed consensus on the design, build, test processes being used in the company. It was important for the researcher to understand this process, as it was fundamental to the classification of the knowledge uncovered as part of developing the ontology for the KBS. This process was then tested continuously by the researcher using the shadowing, observation and interview processes that were happening in parallel in this stage of the research. Understanding this showed the researcher which elements of domain knowledge were fundamental to the design, test, build process and enabled the initial evaluation of version 1 of the KBS. At the end of the meeting the first version of the KBS was handed over to the engineers to evaluate in their professional practice in the Company.

21 December 2009

The purpose of this second meeting was to collect feedback following the handover of the first version of the knowledge-based system at the end of the last meeting. The researcher discovered that the engineers had found it difficult to make time to use the system in their normal work. The researcher had already noticed this in observation so decided to change the approach. In the meeting demonstrations using the KBS were used. The demonstration included examples of knowledge re-use scenarios. The researcher developed 19 scenarios to show the engineers how relevant knowledge could be re-used. The scenarios were designed to provide a valid and consistent approach to evaluation as each engineer was responding to the same material. These scenarios were developed around identified issues either observed by the researcher or noted by the engineers. For example, during the shadowing process the researcher had identified specific outcomes in the product development meetings. In those meetings the engineers often gathered information from multiple locations and this wasted considerable time. The researcher used one of the scenarios to test process improvement using the KBS. For example, one scenario related to retrieval of explicit knowledge from the system, The KBS could show information such as ‘how many times changes to suction pressure’ had been modified, on what date, in what type of cabinets and what the results were. The engineers could find solutions to questions such as: How many cabinets have 1500 mm width and what they are? These scenarios reflected the engineer’s actual knowledge gathering.

Three of the scenarios and the outcomes are described below as examples of what emerged from each iteration in the use of evaluation scenarios.

Scenario 1: In this scenario the researcher asked the engineers an initial question: ‘If a customer wants the new cabinet with a specific height at 1500 mm, how do you find previous products which have that height when the cabinet product codes don’t contain the cabinet’s height detail?’ In cabinet testing when the team gathered information for the new prototype development they often looked at information from previous product specifications.

The engineers responded: ‘We have to look at the files in the computer and open each file which contains cabinet overall specification and look for 1500 mm height ... There are hundreds of these so it can take a long time’.

The researcher: ‘In the KBS if I select the ‘Class_Model’ in ‘class’ field, ‘Case_height’ in the ‘slot’ field, then select ‘is’ in the next field and type ‘1500’ in the ‘integer’ field and click the ‘Find’ button, the KBS then shows the query results. In this case in the 15 testing reports that I have collected and entered into the KBS, there are two cabinets which have 1500 mm height. The results are ‘GLR 12 DAC’ and ‘GLR 12 PRC’.’

The engineers responded: “That’s very good … Its exactly what we need … This will make the work involved quicker and enable us to do the things we need to do at a faster rate.”

Scenario 2: In the cabinet testing procedure the engineers set testing goals by determining the performance class required. This could be 3M1, 3M2, 3L1 and/or 4L2. This cabinet class details are listed in the National Standard. The researcher asked the engineers: If you set the target of the new prototype cabinet to be 3M1 and use a specific refrigerant such as R134a, how can you now find such information?

The engineers responded: ‘Again, we have to look at the files and find the information we want …This is difficult as there is no ordering of the files on anything except dates. So we have to look back through them all ...We don’t use any system where we can search for something like this.’

The researcher then used the KBS saying: “You can find such an answer to the question by doing the following: firstly you select ‘Case_Model’, then select ‘Rated’ in ‘Slot’ field, then select ‘contain’ in the next field and select ‘3M1’ in last field. However, this time we make a query from more than one specific detail. Therefore, we need to add the second query detail by clicking at the “More” button at the bottom left hand side of the query area. Then we select ‘Case_Model’, then select ‘Use_Refrigerant’; in the ‘slot’, select ‘contain’ and select R134an in the last field. Then click the ‘Find’ button. The KBS now shows the result from the query which is ‘GLS G 375 DAW’.”

The engineers: ‘Again this is very good. You have saved us hours of frustration trying to find this out. Often we don’t even look we start from scratch and use trial and error to find the result again and again. Can we make a query for other information?’

The researcher: ‘Yes indeed. The system can find information on any aspect of your work.’ The researcher showed the engineers more scenarios.

The Engineers responded: ‘now I can see how we can use it much better.’

Scenario 7: Tacit knowledge captured from the engineers during data collection showed that the engineers often made modifications to parts of the cabinet and they noted these changes in the paper testing log sheets.

The researcher asked: ‘How can you find how many times that you have modified the ‘rear duct’ and what were the results?’

One of the engineers replied: ‘As you know we cannot re-use that information on the testing log sheets because it is irretrievable and we hardly look at it ...It would be nice if we can re-use this information so we don’t have to reinventing the wheel for every cabinet we build.’

The researcher then explained: ‘You can now find information form the testing log sheet. If we now select ‘Comments_From_Testing_Log_Sheet’ in ‘Class’ field then select ‘Comment_In_Log_Sheet’ in ‘Slot’, then select ‘contain’ and type the word ‘rear duct’ in the last field and click find. The KBS now shows the result from the query.’

The results included the number of times and the date that the engineers had modified the rear duct, plus other modifications also made on the day that the rear duct was modified. The researcher added: ‘From this we can also see how the results different from each modification.’

The engineers: ‘Very good again. There is no doubt that this is what we need ...
We therefore have to use the system and get the benefits it brings.’

The feedback created with the scenarios was shared between the engineers and was specific to their work tasks. The major issues noted were:

- Engineer S1 stated that the KBS user manual was quite straightforward. However, there was one point he did not quite understand regarding how to enter information about the cabinet series that was not in the system. As a result the researcher noted the problem and it was addressed in the next version of the system.
- In the meeting the engineers referred to various other elements in the KBS that met their professional requirements. The class, sub-class and instance creation process was explained and one engineer noted with the consensus of the other engineers, that it was not difficult to use. The Queries feature was demonstrated regarding knowledge re-use. Again this was explained and it was agreed that it met the engineers' needs. However, one weakness was noted. One engineer asked about the print function of the Protégé to print the results of the queries. The researcher noted that unfortunately, 'there is no print feature in Protégé at the moment' (as of June 2011, this is still the case).
- The engineers noted that there were some classes and subclasses in the system structure that were a bit confusing. However, the reason for the confusion was that the term that the engineers used themselves was unclear. For example, with regard to both the temperature class and the climate class, the National Standard defines the nature of temperature and climate as it applied to Australian made refrigerators. The engineers had been using another definition. This was acceptable to the authority involved and is used as well as the National Standard. The KBS structure was subsequently revised as requested by the engineers.
- One of the key issues with the KBS Version 1 was the engineers' perceptions about their use of paper. In the meeting the researcher noted that the system had been built by integrating the electronic log files, which they kept as print-outs on a paperclip in the office, into the KBS. This meant the engineers didn't now need to fill out the table on the paper files anymore. This they agreed suited them better. The engineers noted that the KBS linked each day's comments to each day's results and stored them in the system. They noted they then didn't have to shuffle paper to find information. The researcher noted that 'The log files are now classified as an instance in the testing report class'. One engineer noted that 'it would be

easier if this instance is located in the comment testing log sheets instance'. These requests were addressed and the KBS was revised as a result.

- Other issues raised by the engineers for improvements to Version 1 included:
    - agreement that integrating an electronic and hard copy of the company documents, plans, drawings and brochures together in one place was what they needed;
    - that it could be good to integrate the company's testing log software with the KBS so that it could be utilised to feed measurement data into specific locations of models; and
    - that the cabinet's parts drawings should also be included in the KBS. The revised version (Version 2) added this feature.

Overall the evaluation comments by the engineers were quite positive in this meeting. However, they noted that it was hard at this stage with limited use, to answer how well the system would help them speed up their cabinet design and testing processes. In the final meeting with the engineers in January 2011, it was revealed that the system and the subsequent work on the make-span by the researcher and his constant asking about their domain knowledge and the issues involved, had had a significant impact. The three remaining engineers in the company noted at that final meeting that they had reduced the make-span 'from months to weeks'. They also noted that they had changed their approach from seeking optimal solutions all of the time, to ones that were 'good enough'. They had learnt 'how to re-use their knowledge in better ways'. This is significant as the research activity *per se* has assisted in make-span reduction. They saw the advantages in the knowledge which had been organised according to their work practices and classified accordingly in the KBS system. The research process in developing the artefact has itself shown indirectly and unexpectedly that the needs of the Company strategically were met by the research.

In the period between December 2009 and September 2010, the researcher used a less formal technique for evaluating the applicability of the KBS to the engineers' needs during continued building and evaluation of the KBS. In addition to the development of versions of the KBS and its components, the researcher was testing the efficacy of the processes involved in mining the knowledge stored in the KBS to develop solutions for the make-span problem. The approach taken was to visit the factory on a regular basis checking small elements of the KBS against the needs of the engineers, make alterations where necessary and seeking comment on it from individual engineers. This was important as, during this period, the Company underwent some significant changes.

The CEO was replaced in March 2009 as was the COO, and two of the engineers left the Company. One of the testing engineers was removed from the test labs and put into initial design work only. Work continued in the Company and the engineers' work didn't change, albeit with two less staff. The researcher continued with informal and sometimes serendipitous interviews and with observations of meetings and testing. Ultimately this meant that Version 2 of the KMS was continually modified and altered, which over 12 months of revision to the system and alteration to the ontology, eventuated in Version 3. This latter version was taken to the next formal meeting with the engineers together with details of the solutions being developed for the make-span problem, where detailed analysis of the assumptions made and the outcomes needed, were tested.

20 September 2010 - Evaluation of the KBS

The evaluation of the KBS at this stage was only focused on confirming that all of the tasks included in the ontology and the KBS itself covered all of the tasks that had been done to the cabinets during the testing process. This was confirmed. In this meeting the researcher checked every element in the KBS, class by class with the engineers. Again a set of scenarios was used and at this stage the engineers said that the system was as complete as it could be. Version 3 was given to the engineers to continue to use on a daily basis. Details of all elements tested are shown and discussed later in this chapter when both artefacts are evaluated using the framework described in Chapter 3. However this represented only one part of the research process. There was the need also to evaluate and test the efficacy of the HPM application.

7.3 Testing the assumptions and outcomes of the Knowledge-Based System Heuristic Process Mining

Considering the nature of the problems involved in this research and the iterative nature of the design and evaluation process through the collaborative process used, it is considered appropriate to also use the group consensus technique to evaluate the second artefact – the outcomes of HPM analysis. Throughout this research the researcher had multiple meetings with the domain experts, the engineers at the company. In the meetings the researcher discussed firstly the classification of knowledge, both tacit and explicit, derived in the initial part of the research, to frame the ontology which underpinned the knowledge-based system developed; and then in later meetings discussed the outcomes of the application of heuristic mining to reduce the make-span. The objectives of these meetings with the engineers were to gain agreement on the efficiency and usability of the KBS and agreement about the validity of the HPM results. It must be noted that every meeting was different and was attended by different engineers. The researcher believes that this was advantageous because the impact of 'group think' (Esser 1998) was minimized. The researcher had noted in observation of the daily meetings that this was sometimes a problem and that the meetings were often dominated by one or two engineers. However, over the period of meetings and through serendipitous discussions with the engineers, all of the views of the engineering team were both collected and used in the two solutions created in this research. By the time of presenting the final solution, four of the engineering team had left the company and a core of only three engineers remained. It is their consensus that frames the final part of the evaluation of the HPM.

At the meeting on September 20, 2010 the researcher made a presentation on the heuristic mining process in a way suitable to suit the engineers' understanding. The presentation included only the heuristic mining process as the software investigation related to the process details were not considered necessary for the engineers. All three remaining engineers participated. The others, as noted above, had left the Company. The presentation included a number of questions regarding the analysis of the company processes using a heuristic mining algorithm. These questions were asked in order to test the efficacy of both the measurements made and the assumptions used in the analysis. The responses to these questions, like proceedings of all previous formal meetings and all interviews were recorded and transcribed. The questions asked by the researcher related the various processes described previously in Chapter 6. The questions were:

1. Do the values from D/F table reflect reality in the testing procedure?
2. Are the relationship percentages valid?
3. Are pairs of tasks with D/F value <0.60, that have been ignored in the analysis, still important?
4. Are there any tasks that have to be done together with other tasks?
5. Do the new workflow models reflect the reality of the development process? If yes, which process? If not, why?
6. Could you build model GLR 12 DAC again with the process shown on slide 47? (The information shown in slide 47 is shown in Figure 6.51 in Chapter 6.) The researcher used a presentation of the analysis used in the HPM applied to the Company's knowledge stored in the KBS. This question was asked in relation to applying new possible solutions derived from the D/F matrix to re-develop cabinet GLR 12 DAC again.
7. Do the task types listed in the tasks list cover all of the tasks that you perform?

These questions were targeted at the assumptions made during the analysis of the workflow nets. The properties of these questions are important to understand the relationships shown in the workflow nets. The researcher was concerned to use the expert knowledge of the engineers to validate the efficacy of the paired relationships as they emerged in the analysis. In essence this reflected the intent of the group consensus technique referred to above.

1 Do the values from D/F table reflect reality in the testing procedure?

In the following analysis the researcher has generally reported the consensus view of the engineers rather than give individual quotes from the recordings. In some cases specific quotes are used where the analysis warrants.

Collective answer: Yes, in some pairs of tasks. However, there are some pairs of tasks where the measured value derived from the analysis was indicative of a strength of relationship unfamiliar to the engineers. Therefore, further review by the engineers in their day to day work needed to be carried out. Their uncertainty related to their need to consider these indeterminate values whilst they were engaged in the design, build, and test processes. The researcher re-evaluated these relationships in the weeks after the meeting and then rechecked the outcomes again with the engineers.

2 Are the relationship percentages valid?

Collective answer: There was neither confirmation nor rejection of the values. Rather there was uncertainty. They considered the paired values needed to be reviewed by the engineers in their normal work routines. This process of review was undertaken continuously over a period of three months through interaction between the researcher and the engineers. At the final meeting in January 2011, there was consensus that the relationship percentages were a real approximation and could vary by only small amounts. However, the engineers noted that the relationship measures were very useful to them. The engineers ultimately confirmed their validity.

3 Are pairs of tasks with a D/F value <0.60, that have been ignored, still important?

Collective answer: Mostly yes. However, one issue was raised and discussed in some depth. One of the engineers S3 began:

> 'If we were modifying the fan speed the affect on suction temperature such as if the fan speed goes up suction temperature will do what?' He continued: "There are things that you expect to happen … If we do this, that will go the other way … We would not be able to quantify the change but we know that general direction of the change … 'This is where experience comes in … For example blind up and blind down will affect the coil temperature'

These statements related to a number of the paired relationships where the value was <0.6. However, the engineers were reacting to something they hadn't seen before and indicated that they needed to check. This issue then needed to be re-evaluated by the engineers before it could be accepted that all paired values of <0.6 could be ignored in the analysis and in the subsequent shortened workflows.

The discussion became more detailed with Engineer S4 stating:

> 'The question is, is the value 0.6 a real fit? I really don't know … We know through experience that the biggest change comes through the setting change.'
>
> Engineer S2 added: 'It's a tough one … When we are testing the cabinets we get the result the first time around … It is easy to get to 95% result and the next 5 % is difficult… we know that it is a bit of this, a bit of that and a bit of something else.'

He added:

> 'We have no experience on the lower numbers on some sets of tasks'.
>
> 'Why don't we take a couple of steps further and have a look at what we've done with this task, and what is the effect on design outcomes'.

Engineer S3 then added:

> 'How can it become a fair test, if you put the case in it now, the case that you have now has been developed to the certain stage. That should be a lot easier to get to work, unless you can do something completely different?'

The answers to the question asked by the researcher raised considerable variation in answers and a lack of initial agreement amongst the group. The level of uncertainty about relationships was also evident in their own work processes.

Engineer S3 continued:

> 'I think we always get to the end goal. If something like the requirements change, like MEP changes, then we are further away. If we are making the case for high efficiency, which is probably what we are doing, it's not like a prerequisite. Normally we are getting into that range but if they change that we are sort of further away from what we started it up with … but in some certain case types we are getting better and better. For example, in the case of the 3A coil, we know that cases that we didn't know right at the start

works better, but we don't know that it works 10% better than another. Perhaps that means we have to use your figures to check what we know.'

Engineer S4 added:

> 'Can you have a different weighting for an action, for example changing suction temperature…we might rate it as a 0.6. If everything below 0.6 does not have a relationship that we cut out (sic) but could you have a different one, like if we are changing the holes in the rear duct with the lower number but it might have more relationship to it.'

Engineer S2 continued:

> 'Like anything in refrigeration settings typically, just that almost the starting point you change that and this you know pretty much what it is going to do. What you don't know is we put the case in and throw a number at it. In 85 % of the case work the problem is in the 15 %…like the holes positioning rear duct thing… I don't know that there is some science that you can apply to it. It's not like fluid dynamics or any thing like that, but we find it in our testing. It is a bit of trial and error at that stage.'

Again there was uncertainty because neither they nor anyone else in the Company had ever evaluated their processes and the relationships and the impacts of tasks and the order of their completion. This HPM analysis was beginning to challenge what they thought happened. It provoked a lot of discussion.

Engineer S3 then used an example where the temperature at a certain spot in the case could not be controlled to the level that they wanted e.g. 'where the temperature is low we block the hole and let the air go to an opposite side of the cabinet. This action sometimes gives the opposite effect. That is where the testing gets difficult.'

Engineers S2 added:

> 'Is it worth collecting the data in a new project and you do the comparisons in parallel to your system from your inputs?'

> The researcher responded: 'You can do the new testing by using the numbers based on the mined process but when it comes to the point that they disagree they will split out from it.'

Finally the engineers noted that it appeared that some of the tasks had values which were surprisingly high. They agreed they should review the results further. At this stage they were not discounting the figures but since this was the first analysis ever done on their work processes, they needed to consider the outcomes as they went through normal work activities. However, the engineers did note at the end of the meeting that they reviewed their testing procedures, based on this work and the use of the KBS, and found that the average of cabinet testing was 12 weeks, considerably less than the 4-5 months of a year ago.

4 Are there any tasks that have to be done together with other tasks?

Collective Answer: Whatever we do, whatever the outcome is (or we are looking for), there are certain actions that will produce outcomes that give us what we are after, but it is not the only thing that will produce that. The engineers highlighted that no one solution is possible or desirable. This reflected the outcomes of the analysis of the workflow nets in Chapter 6. Multiple solutions emerged in that analysis and showed that the same end result can emerge from a different starting point, a result confirmed by what the engineers discussed in this meeting.

One key point was that the human element in the design process and different levels of experience in the process meant that different pathways were common outcomes. The key issue for the engineers was to find the most effective way of getting to the outcome they wanted. They felt that the analysis, presented to them in this research, offered them the potential to look at different solutions and still reduce the make-span time.

Engineer S4 said:

> 'Ideally we don't want to do more than one change a day but…from a pure data collection and information assessment perspective, we won't change generally or make a change. We let it settle. That will give us enough information…if we were pushed for time, we may have to do more than one

> task…we know that one task may give us a positive result but it will not get us to the point where we need to be, so we need to do something else with that, but its related to time…if we have 10 actions to do but have only 20 days, it might be two days each but the problem is we don't know how many tasks there are with the limited time. So we throw ideas in it.'

Engineer S2 then added:

> 'But we have good results at the end.'

This discussion showed, as it continued, that the engineers thought that many of their actions were not determined as ordered. However, the analysis of their work from the logged information stored in the KBS showed that they were substantially more systematic than they realised. The researcher showed them this and they indicated they would consider that result as well as the various relations that emerged over the following weeks.

5 Do the new workflow models reflect reality of development process? If yes which process, if not why?

Collective Answer: Simply, the engineers had never reflected on the nature or extent of the relationships in the work processes they were using in their design, test and build actions. They were uncertain and needed time to consider what they had been shown in the presentation and what had emerged in the discussion. This was an additional consideration from what they had realised, reported above, that they were not certain they actually did follow ordered and repetitive processes in paired groups of tasks.

6. Could you build model GLR 12 DAC again with the new possible solution process?

Collective Answer: Question 5 and 6 are similar, the engineers indicated that they had no idea at this stage what might be the case with this cabinet, but stated they would like to review the values in the D/F table again with this cabinet and others they were working on, to confirm firstly, what was emerging; secondly, that they were systematic; thirdly, that they followed relatively ordered procedures; fourthly, that the work flows they used could be shortened by re-mining tasks that were shown to be insignificant; and finally, that they often reached the same result even though their starting points were different.

7. Do the task types listed in the tasks list cover all of the tasks that you perform?

Collective Answer: The engineers confirmed that the tasks listed in the table were very comprehensive and covered the general actions that the engineers performed. They noted that in some specialized, or rare ‘cases’, there could be more tasks, apart from the ones that have been collected and stored in the KBS. In the discussion they were not able to add any to the list and the research was able to confirm the completeness of the task list used in the analysis and thus the efficacy of its completeness.

The key conclusions from this long meeting were:

- that feed back from engineers was positive about the comprehensiveness and completeness of the tasks involved in the product development process, assuring the efficacy of the data on which the analysis was made;
- that three of the tasks defined in the analysis T16, T23 and T28 were actually the same activity. The researcher would change the analysis to reflect that. In addition, the engineers identified one task that could mean two things. The problems occurred from data collection and interpretation. The second issue relates to T26 ‘Honey comb’ and ‘Front duct’ being different things. However, these have been combined into one modification. D/F values of these two parts and other tasks that it is associated with need to be recalculated. Subsequently this was also changed in the analysis;
- that the engineers liked the concept of the heuristic process mining and the resultant ordered relationships of pairs of tasks that emerged, confirming the professional strength of their work;
- that the analysis of the task relationships in their work flow processes highlighted uncertainty in their own minds about the extent of the ordered nature of their work;

- that the engineers could end up with the same result from different starting points. This confirmed the efficacy of the results of the analysis where the researcher reported a variety of solutions, rather than a singular solution, in shortening the make-span; and
- that some questions about the analysis had not been answered in this meeting and would be addressed by the engineers in their work.

Uncertainties remained about the efficacy of the values of all pairs and about the decision to eliminate processes with values <0.6. However, it was agreed that further investigation would be carried out by the engineers and the researcher would re-check the analysis before the next meetings, planned for November and December.

17 November 2010

The engineers had not recorded anything to this stage, but had some further questions to clarify the analysis and give further details about the presentation in the last meeting. They needed clarity to enable them to evaluate the results of the analysis of the engineers' modification tasks in each exemplar. Engineer S2 noted that they were still unable to determine whether 0.6 or 0.8 is the right value to eliminate tasks. The meeting reconfirmed the extent of the analysis and the researcher showed them the analysis was little changed as a result of their conclusions from the last meeting. The researcher answered all of their questions relating only to the strength or weakness of some selected pairs of activities/tasks that were still of concern to the engineers. The group agreed to meet in December.

22 December 2010

a) Evaluation of the KBS

The conversation in this evaluation session began with a discussion about significant changes in the company and with a team that was feeling badly. They noted their drive had gone and they were uncertain about their future. Engineer S2 mentioned that it took him about eight months when he started with the company in the case testing team to get to understand the cabinet design and testing process. He noted that his process of learning the design and testing procedure could be ‘best described as a non-linear curve’. This is because he learnt many things in the early stages of on-the-job training and the amount of new knowledge was then getting to be less and less. He noted that he especially had learnt from interaction with other engineers in the team.

The researcher noted that the team played a vital role in knowledge sharing and learning in this company. That conclusion was again confirmed by Engineer S2 and further confirmed by the other remaining engineers. Things had changed. Engineer S6 was considered as a master in the Company. Engineer S3 said: ‘In refrigeration, there are not many guys like S**** out there. His leaving has affected the work processes of the engineering team.’ Engineer S2 noted that ‘The whole group dynamic has broken up; it not like it used to be anymore. We used to have a big group meeting of the engineers every morning. People have left and the company has re-structured and taken the design direction away from the group. We are not testing as much as we used to.’

The engineers noted that there were also more problems in the market when the manufacturers could not control user’s conditions. Therefore engineer S4 noted: ‘The cabinet cannot perform like it says it should in the standard. The amount of case testing is going down and the problems outside have increased. The problems with maintenance falling behind are a financial and time cost to the company to find out what the problem is. There are also lots of refrigerated display cabinets that have not been registered, but are used in the market. It is the law in Australia that the cabinets need to be registered. However, many companies don’t comply.’

Having listened to the discussion about the state of the Company and the team, the researcher then went ahead with a detailed evaluation of Version 3 of the KBS based on scenarios developed by the researcher from his observations of the way the engineers worked in design, testing and building new and existing products. The testing procedures were based on questions a ‘new’ engineer might ask when put in a position of having to develop a new product or learn from existing products built previously. Other scenarios related to questions the existing team of

engineers might be faced with where they knew knowledge already existed and they had to use the KBS system to find answers. In the following evaluation, each scenario is labelled Demo1, or 2 etc. In the report below only examples are used to demonstrate the various responses to show perceptions of the system and its evaluation by the engineers. The examples used are illustrative of the consensus of the engineers about the system. The researcher selected only some scenarios in the evaluation process because the method of retrieving the engineers' knowledge are similar. However, they are only different from each other in context.
Demonstration 3, 4: Can you name all of the cabinets that you have tested that have five shelves?

> Engineer S3 said: 'I knew all of the models'. However, they agreed with Engineer S2 that 'new staff would not be able to find this answer based on the existing information management in the company. We need the system to do that. The cabinet testing process begins with requirements gathering. This includes information from previous products that the company have made but only few specific details will change. For example the company has manufactured cabinets with 1500 mm height but the customer might want a 1400 mm height cabinet. Or sometimes everything is the same but the customer wants different shelf orientation. We then have to change the rear duct panels to suit the new shelf orientation. What we would have done is look at the previous cases that we have done, see how many rows that they have on each shelf and determine the position relative to the shelf. Without the KBS this would take a long time. The system just shows us almost immediately.'

Engineer S4 mentioned that the Company had previously worked with the CFD Company to put a testing process model using computer software in place. He said: 'values have to be validated and fed into the model to be able to get accurate results. The nature of cabinet testing is at the edge of the measurement levels the equipment can perform at. The fluctuation of the values read from equipment is difficult to validate. Therefore, using computer modelling was not successful. The cabinet capacity measurement compared to the standard is different and most customers don't understand.' The engineers agreed that using the KBS gave them access to their information from previous work. It didn't act as a substitute for the modelling. The discussion confirmed what had previously been observed and noted by the researcher and by the engineers and CEO in the company. Knowledge and information can be found faster using the KBS. The discussions also confirmed that manufacturing bespoke cabinets is not a process that produces the same result time after time. In this case slight variations in design to meet the demands of the client meant that changes are difficult to predict as the systems are so complicated. Modelling had failed but the KBS provided exemplar information of like solutions that were, in the words of Engineer S4, 'good enough'.

Demonstrations 1, 13 and 14 related to applications of the National Standard in the KBS. Engineer S2 mentioned that it was difficult to find information regarding any tested cabinet that linked to the National Standard. He noted: 'The way reports are currently kept does not facilitate knowledge sharing and/or re-use.' He mentioned that queries, for example about demonstrations, 'are always crucial to the case testing process'. Their processes in the company, he continued, 'however, often rely on someone's memory'. Often they spent time finding information they needed to use, and it did not mean that they were going to find it. This especially included their own domain tacit knowledge. In the evaluation the researcher showed the engineers that the tacit knowledge captured from their work was available to be searched and that solutions could easily be found. They agreed with engineer S4 that, 'this was far more efficient than what we have now'. One engineer in the meeting (S2) noted that 'the sheets in the testing room got filled in and then piled up in the cabinet in the corner and really to me the information has been lost and not used. If it is in an easy access form it's going to be of benefit to us and the company.' They agreed that the KBS filled this need effectively.

If the engineers had to spend time writing their case testing results from the previous day and noting the modifications that they were going to do every day on paper, which they noted they will never retrieve later, the researcher used Demo 12 and asked: why don't you input this information into the KBS? The engineers noted that putting these details straight into the system was far easier to do. They agreed with S4 who admitted that 'when the two previous engineers were working with them, they resisted any attempts to change. It suited them to keep the paper-base system going. It now suits us to use the new system. It's easier.'

Engineer S2 noted that the existing case testing database that had been created for the engineers, was far too complex and difficult to use. He said that he 'had used the data base for a short period of time then gave up because it was impractical to use.' Engineer S3 admitted that he did not know any thing about this database. They agreed that any existing knowledge sharing in the company was not effective. However, they agreed that the KBS did enable access and sharing and was easy to use. Engineer S2 agreed that 'the existing information management system cannot access such information as shown in the KBS.'
Using Demonstration 18, the researcher then asked: Did use of the query system in the KBS assist you to speed up the testing process?

> Engineer S4 said 'I'm sure yes, because you are not losing information, that after designing 30-40 cabinets that also have been tested and all that stuff (sic) that has been written down on sheets just gets filed away in cabinets not to be re-used. Anything that has been learnt here previously, has been learnt by people doing it and not because it is stored any where. New staff would have no hope. This system allows the information to be found.'

These exemplar responses are used here to show that the engineers were accepting of the KBS. It provided them with certainty about their knowledge and the information collected over periods of time. All existing explicit knowledge in artefacts held in the Company together with their captured tacit knowledge was stored and able to be used, relatively easily. There were no longer multiple storage spaces or filing cabinets with unordered pieces of paper reporting previous testing outcomes. The system had enabled it to be stored in a way that used the engineers' own practice through an ontology reflecting their domain knowledge and their work practices.

It was agreed that one further evaluation of the system would be done in January 2011. The engineers had noted that the testing log sheets in the KBS needed to be further modified to expand the log files to include columns like the paper format.

They felt this would make the transition to the system easier. The researcher agreed to make that change.

The knowledge-based system evaluation result from the iterative process since version 1 through the final evaluation through out a series of interview with the engineers can be summarised as shown in Table 7.1 below.

Table 7.1 Evaluation framework for knowledge-based system

Evaluation Criteria	Forms of Evaluation - Artefact 1 – the Knowledge-Based System	Results
Functionality	Observation: Case study Description: using Scenarios, and Testing using demonstrations, and interviews,	The engineers confirmed that the KBS had the features enabling them to retrieve stored expertise and past design processes, and both tacit and explicit knowledge from their product development process.
Solve the problem by offering better solution	Observation: Case study Description: using Scenarios, and Functional Testing using demonstrations, and interviews,	The engineers confirmed that the KBS had the features enabling them to search and retrieve their product development process knowledge as previously they were unable to do. They confirmed this was a better solution and more effective for their work.
Quality	Observation: Case study Testing: using evaluative interviews	The engineers confirmed that the KBS had the features enabling them to retrieve their product development process knowledge from various sources. The KBS had integrated knowledge from various sources together, improving the quality of the knowledge available to them.
Efficacy	Observation: Case study Informed argument	The KBS has shown to the engineers that it can capture and reuse knowledge on a real time basis. The engineers confirmed that the quality and types of knowledge in the system reflected their reality. They confirmed that the structure of the knowledge in the ontology reflected their work practices
Performance	Observation: Case study Description: using Scenarios, and Functional Testing using demonstrations, and interviews,	The KBS helped the engineers capture their own knowledge during their daily product development meetings. The system also provided them with accurate information and knowledge when they needed it. The system was shown to do what they needed it to do and saved them time.
Reliability	Observation: Case study Description: using Scenarios, and Testing using demonstrations, and interviews,	The KBS development process was an iterative cycle. The iterative development process meant the engineers were part of the KMS development and testing through 3 iterations of building and testing the system. Therefore the KBS's structure was framed by discussion between researcher and the engineers. The irrelevant concepts in the KBS were eliminated. The engineers have confirmed that the KBS always gave them the relevant answers when asked. The engineers confirmed that the system itself was reliable both in operation and functionally.
Consistency	Observation: Case study Experiments and testing	The engineers confirmed that the KBS gave them the relevant answers when asked and that the answers were consistent.

Effectiveness	Observation: Case study Informed argument Description: using Scenarios, and Testing using demonstrations, and interviews	The engineers confirmed that the KBS gave them the relevant answers when asked, as previously they were unable to do. It improved their work. The engineers noted in evaluation that to be effective, the system had to be available at all times. it was, and needed to provide the knowledge they needed immediately. They confirmed it did.
Accuracy	Observation: Case study Functional Testing Informed argument	The engineers confirmed that the KBS gave them the answers they needed when asked and that the answers reflected what they thought that they knew. The knowledge stored in the KBS from all sources was checked and verified as accurate by the engineers.
Predictive (Always give the same solution when use)	Observation: Case study Structural testing	The engineers confirmed that the KBS gave them the relevant answers when asked in various knowledge re-use scenarios. The system did what the engineers expected.
Feasible	Observation: Case study Interview, questionnaire	The research clearly shows that the engineers believed that that the system and its use were feasible and could be developed continuously.
Ease of use	Observation: Case study Interview, questionnaire	The engineers have confirmed that the KBS is understandable and not difficult to use.
Presentable	Observation: Case study	The engineers have confirmed that the KBS user interface is not difficult to use.
Usability	Observation: Case study	Similar to any new system implementation, it initially takes time to learn to use it. The researcher conducted 2 user training sessions with the engineers. The outstanding errors were solved multiple times. Each iteration improved system useability.
Understandability	Observation: Case study	The engineers confirmed that the KBS is understandable and not difficult to use.
Simplicity	Observation: Case study	The confirmation from the engineers that the KBS is understandable and easy to use. The engineers confirmed that the system is simple because it reflects their participation in its building and its structure reflected how they worked.
Level of completeness	Observation: Case study Testing using demonstrations, and interviews	The KBS is a knowledge repository system. Therefore, it is not complete and still continues expanding when used.
Quantitatively measurable	N/A	The nature of the system and number of engineers involved in this case study do not facilitate quantitative measurement. The researcher had to rely on multiple forms of evaluation in groups and with scenario evaluations with the group of engineers, the CEO and COO.

Testable against all requirements	Observation: Case study Testing using demonstrations, and interviews Description: using Scenarios, and Testing using demonstrations, and interviews	Testing was done qualitatively against the stated needs of the company, both management and engineers.
Plausible (sensible)	Observation: Case study Testing using demonstrations, and interviews	The engineers confirmed that the KBS had a sensible structure and contains relevant knowledge.
Side effects	Observation: Case study	During the evaluation process the engineers informed the researcher that some of their product development processes had already shortened. This is due to KM awareness created during the time that the researcher was working with the engineers. Having the system in place was acknowledged in the end as having had a significant effect on the length of the product development process.
The process is contributing to knowledge	Observation: Case study	The structure of a KBS when related exactly to the needs to users and built through inherited relationships identified from domain knowledge, produces an effective tool to assist businesses strategically.

The researcher then began a second evaluation of the outcomes of the analysis of their workflows and the design and testing processes, following the questions that remained after the first evaluation in September.

b) Re-testing the assumptions and outcomes of Heuristic Mining

The engineers re-confirmed in this December 2010 meeting that they did not have patterns to follow during case design and testing processes. They noted that they thought that they came up with ideas for solutions based on how the cabinet worked after they had made previous modifications. However, on consideration of the information given in September 2010, they had begun to notice the patterns were more obvious. Engineer S2 said, 'But we just do them and don't think about it.'

The researcher then asked: Are the possible solutions reflecting reality? For example with reference to the task pair T1 → T6 Engineer S2 mentioned that 'the value at 0.85 seems to be high because T6 is not common'. The question was raised: what is the definition of 'Modify valve and orifice', because it did not seem right to him. Then the researcher showed them the actual words written in their log sheets. At this point it seemed to the researcher that the way the engineers had noted their modification tasks was inconsistent. One engineer's reaction to the results that were shown to him, based on notes in the KBS from their log sheets, was contradicted in his opinion. Engineer S2 added: 'I don't want to introduce my bias into what your numbers are. If you are saying 0.85, that is not for me to discount. That is my bias; that is what I think. It shouldn't be like that.' We agreed to check that one again.

The other modification task that seemed to be uncommon was 'modify shelves layout'. Engineer S4 noted that 'this is because the shelf layouts should be determined and finalised before the case testing starts. If you try to optimise the case you shouldn't be doing things like modify the shelves. Blind down and blind up tasks are also not specific to optimising the case. It is just that you want to see what is the effect. You should be doing that before you do your test. Blind up and blind down give the effect to the product temperature pretty much the same.' The researcher then asked if you already know that it was going to give the same outcome, why you do it so many times? From the 13 cases in the KBS, blind up and down had been done seven times in each case. The explanation given by the engineers is that perhaps one of the other engineers did this as a matter of course in the testing lab without reference to the group. Engineer S2 said: 'the problem with blind up and blind down relates to temperature consistency in the supermarket and must be tested for'. Again it became obvious that there were discrepancies in the shared knowledge of the engineers. This task was indeed very commonly used.

Engineer S2 then mentioned that some of the tasks, such as the one above about shelves, should be done before the case testing started. He said: 'It should not be done during the flow. It should be in the design criteria. The reason the evidence shows T7 during the testing is because the case doesn't work. The shelf has been moved because the cabinet is not working originally, which is not the way that it should be done. You test it and then not move the shelves, but it didn't work; then you modify the shelves but the cabinet works. You then have to tell the customer that this happened. And then the cabinet will go to the store and be moved anyway!' In the discussion that followed it was noted that the value of T7 probably was high because it was such a key element in design, but it initially seemed unusual as it was more usually done prior to testing rather than during. However, this result did challenge the engineers' perceptions about what they did and, on evaluation, they agreed that this had not been obvious to them and offered another means to improve the make-span time. The analysis had showed habitual tasks being done without recognition of their value to the process.

The only other issue of contention related to task T16, suction pressure. All three remaining engineers noted that this was often an initial task in their opinion, even though their test logs didn't agree. Engineer S3 noted that: 'T16 is a crucial and variable task that has significant impact on cooling temperatures but is not the most effective'. The researcher confirmed previous observation that the cooling coil was something that gave the most effect but the engineers resisted not changing it. This, they confirmed again, was because they had to disassemble every part and put the new coil in and the testing process had to start all over again. They engineers wanted ideal equipment that could help them change the cooling coil so they could experiment with the effect of changing the coil. However, in reality, it was difficult. They preferred to change the suction pressure, T16. Its relationship measures were lower scores and the engineers believed this was explained because it is a ‘we can do that instead of something more dramatic, but it is much more complex’.

Only one issue remained, the level of D/F values was still difficult for the engineers to judge whether the relationship D/F value of 0.6 was low or then which value is more appropriate in the minds of the engineers. They were convinced that the values “seemed right” and intuitively they accepted them and would utilize them in practice. However, they believed, based on their experience, that proper verification could only occur over a two to three year testing regime based on every product developed. The engineers agreed that the possible solutions from analysis were also possible in reality. They further noted that ‘each pair seemed to be OK but when it comes into the same line, it difficult to say (S3)’. Engineer S2 then added: ‘all the modifications have been done based on the cabinet performance at that point. Like all engineering, the human factor will make any change a variable’. Their designs as engineers are subject to human interpretation and therefore they believed that they are ‘fit for purpose’ but not perfect. The engineers and the researcher agreed to one final meeting in January (year) for final confirmation of the efficacy of the outcomes of the HPM analysis

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The researcher was contacted by the engineers on 20th of January 2011. They informed me that the company had not been doing well. The company had now gone into administration because it was not viable to continue business anymore and would probably no longer be operating. The operations of the company had been adversely affected by the failure of a major client to pay invoices over a six to eight month period and this left the company with a liquidity problem. This was made worse by staff leaving and an inability by the company management to reverse a downward slide in demand for their products. The engineers noted they were still operating ‘as normal’ right up the day we met. The engineers wanted to finalise the work that they and the researcher had been doing over the period of almost three years.

This meeting with the engineers covered a variety of topics from the state of the company and its competitors, to the value of the KBS and the utility and validity of the analysis done on the workflows, all of which had involved discussions and evaluation over the previous 18 months. This meeting was the last one that was able to be held, as the company was to stop all operations five days later.

The first part of the discussion centred on the status of the marketplace and of the company in that market. The company had only one important Australian competitor, which was based in Sydney. They also had the same problem as that company, which is that they had to compete with products from overseas, such as from Europe and China that are cheaper and did not necessarily meet the National Standard required for manufacturing in Australia. Part of the problem for the company also lay in the loss of part of their business. In the past the company used to make their own spare parts but lately products from other companies had been used. These companies too could not survive the economic downturn. These outsourced cabinet parts appeared to cost more than it did for the company to make themselves. The other element in the market place related to the impact of having only two major clients who were massively powerful and who 'beat prices down'. The manufacturers thus tended to reduce their prices to sell their product. The suppliers of commercial refrigerators like the company were not able to compete with overseas competitors such as those products from China. The company and its only Australian competitor had been taken out of the market because they could not keep up with the prices set by the two major Australian clients. One of the engineers noted the irony of the situation. Engineer S2 said: 'here we are with solutions that enable us to be more response to the market and we have captured all of our knowledge. To what avail?' He then went on to re-iterate again that because of this work they 'now design, test and build in weeks rather than months'.

The second part of the meeting offered a final evaluation of the KBS by the engineering team. Engineer S4 stated that there was no system in place that could do the queries like the KBS. He said that 'the KBS helped the engineers to find the answer to their questions'. However, he added that whilst the system did capture their domain knowledge, they questioned the motives of the CEO in doing this. They noted the public statement that it was to ensure knowledge stayed in the company. However, as a team, they felt otherwise. Engineer S2 said: 'the reason that the CEO of the company, when the research started, wanted the KBS developed was to try to take knowledge away from the engineers and make them less important'. He added that they thought 'he wanted this so other people can use the system and access information that they know to do the job'.

Engineer S4 added that whilst this was their perception, it did help them significantly. He said 'the system can capture the process, preventing the engineers form re-inventing the wheel. …It looks very good.' The team of engineers agreed that the system enabled them to be more certain that if they undertook one task then there was a reasonably predictable result. Up to the point of using the KBS, they admitted, they could not differentiate the results of the same modification task. They noted that the KBS 'made information ready in an accessible form' and gave 'consistency to how data present as well'. Engineer S2 added: 'Often the comments and stuff put in the old way didn't show any negative or positive effects, just an outcome. This system allows us to do that now.'

The Researcher asked 'If your biggest competitor comes to you tomorrow and asks you to make a new cabinet will you continue to use the KBS or do something from experience by starting from scratch? What is your perception of the way you do things?'

> Engineer S4 responded 'I guess nine times out of ten we would look at something close to what they want and work it from there. But the system would then shorten what we do. It would give us access to what we need.' The other engineers agreed.

The Researcher then asked, 'How can you replace your intuition, as a professional and have made probably 100 cabinets but you still intuitively do things?'

> Engineer S3 responded: 'Yeah no doubt about that, we do things but at the same time we think that, I don't think you can always take that approach and

because you did something and it fails it doesn't mean that was necessarily a bad idea.'

The Researcher then said, 'Can I ask another one, did you ever like the supermarket in the Docklands which is a green supermarket? How did you start that process? Because it's supposed to be different to the others. Did you start from intuition or start from facts or the things that you have?"

Engineer S3 again responded: 'There are two parts to it. First is the cabinet that we have; the rest is probably more the green side. The whole air con and CO2… it is a total package. It shows that what can be done'.

The Researcher replied: 'When you have to build the cabinets for that store, did you start from your knowledge or did you start from some other store?'

Engineer S2 stated: 'No! On something like that the cabinets used in that store are the same as cabinet used everywhere else. They want pretty much the same things. But they use CO2 so we had to pretty much look at the whole cabinet; but we tried to replicate the same parts in a different way. We looked at the internal bit that was going to change. Yeah, but again there is nothing particularly different about the cabinet; but the only thing that we have to do is the thing that you cannot see, which is the air in and out, and replicate what we did in previous products. The system you gave us would have made the whole thing easier'.

Engineer S4 added: 'but the plant room is different from what we normally work with'.

The Researcher said: 'Is it completely new?'

Engineer S4 replied, 'someone else has done it in Denmark before but they didn't give us that much. They just said we use CO2 and this is the temperature and that's it'.

Engineer S2 added: 'I guess when you work, we don't pretend that we invented CO2 but like a lot of things, we do it. We send people overseas to look at this new high level without an in-depth understanding; but we can get the idea.'

The researcher then asked: 'With a lot of the things you did you used your expertise and you try whether it is right or wrong and then move on. It's not what you guessing? It seems to be based on experiments and you expand it and get it right'.

> Engineer S4 responded: 'It's not guessing. Yes we still work on it and we haven't got it right yet, like we get 80% right but the other 20% we still work on it. If we could spend the effort and spend the time on refining that 20%, well it would be better. Again the system would be part of improving that 20%.'

This exchange is used here as illustration of an acceptance by the engineers that they operate very much using their domain knowledge and expertise and intuitively act in the design, test and build process. They admitted this ultimately leads to errors but they are '95%' right. What the KBS does in essence is that it provides access to the knowledge for that final 5% which could make a competitive difference in getting the product to market. They also acknowledge in this evaluation that it did capture what they did and so it could be used and reused. One of the engineers both jokingly and seriously noted that the 'KBS could be part of the sale!'

The researcher then asked about the outcomes of the workflow analysis in terms of whether the assumptions made and the outcomes reflected real practice and offered better solutions to the design, build, test process. The researcher asked 'Going back to the CEO, if a system like that can be used strategically, do you think having one of these (the outcomes of the HPM) for you as an engineer is useful to convince the management that there is a sense that a system and having solutions assists?'

> Engineer S4 replied: 'I think we have to try. We know ourselves that there is a significant cost attached to having cabinets testing in the test room and it's more than just cost but also time…when we started with the G series it was excessively long and we improved our testing time a bit, since then there is nothing showing good management but rather good luck. We have just been lucky that we started up with the design that worked. We need evidence to avoid this. The solutions offered by you would help that.'

The researcher then asked about the mapped workflows and the relationships measured. Researcher: ‘In the last meeting you noted that some of the relationships might be questioned.’

Engineer S3 replied: ‘I think we have reason for that and they are not good reasons!!!!’ (laugh!!!)

Researcher: ‘But the point is they are there, the data shows it. Do you think it’s because over time it becomes a situation that you establish your expertise and you know these things happen one after the other, but it might not be related in an engineering sense, but in some other way they are, like T1 and T5. Your initial comments said that these are not related, but they appear after each other very often.’

Engineer S4 added: ‘The value might be related but in engineering terms the processes must be related somehow. We do it so it must be’

Engineer S3 added: ‘I think sometime we do things in a set order, not necessarily the best but easiest thing to do. For example, in the cabinet that is fully loaded with packages and cabling, to modify the holes in the rear duct is too difficult. Maybe changing a valve setting or defrost setting time might get us over the line. It is a matter of you making the best engineering product or do you want to achieve the best possible outcome?’

Engineer S4 then noted: ‘You can spend a year on testing. The question is, is it going to perform better or not; but reality is, are they going to wait for it or not, and if its works good enough (sic) then why don’t we put it in the factory?’

Engineer S4 added: ‘If you work as good (sic) as your competitors and fits the cost criteria, then go for it. We have got examples of that, like the square glass dairy cabinet (GLDs). This is an example of a product that has been through enough model change variations without spending a lot of time up front. We introduced the product and made changes. We probably have a design of third or fourth generation that is actually efficient. The first one is suitable for what they asked for and as good as what is available in the market but the last result we didn’t even publish because we think its too good. We didn’t believe it ourselves, when something works too well you think there is going to be something wrong’.

The Researcher then questioned the engineers about the time issue: ‘When we first came 3 years ago, the CEO and COO had a talk to us and said their concern was not the quality of the product but the time in getting things finished, but you have been talking about getting stuff done in 8 weeks?”

Engineer S3 interrupted: ‘…that’s average’

Researcher: ‘…but you also said that there are some that went forever!’

Engineers S4 said: ‘Yeah at that particular time. We reduced it. We saw from this work (referring to the KBS and the outcomes of the HPM analysis on the computers in the office) how it can be done. Having someone talk to us about we did allowed us to do it. The action of the CEO and especially your research enabled that’.

Researcher: ‘Coming back to the issue of being good enough, you are trying to be the best?’

Engineer S3: ‘Yes’

Engineer S2: ‘There’s also the fact to that we are testing the entire standard, we have to meet standard as well.’

Engineer S4: ‘True, the introduction of the Standard was something we’ve never dealt with before.’

The Researcher asked: ‘How about some tasks such as blind up, blind down, light on, light off; you have made all these modification tasks to get the cabinet to pass the standard but you don’t know what the usage condition is like? How do you deal with this?’

Engineer S3: ‘That’s a good point. Since the introduction of the Standard, I sort of think that the Standard is driving everything down, they don’t really give the best outcome. Essentially we have to compete with a number of manufacturers, before we ever sell the price and cabinet to anybody. We provide everything documented. Our cabinets can work as efficiently as the others and then somebody else will come out with things like “oh we think the product sold in Western Europe is far more efficient than your product” and our customers go at us, like look, the other manufacturers have better products. Then you guys have to go higher. We tend to get cabinets to work in an environment of 25C with 60%RH. The reality is there never will be that environment. It's generally that you never have the most efficient system that comes out of the test lab but not in real world. Some of our designs are now having trouble because they have been used in environments outside of the set criteria.'

The researcher then addressed another issue: 'When I first came here engineer S6 seems to have played an important role in the team. How different is it since he left?'

> Engineer S4: 'To be honest, we didn't necessarily replace S6's knowledge, but probably we have always had someone like S6 who wants to design the best products, but we were building them and we always had conflict; for example if you have a specific coil which will make a cabinet work better, but it is too difficult to change in the manufacturing plant, then we don't do it. If it is going to change in every product, we probably will look at it but if they want to change only 5-10% of the products range we have to live with it because its not worth the problem that its going to cost with manufacturing. We are balancing theory and practice. S6 is dealing with theory but we are dealing with the practical as well. Often with something like CO_2, S6 will be involved very heavily early on. If we make a new cabinet we are going to put what we have in first unless what we've got is not going to work at all; that's when we are going to go with him'.

Following on the researcher asked: 'Is there an issue like, if you have a system like this and you have got theoretical and practical engineers, could the system end up with too much theory and not enough practice? If I asked you to build a particular cabinet, what level of expertise will be in that cabinet? Is it you building a thing or the theory behind it?'

> Engineer S4 said: 'I think we do something with what is easier first, not changing something. We probably stay with it, but sometimes we have to accept and change it because we can't get the results we need if we leave it. That's something I guess; it's a little bit outside what we are doing.'

The discussion showed that there was an issue in developing solutions for real application in the Company based on trying to apply the National Standard and to deal with the internal disagreements on the nature of the product being developed. This, in turn, reflected on the tasks that had to be followed and highlighted some of the inconsistencies between what the engineers did in practice and what they thought they were doing. Their discussions about the workflow logs and the relationships between pairs of tasks focused on what they thought they were doing, rather than what they did. The HPM analysis showed them their work was repetitive in terms of the ordering of tasks. It highlighted to the engineers what they actually did. Being aware was part of the reason they had reduced the make-span during the course of the second part of this research. It appears as if the National Standards diverted their attention from normal practice because it was new and an afterthought to each set of tasks they performed. The demand to meet the National Standards, on the one hand and the demands of their clients on the other, meant that solutions were not optimal, nor given the fundamental nature of the refrigeration problem could they ever be. In fact the engineers recognised that multiple solutions emerged even on the same cabinet when designed for two different clients. Using solutions derived from the workflow analysis, the researcher verified that this was possible and that such variations are all possible. The previously recognised make-span reduction that emerged during the time of this research reflected this reality and made it obvious to all involved. The combination of the analysis and the alternative solutions created together with the 'action research' impact on the results, i.e., the effect on the research process *per se* on the design/build/test process, meant that change was at the same time both emergent and created. The analysis and the research processes became complementary.

The researcher then addressed the only unresolved issue from the make-span analysis. Researcher: 'Again what do you think about the outcomes of the workflow analysis? For some relationship values, do you do things because you think it's the easiest way to do it?'

> Engineer S3: 'I think that's fairly true. We put cabinets in the test room and within the first couple of days the group would not look at it.'
>
> Engineer S4 added: 'You come up with a number of things that you need to do and then look at the result, When it is settled down then other engineers

will use their experience trying to get the parameters right and then after that if its still not working, well that is when we start looking at it as a group and make changes and go through same process again.'

The researcher then added: 'For example T1 followed by T6 happened many times and their relationship is high.'

Engineer S3 responded: 'if you make a change like that there are a number of things that you look at. There are three or four things that you normally check and changing the valves is one of those things that we change but these are not related. We change things. We've got to check this and this and look if the parameters are still ok.'

Engineer S4 added: 'They are not actually related but I can see how it fits in the process, for example with the defrost setting you just go with what you think and then alter it, make it lower or higher to get it right; but that is a bit more problematic if its not right.'

Engineer S3 noted in addition: 'It would be nice if we could try starting the cabinet with it.'

The engineers accepted that the assumptions involved in the particular queries they had on the small number of task relationships were suitable to be applied to their work. They agreed that the analysis highlighted the variation in outcomes they normally expected and they confirmed that such analysis reflected their practice. In their view customization is based on good enough, cheap enough, and timely enough to sell, not necessarily perfect enough. This can be argued to reflect the variation in results that emerged from the workflow analysis and supports a view that the solutions made are applicable to this type of engineering design, test and build process.

The Heuristic Process Mining analysis evaluations have been done iteratively in collaborative with the engineers over a 12 month period. These evaluations have been collated and common themes developed through the application of the evaluation criteria presented in the artefact evaluation framework. The result is shown in the Table 7.2 below.

Table 7.2 Heuristic process mining evaluation framework

Evaluation Criteria	Forms of Evaluation Artefact 2 – the Heuristic modeling solutions	Results
Functionality	Analysis using algorithms and optimization	The engineers agreed that stored knowledge from the KBS can be use strategically by applying HMP with it.
Solve the problem by offering better solution	Analysis using algorithms and optimization	The engineers have agreed that the new possible solutions created in the analysis can shorten their previous processes and that the logic behind this is sound.
Quality	Testing: using evaluative interviews	The results from applying HPM significantly shortened and simplified the testing process without any apparent loss of quality.
Efficacy	Testing: iterations using evaluative interviews	The results from the HPM analysis has shown that the product testing process can be shorter than the original. The engineers were used to test the assumptions made during the HPM analysis. There was significant discussion with the engineers about the cut-off values used in the analysis and about the elimination of certain tasks from the design/build/test process for the various products used. In each case the efficacy of the decisions made or the conclusions reached were confirmed as feasible by the engineers.
Performance	Description using informed argument and Analysis using algorithms and optimization	The performance of the HPM reflected the real testing procedures used by the engineers. This was agreed by them.
Reliability	Analysis using algorithms and optimization	The engineers agreed that the HPM method is sound. They confirmed the best possible solutions as the outcome emerged.
Consistency	Analysis using algorithms and optimization and dynamic analysis	The engineers agreed that the various possible testing process form HPM have consistency.
Effectiveness	Analysis using algorithms and optimization	The engineers have agreed that the HPM method is sound and effective. Participating in the analysis helped them make changes to their own work processes, making what they did more effective.
Accuracy	Analysis using algorithms and optimization Testing: iterations using evaluative interviews	The possible solutions derived form the analysis were verified for accuracy by the engineers.
Predictive (Always give the same solution when use)	Analysis using algorithms and optimization Informed argument	The analysis offers algorithmic consistency and will produce a set of outcomes and models which are consistent with predictability.

Feasible	Testing: iterations using evaluative interviews Informed argument	Result of the research shows that through iterative modification of the KBS, applying HPM to the product design, build, testing process is feasible.
Ease of use	Testing: iterations using evaluative interviews	The engineers have confirmed that through the researcher’s instructions they can follow and plot other possible solutions from the D/F matrix base using different starting tasks.
Presentable	Testing: iterations using evaluative interviews	The engineers have confirmed that they understand how the HPM analysis works.
Usability	Testing: iterations using evaluative interviews	The engineers have agreed with that HPM has usability applied to this dynamic type of workflow.
Understandability	Testing: iterations using evaluative interviews	The engineers have confirmed that the HPM process is understandable.
Simplicity	Testing: iterations using evaluative interviews	The engineers have confirmed that the outcome from the HPM is simpler than their existing testing process.
Level of completeness	Testing: iterations using evaluative interviews Informed argument	The HPM result is not complete. It grew along with the KBS. If the testing process is expanded with new products then new knowledge capture would expand the dependency and frequency values and they as a result will change. KMS systems should change with every iteration. They are dynamic. Therefore analysis subsequently will alter the outcomes until a very large sample is reached and more certainty in the results eventuates. In this study and with small scale engineering, such limits would probably never be reached.
Quantitatively measurable	Analysis using algorithms and optimization Informed argument	The research needed further simulations to measure product testing time changes to show how many percent shorter the result was than the original each design process becomes. The demise of the company made this impossible.
Testable against all requirements	Analysis using algorithms and optimization Informed argument	The research needed further simulations to measure product testing time changes to show how many percent shorter the result was than the original each design process becomes. The demise of the company made this impossible.

Plausible (sensible)	Analysis using algorithms and optimization Informed argument	The engineers have confirmed that the concept of the HMP and algorithm is sound.
Side effects	Observation: Case Study	During the evaluation process the engineers have informed the researcher that some of their products development processes had already shortened. This was due to awareness and use of the KBS created during the research while the researcher working with the engineers. It was an unintended outcome.
The process is contributing to knowledge	Observation; Case Study	Previous research applying HPM to KBS systems had only been on static and regular business processes. This work has shown it applicability to dynamic engineering product design processes.

7.4 Evaluation of the research process – testing the efficacy of the artefacts

The previous section described the outcomes of the research. This evaluation included the knowledge-based system and the result from the Heuristic Process mining through application of an evaluation framework. However, the methodology itself also has to satisfy the Design Science principles suggested by Hevner et al. (2004) and accepted as part of this study in Chapter 3. In Table 7.3 below each of the principles of Design Science as a research method are applied to the research process and results of this study of strategic knowledge use in the engineering company.

Table 7.3 Design Science methodology evaluation applied to this research

HMPR Principles	**Application**
1.Viable artefact	The research has produced a viable design artefact in this case in the form of a knowledge-based system to manage engineering design/build/testing in a refrigeration company.
2.Problem Relevance	This technology-based solution was vital to the strategic operations of the company and was designed and then used to resolve two identified strategic problems that the company had. The artefact built also resolves an operational issue in terms of work processes which enabled the company to better address on e of the strategic issues identified.
3.Design Evaluation	Heaver et al (2004) noted that designs have to be properly evaluated for utility, quality and efficacy. The KBS was tested 6 times formally through evaluation with the engineers involved. In addition the iterative nature of its development and the use of multilayered data collection techniques meant that every conceivable testing of utility, quality and efficacy approach was covered. Throughout the needs of the engineers in practice and the needs of the CEO and company strategically were included and each version reflect

	changes needed through application of the system by the engineers. In the very last evaluation in Jan 2011, the chief engineer noted that "what the CEO wanted the system delivered. What we wanted and needed the system provides". The evaluation of the MBS focused on the extent to which the needs of the engineers and company were met in a dynamic way. The effectiveness, utility and quality of the system were analysed with reference to the goals stated at the beginning. Further evaluation of the systems utility was done through application of heuristic process mining seeking out optimization solutions to address the make-span problems noted by the CEO. This enabled simulation of design/build and testing processes and the derivation of a number of more optimal solutions for the engineers to use. The efficacy of the assumption in this optimization process was tested with the engineers to ensure accuracy, reliability and completeness. Undertaking optimization requires sets of assumptions that enable simplification of the complexities in processes being modelled. The researchers were very aware that the assumptions being made reflected practice in reality and would not of themselves created distortions to the solutions created. Arnott and Pervan (2005) stated that a significant number of papers in design science do not attempt to establish the worth, effectiveness or usefulness of the

	artefacts. This research has embedded evaluation to determine the effectiveness, worth and usefulness of the KMS in every stage of its development and deployment.
4.Research Contributions	This research has made a significant contribution to understanding the application of ontology to resolving business problems, an issue noted by Milton (2010). Ontology applications have very much focused on databases and other forms of classification. This research has intentionally used an ontological structure to develop a solution, a knowledge-based system, to resolve strategic business issues. It adds to our knowledge about the applications of ontologies to design. The research also mirrors other applications of systems designed to assist business in different ways eg developing a business intelligence system (Rouibah & Ould-Ali 2002) or a knowledge–based DSS for radiologists (Markus et al (2002).
5.Research Rigour	Hevner et al (2004) argued that good design science research depends on application of rigorous research methods, which Arnott and Pervan (2005) noted should include the use of appropriate reference theory as a theoretical foundation and the rigour of the research methodology. In this study the research is grounded in the application of strategic management theory to business problems and to theories of effective knowledge management. The development of the knowledge-based system is based in the expectations of business strategy, the theory of knowledge sharing effectiveness and in the applications of domain knowledge by the researcher. The

	development of the knowledge-based system and its evaluation were always couched in terms of the domain of strategic management theory – increasing competiveness and speed to market dealing with competition with external competitors. The research methodology is similarly sound. The research design is built on an exacting premise of triangulated data collection (multilayered data collection Kanjanabootra et al 2010), on iterative system development using evaluation feedback and re design using an action research framework. The evaluation is continuous and involved multiple iterations of assessment by the users. The small size of the engineering team meant that only interviews and discussions as evaluation were relevant and thus were adopted. The final methodological frame was to establish each phase of data collection, data use and then evaluation within the bounds of the application of the theories relative to the research.
6. Design as a search process	Arnott and Pervan (2005) argued that good design requires an iterative search process. This will often involve decomposing the design sample and ensuring the parts fit together. In this research that search process was achieved through an iterative system build and evaluation through the use of ontology. This enabled the artefact that was built to be fully integrative as it was built of domain knowledge relationships. The effectiveness of these relationships emerged in the use of the stored knowledge applying the heuristic mining algorithm as it enabled the researcher to measure

	task and process relationships and use that form of analysis to build solutions that assisted the achievement of the business goals of the company.
7.Communication of Research	Heaver et al (2004) noted that good design-based research must be readily understood and able to be used by both technicians and management. This research emanated from the needs identified by the CEO and Board of the company. The researchers were always aware that the end product had to meet the CEO's goal of capturing the domain expertise (tacit knowledge) of the engineers and design a solution usable by the management and the company as well as the engineers themselves. The evaluation of the knowledge-based systems included management at different levels to ensure that it met the needs of and was able to be used by management.

7.4 Conclusion

This research has created an unexpected impact on the engineers and the way they undertook their cabinet testing process. Most notably was the admission by the engineers that their cabinet testing process had been shortened. This, they admitted, was because this research had implemented an ‘action research’ framework which meant both them and the researcher would regularly coordinate with the engineers during the whole period of the research, try changes and evaluate them in their practice. The coordinating action of the researcher’s observations, interviews and shadowing helped the engineers generate problem awareness. This included them recognising the company’s stored knowledge and information, enabling re-use. The knowledge-based system, as an artefact outcome, helped the engineers gain access to the information and knowledge that they had never looked at before. These included a re-use of modification notes that had been made regularly and generated in every cabinet testing process; use of numerical data from measuring equipment that related to the modification notes; addressing the national standard as they proceeded was also included and made easily accessible in the KBS, assisting the engineers in their practice. The results from heuristic process mining have uncovered information about the cabinet testing processes that the engineers had overlooked. For example, the engineers habitually executed a number of set tasks without knowing that some of the tasks were not related to the cabinet's performance. They just did the tasks. The results impacted the way the engineers tested their prototype cabinets, resulting in a shortening of the cabinet design and build testing process.

As a result of this discovery and the evaluation processes undertaken, the following is a summary of the consensus developed with the engineers.

Contesting Consensus

- The engineers confirmed that the heuristic process mining method was sound. However, the real testing of the mined process still needed to be done.
- The engineers could not completely identify which level of the D/F values were the most appropriate to determine which tasks should be eliminated.
- The engineers based their cabinet testing procedure on their intuition. This could be seen as a barrier to other methods of testing cabinet.

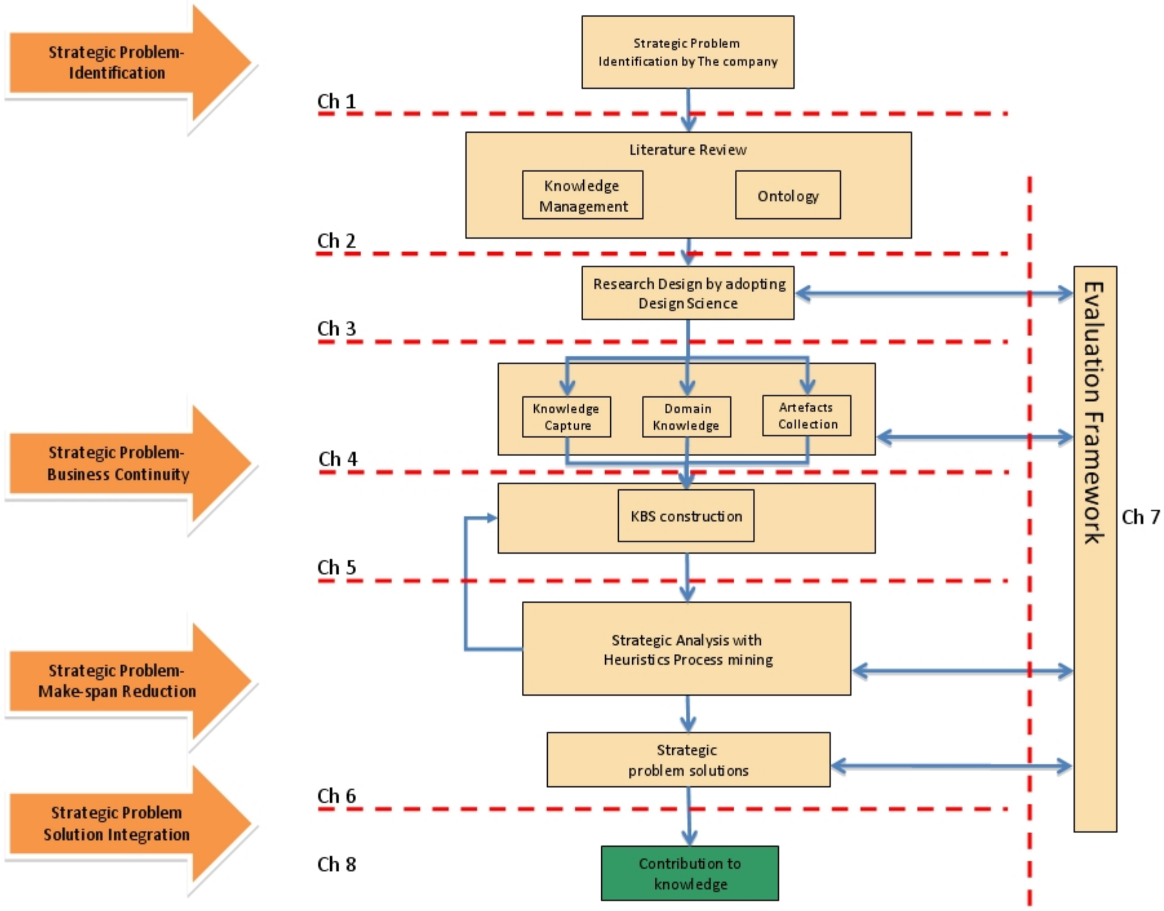
Confirming Consensus

- After multiple interviews it was confirmed that the engineers used their knowledge developed from previous products as an initiative to develop new products.
- Elements of tacit knowledge that had been generated during the engineers' work could be captured and re-used.
- A KBS which contained relevant captured tacit knowledge and explicit knowledge was confirmed as both possible and useful by the engineers.
- The knowledge-based system had features that the engineers agreed could help re-use their knowledge in their cabinet design/testing/build process.

- The engineers agreed they could not identify the differences in the consequences of their modification.
- The engineers agreed that use of the knowledge-based system was not difficult.
- The engineers agreed that the computer skill they had was adequate to implement the system.
- The engineers confirmed that previously, information and knowledge had not been shared between the engineers.
- The engineers confirmed that information from multiple locations could be effectively integrated into a KBS with other forms of knowledge.
- The engineers and the CEO confirmed that a knowledge management system could be used as an operational tool and also could be used as a strategic tool to improve business process.
- The engineers confirmed through agreement with the results that the outcomes of applications of the heuristic process mining technique could enable a researcher to model a complex business process.
- The engineers agreed that the KBS facilitated vertical and horizontal knowledge sharing in the engineering team.
- The engineers noted that one major effect of the research was that the collaboration process of their involvement in it enabled reduction of the make-span as they became aware of their own processes for the first time.
- The engineers noted that they became aware, as a result of the research, that they did not need to 'be perfect' and were satisfied with cabinets that were 'good enough'.
- The evaluation has shown that the knowledge gap in the Company was reduced as a result of the research. The impact of that reduction in the knowledge gap meant that the strategy gap also reduced.

These conclusions confirm previous research and have identified new knowledge. Both new and existing knowledge about knowledge management systems and their impact on strategy form the basis of discussion of the outcomes of the research in the next and final chapter.

Chapter 8 Discussion and Conclusion



8.1 Introduction

This research was a study of how knowledge management can be used strategically to resolve business problems. Initially an engineering knowledge management system was designed and implemented to assist the Company resolve an identified business continuity problem. In the second part of the research a specific analysis of knowledge stored in that system was used to resolve another identified strategic business problem: the need to reduce the Company's make-span for new products. The research showed that the introduction of a specifically designed knowledge management system into the Company studied not only enabled corporate knowledge to be stored and re-used but it also changed their perception about how they worked. Without specific direction, the engineers themselves adopted the process involved in the research and improved the way that they worked.

This chapter firstly discusses the relationships between knowledge management and business strategy and how this research has shown the importance of knowledge management tools to the resolution of business problems (8.2). This is following by a discussion of the contributions of the research to practice (8.3) and to theory (8.4). The outcomes of the research are summarized and discussed (8.5) All research is done within a context of limitations (8.6) and this context raises questions about future research possibilities (8.7). The chapter concludes with a discussion of the key findings and the significance of new knowledge contributed by the research (8.8).

8.2 Knowledge Management and Business Strategy

This research has shown that knowledge management can be used as a strategic tool in business. Knowledge management can strengthen an organization that is susceptible to external impacts such as new competitors or substitute products. Technologies such as production machinery or computers are available to all businesses (Drucker 1998; Porter 2008; Quintas 2001), but to be able to survive in the market an organization needs more than just technologies. Organizations require knowledge or intangible assets (Drucker 1998; Quintas 2001). Davenport and Prusak (1998) have suggested since the late nineties that knowledge is a key to business success. The organization first needs to know what they know (Davenport & Prusak 1998). In this research the Company had been competing in the refrigeration industry for more than two decades and collected significant amounts of data, information and knowledge. However, the Company had no knowledge management strategy in place. The research showed that knowledge in the Company was kept in a disorganized, almost chaotic form and that managerial knowledge and engineering knowledge was rarely shared. The Company realised that this was an important problem because they believed it was affecting their competitiveness and business continuity. They decided to do something about it and were interested in adopting knowledge management. Empirical researchers have all argued that to strengthen organizational competitive advantage, organizational knowledge needs to be captured, organized and managed and re-used (Martin 2008; Porter 1979; Quintas 2001; Quintas, Lefrere & Jones 1997; Zack 1999). The knowledge-based theory of the firm (Grant

1996; Grant & Baden-Fuller 2004; Nickerson, Jack A. & Zenger 2004) argues that having useable knowledge in an organization is the basis for sustainable competitive advantage. This research has shown that the application of knowledge management provided the basis for improving the competitiveness of the Company, initially through the maintenance of expert knowledge in the Company, and the ability to use captured knowledge for analysis to reduce their make-span problems.

In this research a knowledge-based system was created by using ontology as a knowledge representation structure. The knowledge-based system helped the engineers and managers in the Company capture both tacit and explicit organizational knowledge, and integrate all existing information and knowledge into one place. This facilitated the effectiveness of the engineers' design and testing process and increased their organizational performance as engineers, confirming previous research by (De Long, D, W. & Fahey, L 2000; Nonaka & Takeuchi 1995; Nonaka, von Krogh & Voelpel 2006). In the following discussion the major findings of the research are addressed.

The research shows that that the strategic use of knowledge management can be employed to improve business continuity. The Company had been collecting data and information in formats that it could not use. As a result that data and information was not managed, ever analysed or re-used. The tacit knowledge generated in the work practices of the engineers was also never captured. The researcher, in collaboration with the engineers, designed and built a knowledge management system, which was used as a tool to change the way the engineering team recorded data, information and knowledge in a re-usable form. The intention was to provide a system (artefact) to enable business continuity. The Company wanted a system that kept and organized all corporate knowledge in all of its forms, confirming the expectations of companies studied by other business researchers (Jay 2009; Martin 2008). The expertise was captured and stored in the knowledge-based system and remained in the Company.

The other benefit of retaining organizational knowledge within the organization was that it could be re-used. The research showed that this lead to organizational knowledge strengthening. This is because re-use of knowledge facilitated operational improvement in the Company. Once the organization's knowledge was strengthened, it enabled business continuity through improved competitiveness in product design, confirming a previously argued case by Martin (2008). In this research the knowledge-based system was used as a knowledge management tool to initiate day-to-day operational effective knowledge capture and re-use.

The evaluation of the knowledge-based system showed that the system captured, organized and stored the knowledge that the engineers needed to improve the design and testing process through re-use and accessibility to that knowledge. The knowledge-based system enabled the engineers to integrate various forms of related knowledge into usable formats. The evaluation of the various versions of the knowledge-based system showed that the work processes involved were made more efficient and the resultant time involved in designing and developing a new product significantly decreased over the three-year period of the research.

The research also shows that a targeted analysis of stored knowledge can be used for make-span reduction and improved competitiveness. The second part of the research analysed the collected and organized knowledge in the system to find possible shorter cabinet design/testing processes. The application of a Heuristic Process Mining technique enabled the Company executives and engineers to see what knowledge was hidden or overlooked in the cabinet design/testing process. The analysis verified an early observation of the researcher that the engineers had been doing their job intuitively. The analysis enabled the engineers to gain a real understanding of what was actually going on in the cabinet design/testing process. The HPM analysis showed that there were irrelevant tasks being performed throughout the design/testing process. Results from the HPM analysis also identified patterns in their work which helped the engineers make decisions to eliminate irrelevant tasks from the process. Once the irrelevant tasks were eliminated and only relevant tasks were left to be performed by the engineers, the make-span for new products decreased. Interestingly this emerged as an indirect effect of the researcher working with the engineers, iteratively showing them what they were doing and then questioning them as to what their own knowledge processes were showing. In their words, operational effectiveness had increased and enabled them to deliver new products to market in a shorter time.

This research has confirmed some key issues that Porter (1979, 1991, 1993 and 2008) has highlighted regarding where competitive advantage can be gained. Porter argues that competitive advantage can be gained by performing similar tasks differently, or faster and more effectively (Porter 1979, 1993, 2008). The HPM technique, applied to the stored knowledge in the knowledge-based system, resulted in real change by the engineers. They were being more effective and changing how they worked in ways that produced shorter time to market product development. The iterative cycle of design and re-use of domain knowledge is also another method of organizational learning which is a powerful way of developing innovative thinking in an organization. Learning from previous design concepts and physical components (knowledge utilization) helped the engineers in the Company to produce products quicker and therefore more cost effectively. This led to this Company taking a shorter time to get new products to market, confirming previous research (Cross, M & Sivaloganathan 2007; Prasnikar & Skerlj 2006; Rao, Y et al. 2007; Wiig 1997).

Again, the knowledge-based theory of the firm concept can be applied. The theory argues that integration of employees' knowledge in the organization through their coordination improves outcomes (Grant 1996, Nickerson & Zenger 2004). The theory focuses on the employees as the actor in knowledge creation and the principal of repository of knowledge. The knowledge then can be managed and shared. There was a significant amount of organizational knowledge created by the engineering team working together in the Company. However, they had not effectively captured their knowledge. The missing element was a system that can act as an organizational knowledge repository. The knowledge-based system as an outcome of this research filled that gap. It integrated employees' knowledge and improved its coordination. The Company applied this knowledge to improve outcomes in terms of design and testing processes to achieve their business goals.

In summary, the research demonstrates that knowledge management, strategically focused, can be successful because the research shows that by developing a heuristic process and applying an algorithm allowed this to occur. This development adds to our knowledge about better means of applying knowledge management as a strategy in business and organisation. Empirical research has listed the problems causing failure of knowledge management implementation. There are three common problems. First, there are large amounts of knowledge that need to be captured and stored and this is often incomplete. Second, tacit knowledge is difficult to capture and store. Finally, domain knowledge is difficult to communicate. These three problems make the size of knowledge management system too big (Alavi & Leidner 1999, 2001; Shadbolt & Milton 1999; Shadbolt, O'Hara & Crow 1999). Capturing knowledge across departments in an organization can fill up a knowledge-based system with irrelevant knowledge because different departments cannot understand each other's technical jargon and doing so will consume vast amounts of time. This research has shown that implementing a knowledge management system can be successful if the system aims to capture only relevant knowledge, focused to address strategic issues in an organization. The system in this research was built only to capture the Company product development process knowledge. There were only six engineers and the CEO and COO as the users. Therefore, capturing the relevant knowledge, both explicit and tacit, did not consume large amounts of time as the users were familiar with all of the technical terms and only relevant knowledge that related to product development process was captured. Storing the captured knowledge in this research was also not a problem because the knowledge engineer (the researcher himself) is a practicing mechanical engineer and was familiar with the technical terminologies and communication of expert knowledge in the domain.

A key lesson from this research is that knowledge management needs to be strategically focused to be effective and that effectiveness can be significantly improved with a detailed understanding by the researcher of the domain knowledge being used. This research also showed that when knowledge management is strategically focused it could make its use cost effective. In this study the elimination of tasks through the application of the heuristics meant that redundant task no longer added to the costs of the design/build/test process. This application of heuristics was enabled only because the captured knowledge classified and stored in the knowledge-based system was that ultimate use of that knowledge, both tacit and explicit.

In Design Science research, one of the “ideal” characteristics that research needs is a researcher who is an expert in the field of study (Baskerville & Wood-Harper 1996). This is important in all kinds of research. If the researcher understands the research context it should potentially reach a better result overall. The importance of the researcher having domain knowledge is evident in previous knowledge capture and re-use research (Bailey 2010; Heisig et al. 2010; Perry et al. 2007). This is because the researcher has to be able to identify what knowledge needs to be captured. During the capture process in this research, the expert domain knowledge of the researcher enabled the researcher to capture the knowledge that being used, both efficiently and effectively. To build an ontology requires codifying knowledge and this requires domain knowledge. This is because knowledge has to be codified using the right terminology and be understandable by users. The other important element during the knowledge codification process is that knowledge needs to be codified to reflect how it will be re-used (Kanjanabootra, Corbitt & Nicholls 2010; Perry et al. 2007; Sharif & Kayis 2007; Torres et al. 2010). In this research, the researcher is a practicing mechanical engineer who is a specialist in refrigeration, which matched the research problems. The researcher understood the nature of the cabinet testing process and understood the specific terminologies used in the process. Therefore, it enabled the knowledge to be classified appropriately and then the system built with the features required by users. The researcher had also worked together with the engineers in the Company over a long period of time. This allowed both researcher and the engineers to have time to reflect what had been done.

This research has shown that knowledge management implementation does not have to be expensive and that adopting knowledge management and implementing a knowledge management system can be done in a cost effective way. This is in contradiction to some empirical studies that have mentioned that implementing knowledge management comes at a high cost. For example, (Alavi & Leidner 1999) have mentioned that the cost of implementing knowledge management system depends of various factors. These include the organizational

IT infrastructure such as hardware and software, specific software such as groupware. The knowledge engineer needs, they argue, to spend time utilising the built software to suit the nature of the client organization. Often, it is the case that the software is not flexible enough to suit the client. This can result in difficulties for the users and it has subsequently not been used. Furthermore, these previous research has shown that package software costs increase because it is not compatible with the existing software used in the organization. It is often users who have to acquire new software knowledge just to be ale to implement a knowledge management system (Alavi & Leidner 1999). This research has shown that implementing a knowledge management system can be done in a cost effective manner[4]. In this research an open source ontology editor call "Protégé" was used. Protégé is highly flexible and knowledge engineers can design their knowledge-based systems by using ontology in any way that suits their client's requirements. The ontology developed allowed the structure of the knowledge-based system to communicate with any other software. This means that there is no issue about software compatibility. Protégé does not require complex IT infrastructure. This knowledge-based system development and implementation produced a system that represented what the Company wanted, and how the engineers involved actually worked. This research strategically focused on a key area in the Company and by using a collaborative process of build and evaluation, the researcher was able to show the relevance and use of the system to the engineers, making it possible for them to use. This technique also allowed the research to integrate the systems into the organization's existing IT systems so that implementation was gradual rather then immediate. The end result was a cost effective system that worked.

This research has shown that knowledge management applied strategically in organizations, using collaboration and supported by researcher domain expertise, can be effective in terms of time and cost and can help those organizations address and resolve strategic problems. These results confirm and more importantly extend much of the existing research. This is summarised in Table 8.2 later in this chapter. The elements of Design Science method ensured that the

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o [4] The researcher notes that his services were provided at no cost to the Company!

outcomes of building the artefacts in this research were effective i.e., improved performance, and improved business strategy. These contributions are discussed in detail in the next section.

8.3 Contributions of the research to knowledge

In Design Science there is an overarching need to produce an effective artefact that improves business outcomes. In doing this and by the application of rigorous research methodologies, the research can be shown to make significant contributions across a number of areas.

8.3.1 Ontology and Business

This research has confirmed the research of Milton et al (2010), who argued that ontology can be effectively applied to business problem solution development and that an ontology has more benefit than just data logging. The research has shown that ontology can be used as a tool to increase the effectiveness of tacit knowledge capture and its integration with other existing sources of knowledge. Ontology has four important characteristics which can carry out the meaning of the real world (Gruber 1993; Studer, Benjamins & Fensel 1998; Wang & Li 2010). These characteristics include, first, generalisation which can describe natural world phenomena; secondly, ontology is explicit and has explicit definition and explanation to describe concepts and their relations; thirdly, ontology is used to explain domain knowledge with specific terminology, therefore, it can be shared and understood by people in the same domain; and lastly, ontology is used to describe the real world in specific domains, which means that in some domains people refer to different things by using the same terminology. This powerful expression can be used to explain the concepts and the relationship within and between both tacit and explicit knowledge.

Applying these characteristics of ontology in this research has given practical application to the mostly theoretical argument of Milton et al (2010), that ontology could be a useful tool for business development. In this research one key element that affected business strategy and performance was related to capturing domain knowledge from the engineers. The Company had indicated that this was crucial to their business continuity. The engineers' domain (tacit) knowledge was captured in interviews, meetings, observations, shadowing episodes and from an artefacts study. That tacit knowledge often related to the engineer's tasks (actions) to problem scenarios, physical cabinet parts making, cabinet modification tasks and to the engineers themselves. Each component of their captured domain knowledge was created as a concept by using an ontology structure and the relationships between the concepts to make sense out of the phenomena description using methodology following (Barb, Chi-Ren & Sethi 2005; Gruber 1993). Using the ontology was a means to classify the knowledge in ways that the engineers could use it. It provided a structure for knowledge they used, but previously had only shared orally.

Ontology allowed the researcher (knowledge engineer) to create tacit knowledge concepts and create relationships from these concepts to other objects. This was then stored and expanded continually improving the usability of tacit knowledge and its re-use by the engineers in the Company. Problem scenarios were used to link the ontology and physical objects created to the name of the engineer involved, making referencing of knowledge easier to create and search following methods used by (Ioana 2002; Studer, Benjamins & Fensel 1998; Sun & Chen 2008). This domain knowledge was stored in the system and became available for re-use through knowledge browsing or knowledge query. This captured tacit knowledge became available in the Company for organizational knowledge sharing and transfer in ways suggested by (Ayazi & Shams 2008; Barb, Chi-Ren & Sethi 2005; Can & Zhanhong 2008; Fu et al. 2007; Gruber 1995; Hiekata, Yamato & Tsujimoto 2010; Yuh-Jen, Yuh-Min & Meng-Sheng 2010). The ontology created in this research also provided a structure for the Company engineers to deposit knowledge, either held tacitly, or created through their work and reported to each other in daily meetings. The ontology became part of the Company and was used by the engineers thus facilitating business process improvement along the lines suggested by Milton et al (2010).

8.3.2 Knowledge and business strategy

Previous empirical research has shown that tacit knowledge is often embedded in expert's action and is difficult to capture. Experts often perform their tasks intuitively. Sometime tacit knowledge cannot be separated from the owner (Cordeiro-Nilsson & Hawamdeh 2010; Ichijo & Kohlbacher 2008; Nicholls & Cargill 2006; Nicholls & Eady 2008; Polanyi 1966; Reinders 2010). Therefore, to capture and store in the system is seen as problematic. Two elements of this are significant. Firstly tacit knowledge is just difficult to extract; and secondly identifying tacit knowledge with its owner is often difficult, as some users/holders do not want to disclose this knowledge. This research has overcome the first problem by the use of multiple research data capture methods and cross referencing the captured knowledge. Whilst capture can never be complete, the levels of knowledge capture, classified and stored using the ontology in this research met the needs of the users - the engineers. With regards to the second issue, the researcher dealt with this problem by capturing tacit knowledge and attaching each element to the physical objects involved with its owner, making sense of the reality that exists in the Company. The knowledge-based system developed using the ontology in this research has a feature that when the users capture their tacit knowledge and store it into the system, they can record "knowledge contributor" as one of the instances at the time. This feature helps new employees identify who they should be talking to if they want further information about particular knowledge or a particular issue. This can make the tacit knowledge reachable and useable, supporting the arguments by (Alavi & Leidner 2001; Glazer 1998; Schwartz 2006) that access to and useability of tacit knowledge is an essential component of the effectiveness of knowledge management. In this research the effectiveness of using the ontology to classify the captured tacit knowledge of the engineers was highlighted by the evaluation of the use of the knowledge-based system by the engineers themselves. The system met their needs and improved their work processes. Information and knowledge could be found faster and more completely, resulting ultimately in a reduction in the make-span for their new products. Using the ontology has been shown in this research to be an effective tool to resolve strategic problems in this Company: loss of knowledge affecting business continuity, reducing the make-span of new products, getting new products to market and improving competitiveness. The use of the ontology in collaboration with the engineers through action research *per se* also helped reduce the make-span. This process result is important as awareness rising in this form appears to influence the outcomes and achieve results accidentally. This research showed that the identified problems of knowledge capture can be addressed. The results of the research against the limitations noted in existing research are summarised in Table 8.2.

Table 8.1 Addressing Knowledge Capture Issues

Known knowledge capture issues	**Approach adopted to overcome KC issues**
1) Knowledge capture often fails because it consumes huge amounts of time to implement and is not incorporated in the business process.	In this case, the researchers acted with the agreement of the management and the team of engineers collectively to collect their knowledge. The researchers acted as intermediaries, identifying instances of knowledge and capturing it. Knowledge was built into a KMS and returned to the engineers through an action research process. Their time was focused only on their normal work practices and not on entering knowledge into data bases. Undertaking this process over a period of a year, on one product after another, ensured that the usual time needed by employees for a knowledge capture process was substantially reduced. The extended process meant the researchers had time to observe, capture and check in a series of cycles of reflection and action.
2) It is often the case that unuseable knowledge is captured.	All knowledge captured was eventually identified as useable by the engineers as it was captured from their work processes and reviewed by them. The domain expertise of one of the researchers meant that attention was paid to specific domain knowledge.
3) Knowledge has not been horizontally transferred among the employees, but not vertically transferred through generations of employees.	The engineering team had worked together for a considerable period of time and worked everyday in a team. This meant that knowledge had been shared. However, the application of their revealed knowledge was often necessarily individual. This aspect was collected by the researchers and added into the KMS.
4) Tacit knowledge itself is difficult to transform or codify during the	Using an ontological approach enabled the codification of the tacit knowledge built on the engineering design process to be an integrated

knowledge storing process.	system. This enabled the knowledge to be grouped and codified based on the logic plus the specific domain knowledge in the research group. The advantage of this study lay in its focus on one knowledge domain, rather than the broad scope of most previous research (which encompassed whole organizations).
5) Problems with the useability of captured knowledge.	Captured knowledge has been treated as static in many previous instances. Its purpose was not clear. In this case study, the knowledge was collected continuously over a period of many months, and the KMS where it was codified and stored was iteratively reviewed by the engineers involved. Its useability for them was continuous. An evaluation of the system by the engineers and management showed it met their needs. In a further extension of this study, the knowledge stored in the KMS has been mined and analysed to enable reductions in the design processes.
6) Problems with implementation and use of systems that store captured knowledge.	The continuous application of the KMS to the organization was evident over the period of the study as the development and implementation process was iterative rather than delivered on a time line as a completed product.
7) The issue of knowledge capture and organizational culture preventing completeness.	In this case study, the engineers involved were part of the process supported by the management of the Company.

Previous researchers have demonstrated that tacit knowledge has more impact on business competitive advantage than explicit knowledge (Ichijo & Kohlbacher 2008; Nicholls & Cargill 2006; Nonaka, I. & von Krogh 2009; Polanyi 1966; Yuh-Jen, Yuh-Min & Meng-Sheng 2010). Most organizations rely on their employees' tacit knowledge (Barb, Chi-Ren & Sethi 2005; Erden, von Krogh & Nonaka 2008; Mulder & Whiteley 2007; Reinders 2010; Ribeiro & Collins 2007; Smedlund 2008). However, these same researchers also have reported that because of its specific characteristics, tacit knowledge is difficult to capture and store. One of the important characteristics is "tacit stickiness" which refers to the knowledge that is embedded in the knower's actions (Murray & Hanlon 2010; Polanyi 1966; Szulanski 1996). As tacit knowledge is embedded in all of the actions, therefore it is difficult to see when it is/was used. As a result, knowledge engineers cannot easily identify what to capture. This research has shown that by adopting multiple techniques during the knowledge capture process and cross-referencing them, an increase the effectiveness of the tacit knowledge capture process results. The researcher's expert knowledge also facilitated the tacit knowledge codification process. The system was designed to capture the knowledge that the engineers used during the product development process, and adopted a Design Science methodology, with the engineers being involved throughout the process. Therefore, the system structure of the system and terminology used in the system were determined by the engineers.

The research demonstrated that a prior study of existing artefacts could also facilitate the knowledge capture process. This research has shown that when the Company's artefacts were studied this assisted the effectiveness of the knowledge capture process. The researcher found that there were significant amounts of information and knowledge embedded in the Company's artefacts. Investigating these artefacts beforehand helped the researcher to identify what knowledge needed to be captured. The way to structure the ontology and knowledge-based system also derived from the engineers' common practice found in these artefacts. The artefacts mentioned included the Company's product catalogues of all types of products that the Company manufactured. The artefacts also included basic information such as product codes which helped the researcher to understand what kind of cabinet the engineers referred to during the knowledge capture process. The hard copy testing reports contained data and information about each cabinet that had been tested and rated. These artefacts contained useful information linked to the expert knowledge of the engineers. The data, information and knowledge found in the artefacts helped guide the researcher to ask relevant questions and in his observations for relevant knowledge, which was then used to shape the structure of the ontology and capture the knowledge to store into the knowledge-based system.

Previous research focused on point-in-time knowledge capture rather than a continuous process of capture. The process in this research was organic, iterative and targeted the places where tacit knowledge emerged and/or was used, thus enabling through the ontology in the knowledge-based system, constant replication and refreshing as new knowledge emerged. In this way, the problem of capturing unuseable knowledge was also eliminated as the knowledge emerges from practice rather than artificially from knowledge capture web sites or tools. The research has also shown that knowledge is passed across these experts and up and down the vertical lines of reporting in the Company as that knowledge is embedded in what they do, rather than just captured in a separate process.

The knowledge-based engineering management system that emerged in this research represented the complexities of real work and the actual processes the engineers used, yet maintained a simplicity in the classification and re-organisation of significant amounts of information and knowledge through use of ontology. The test of the system's application came with a detailed evaluation by the engineers for whom the knowledge system was designed. The evaluation showed it met their expectations and enabled them to add new knowledge to the system as they continued their knowledge creation processes in meetings, laboratory experimentation and in prototyping.

This research has extended the argument of Frost et al (2010) that there are difficulties with the use of multiple qualitative methods in research because of the differential ideologies that might be involved. Using a singular epistemology, the researcher has been able to capture, classify and interpret all forms of knowledge in the Company in a way that has produced a significant useful artefact for the Company to use. The multiple methods enabled the researcher to represent the complexity needed for real work use and made the system more useful because of its completeness. Multiple qualitative methodologies can be used productively to reproduce existing systems in meaningful ways and create representational generalisations about the applicability of such outcomes to other domain based knowledge-based systems. The context and domain knowledge may be different, but the process used to capture, classify and utilise the knowledge in this research has real application across many domains.

The other issue that relates to the effectiveness of knowledge capture process is the relevance of the knowledge. Organizations often have problems with identifying content, location and the use of the knowledge (Bailey 2010; Ioana 2002). To design a good knowledge repository the system has to contain usable knowledge. The system should contain relevant knowledge. In this research only knowledge about the cabinet testing process was captured and stored in the system. Therefore, irrelevant knowledge was not captured and stored. The collaborative design and development of the system in this research with the researcher, the engineers, the CEO and COO determined what was relevant or irrelevant. They reviewed and commented on what had been captured and stored in the system. Only the relevant knowledge, which was checked by the engineers, CEO and COO, was kept. One reason for the thoroughness of the extent of the captured knowledge resulted from the domain expertise of the researcher. Because of that domain knowledge the researcher was able to make early judgements about relevance. Again this was checked later with the engineers. Previous researchers, noted above, have highlighted the time spent on determination of relevance, mostly because external consultants or others with no domain knowledge are involved.

This research has shown that using multiple techniques during knowledge capture, having a knowledge engineer/researcher with domain knowledge and having high participation by the users during the system development process can overcome empirical tacit knowledge capture problems.

8.3.3 Enabling Knowledge

This research has shown that a knowledge management system can be used as an organizational knowledge enabler. The knowledge-based system developed in this research has various features. The system allowed the engineers to trace their actions and the resultant outcome during their cabinet design and testing process. The knowledge-based system allowed the engineers to trace and search modification tasks and see the consequences of those actions. Furthermore, the knowledge-based system also allowed further analysis. The application of Heuristic Process Mining demonstrated to the engineers that if they captured their own process and knowledge systematically through the knowledge-based system they could make more use out of what they know. The system was also used as a knowledge-sharing tool. The research showed also that such features which can help the engineers gain access to what they have never had before can stimulate more knowledge sharing in the team re-iterating previous findings in other settings by (Alavi & Leidner 2001; Lilleoere & Hansen 2011). Additionally, the research has shown that a knowledge-based system is one means of encouraging and facilitating knowledge sharing among the engineers. This leads, in their evaluation, to innovative thinking development which was vital in shortening the product development process in the Company, matching the lessons reported by (Lilleoere & Hansen 2011)

Collaborative working between participants and researcher can, this study has shown, iteratively increase the efficiency of the knowledge management system. This collaboration helped the researcher to refine the scope and requirement of the system build in the way previously noted by (Baskerville, Pries-Heje & Venable 2009). This research has shown that a good understanding of the interest problem led to effective and relevant solutions, one of the expectations of Design Science research (Iivari & Venable 2009). During the artefact building process in this research the collaborative work between researcher and the participants has significantly refined the quality of the artefact. The structure of knowledge-based system was constantly refined and tested. The result was a knowledge-based system structure that the users were familiar with and which contained only relevant knowledge in the system. The engineers indicated in the evaluation that they had some ownership of the system and that's why they used it. Using ontology and Protégé software to structure the knowledge-based system allowed the researcher to integrate data and information from various locations in the Company. This facilitated effective knowledge re-use by the engineers. This research has shown that the integration of data, information and knowledge from various locations increased the effectiveness of knowledge re-use. After the evaluation process, the engineers confirmed that the knowledge-based system with integrated data, information and knowledge was very useful and helped them save time to record tasks and capture their knowledge.

This research has shown that past failures of knowledge management system implementation, in which users did not use the system, can be overcome.

Researchers have identified that one of the reasons for knowledge management implementation failure is because the system built does not help users, but it creates more work for them (Alavi & Leidner 1999; Davenport, De Long & Beers 1998; Storey & Barnett 2000). This research has shown that the participants being part of the system development process can encourage the users to see the benefits of the system. Furthermore, in this research the input from the engineers shaped the system to come out in a way that they were familiar with, and contained what they needed and this helped them work faster. This led to successful system implementation. The system built had features that helped the engineers gain access to data, information and knowledge that they had never had before. The engineers could more easily re-use their knowledge. The problem of past failure shown in previous research can be resolved through collaboration of the knowledge engineer and the users and by contextualising the system to their needs.

The second part of this research applied a Heuristic Process Mining technique to the captured knowledge stored in the knowledge-based system. This research has bridged a research gap by applying Heuristic Process Mining to a dynamic manufacturing process that has been captured and stored in a knowledge-based system. Previous research using both a knowledge-based system and HPM by Kim et al (2009) related to fixed formal processes with no change. The process was predictable. Many business processes are static because the process contains a number of tasks which can be done when some other tasks have been executed. For example, in a products purchasing process log, the product cannot be shipped before the order has been placed. Therefore, the nature of the process is less complex than the dynamic process. The cabinet testing process is both dynamic and non-deterministic. This means the tasks that have been performed in the process can happen at any stage of the process and there is no ordering restriction between tasks. This means that anything can happen during the process. This is similar to aluminium smelting and the glass making process (Nicholls & Cargill 2006). The HPM was applied to find relationships between tasks based on their ordering. The result was a set of best possible solutions which can each result in reduction of the design, build, test process for each new product. Using the same method of applying HMP to processes captured using ontology Kim et al. (2009), this research demonstrated that better solutions were also possible in their predictive environment. The research has extended that work to show better solutions can be derived in more dynamic and complex situations. This research has shown that the ontology can be used to structure knowledge-based system for further analysis and HMP can be applied to the dynamic process. This solution was possible because the researcher accepted that ontology allows the user to break the domain of interest down into small elements so that their relationships facilitate flexible knowledge re-use.

Ontology allowed the researcher to model the large number of elements together by breaking down each element into smaller segments (Chau 2007; Staab, Steffen et al. 2009) and to classify them into categories through heuristic classification (Fensel 2001; Studer, Benjamins & Fensel 1998; Uschold & Gruninger 1996). Through the ontology, the researcher structured details of the domain to contain information about components as it had in reality (Milton, S, Keen & Kurnia 2010). Breaking the engineering knowledge elements down into small units gave flexibility for improved knowledge capture and better re-use. The engineers then made use of the system developed to make queries, search for knowledge and information and as a result improved their work processes. As argued by (Conesa, Storey & Sugumaran 2010) the ontology not only allowed complexity to be understood, but resulted with fine-grained answers to queries. The other advantage from the structure used in this research was that when the engineers wanted to make a change to some part of the system they didn't have to change every part. Therefore, it allowed the researcher to model the structure the way the engineers wanted supporting arguments by (Catalano et al. 2008; Conesa, Storey & Sugumaran 2010; Gruninger & Fox 1995; Solskinnsbakk & Gulla 2010) that this flexibility and modelling according to user needs ultimately leads to effective use and acceptance of the system, which evaluation showed was the case in this research.

8.3.4 Unexpected outcome from a knowledge system

Finally, the research showed that there could be unexpected positive outcomes from using a Design Science research method**.** In first part of the research, during the knowledge capture process, the researcher had been to the factory many times over a long period of time. During that time the researcher constructed the structure of the knowledge-based system as a collaboration between researcher and the engineers, and the CEO and COO. In the second part of the research, where the HPM was applied to the knowledge stored in the knowledge-based system, the engineers were also a part of the research process. The researcher had been working together with the engineers and had demonstrated that the system developed would be useful to them. The researcher believes that he had created a trust between himself and the engineers. This increased their willingness to participate in the research and their willingness to share their knowledge. This on-going process created a knowledge management awareness (Hevner et al. 2004; Wittmann 1995) in the engineers in the Company. As a result of this collaboration and awareness, towards the end of the research period, the engineers reported that the design and testing process times of some cabinets had been shortened. The research has achieved one of its aims indirectly, which was to reduce the cabinet design/build/testing time which lead to reducing product make-span.

8.4. Contribution to Theory and Method

Gregor (2002) argues that theory is important in Design Science as it emerges from the study. In this research, theory that was developed related to theory for design and action. Gregor (2002) and Hevner et al (2004) state that design theory relates to the principles for the development of an artefact built to meet certain requirements. In this study, the design theory related to establishing principles for a knowledge-based system. These principles emerged from both an ontology built on expert knowledge of the researcher and the needs of the engineers in the team, and from the strategic business requirements of the Company. The design principles were both functional and strategic. These principles were derived in part from existing theory in the literatures of knowledge creation theory (Nonaka, 1995), the knowledge-based theory of the firm (Grant 1996) and strategic management (Porter 1985, 1991) supporting Gregor's statement that design theory is informed by, and can inform, theory for explaining and predicting and was used to develop an understanding of what the research showed when the artefact was developed and then tested.

Strategic management, in all of its variations, is concerned with enablers for business to develop competitive advantage (Barney, 1991, 1993, 2001a, 2001b; Burden and Proctor, 2000; Cousins, 2005; Fahy, 2000; Fahy, Farrelly and Quester, 2004; Flint and Van Fleet, 2005; King, 2007; Liao and Hu, 2007; Lin, 2003; Ma, 1999a, 1999b, 2000, 2004; Peteraf, 1993; Porter, 1985, 1991; Porter and Kramer, 2006). Porter (1981, 1985, 1991, 1993); and others argued that the external positioning of a firm is the critical factor for achieving and sustaining competitive advantage. A resources-based view of strategic management argues that competitive advantage for a firm derives from their internal resources (Barney, 1991, 2001a, 2001b; Fahy, 2000; Mills, Platts and Bourne, 2003; Peteraf and Bergen, 2003). The knowledge-based theory of the firm extends this resources-based view and proposes that knowledge is the most important of those resources (Gupta and McDaniel, 2002; Lin, 2003 Goh, 2005, Grant, 1996, Nickerson, 2004).

In this research the Company executives saw knowledge as a critical and strategic resource. The solution they accepted to their problem was to manage that knowledge in an effective way. They were concerned that the expertise and knowledge resident in the engineers was not lost. The knowledge-based system, built collaboratively with the executives and the engineers, met those needs. The knowledge was captured effectively, was able to be used efficiently and assured the executives of the value and use of this key resource. The researcher was able to extend the utility of that knowledge showing how it could be used to address another strategic problem affecting the competitiveness of the Company, its make-span. The research on the one hand shows the resource value of knowledge strategically to the Company, and on the other extends that value by showing how it can enable solutions to be found to other problems. This, it can be argued, increases the value of knowledge as a resource for the Company. This conclusion supports a view that knowledge is a key element in the development and implementation of strategy and strengthens the theoretical bases of the various strategic management theories. Knowledge increases the know-how of the organization and enables a better basis for making decisions because knowledge provides real expertise, unlike data and information which are of little use without that knowledge and its re-use. Like Ma (1999a, 199b, 2000) this outcome of the research would suggest that a broader, integrated view of strategic management is necessary to not only achieve business success but also to enable the business value of knowledge management to be realized.

Markus (2001) argues for a theory of knowledge reusability. What this research has shown is knowledge capture and reuse was needed to drive the strategy in the Company and that this was directly related to the shared way knowledge was created and then re-used by the engineers. Without the adoption of knowledge management in this company enabling knowledge reusability, the desired strategy would not have been able to be reached. Knowledge re-use theory also proposes that the organization's knowledge repository should be able to facilitate multiple purpose use and re-use. The effectiveness of the KMS built for the Company confirms this. Together then both elements of the outcomes of this research support Markus' arguments for a theory of knowledge reusability, albeit that the research shows that the situations of reusability with vary by organization.

This research showed that a knowledge-based system can help an organization decrease both the knowledge gap and the strategy gap (Fig 8.1).

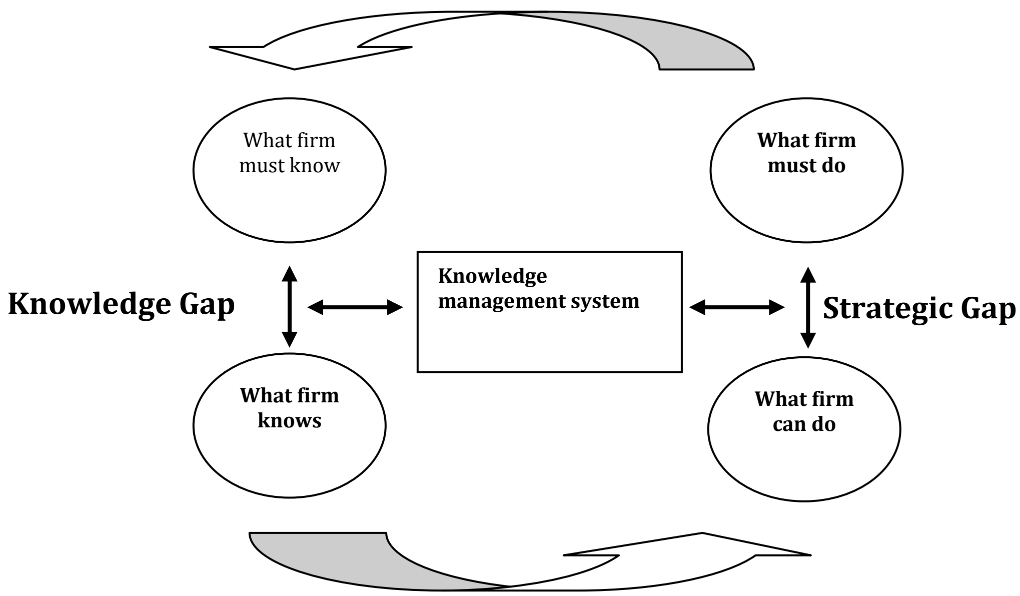

Figure 8.1 Research Framework

The captured knowledge stored in the knowledge-based system enabled the engineers to re-use their knowledge during their operation. This re-use helped the engineers acknowledge what they must know. Because the knowledge-based system built was dynamic and designed for the engineers to enter more knowledge into the system, the expansion of the system meant that the knowledge gap decreased. They knew more and could use their knowledge better. On the strategy gap side, the application of the Heuristic Process Mining and its' result showed that the existing operations can be improved through using the stored and classified knowledge. The participation of the engineers through the HPM analysis also helped the organization to realize that their cabinet testing process can be improved. Once the Company knew what they had to do with their product testing process the strategic gap was decreased. The research supports the representations in the model proposed in Chapter 2 and offers future researchers a framework to assess the impact of the introduction of knowledge-based systems as an action in a knowledge management strategy to improve strategic performance of that organization.

8.5 Summary of Research Outcomes

Table 8.3 below summarises the key outcomes of this research and compares those outcomes with previous research where applicable.

Table 8.2 A comparison of research outcomes with previous research

Literature	**Key conclusions**
Knowledge and business outcomes	
1. Today business is knowledge-based. KM is a useful strategic tool for business (Davenport & Prusak 1998; Porter 1979; Quintas, Lefrere & Jones 1997; Zack 1999).	1. This research has *confirmed* that knowledge management can be used to solve strategic business problems. In this research relevant knowledge was captured and stored in a knowledge-based system to resolve an identified business continuity problem. Then the captured knowledge was analysed to identify and eliminate irrelevant tasks in the make-span process to produce models to reduce the Company make-span.
2. Organizational knowledge is important for business continuity (Cross, R et al. 2001; Martin 2008; Ponn J., Deubzer F. & U. 2006; Studer, Benjamins & Fensel 1998; Webber 1993).	2. The research *confirmed* this importance. The Company's specific organizational knowledge about the cabinet design/build/testing process was captured and stored in the knowledge-based system. This was shown to be important as it enabled the engineers to re-use their knowledge and make their work more efficient. In the case of existing staff leaving the Company, the stored knowledge in the knowledge-based system enabled the Company to carry on business.
3. Well-managed knowledge in organizational employees can result in improved production processes (Barson et al. 2000; Bots & de Bruijn 2002; Cross, M & Sivaloganathan 2007; Falk 2005; Ioana 2002; Kamara, Anumba & Carrillo 2002; Kannan, Aulbur & Haas 2005; Milton, Keen & Kurnia 2010; Porter 1979, 1993; Prasnikar & Skerlj 2006; Quintas 2001; Rao, M 2005; Webber 1993; Wiig 1997; Zack 1999).	3. In this research the employee's knowledge related to cabinet testing process was captured and stored in the knowledge-based system. The knowledge became better managed as it was now available to all relevant employees, the engineers, the CEO and COO. In the past their knowledge had not been systematically managed. This *confirmed* the potential for improvement in the production process.
4. Knowledge is an important source of	4. Captured knowledge both tacit and explicit can be used for improving

competitive advantage. Therefore, capturing this knowledge is vital (De Long & Fahey 2000; Nonaka, I. & Takeuchi 1995; Quintas 2001; Quintas, Lefrere & Jones 1997; Van den Hooff & Huysman 2009; Wu, Senoo & Magnier-Watanabe 2010).	
5 Strategic management theory (Porter, M 2008) argues that there are five forces which shape business strategy. These include, threat of new entrants, bargaining power of suppliers, bargaining power of buyers, threat of substitute products or service and competitive rivalry within an industry.	5. The research has shown that KM is very important in dealing with company positioning and strategy. It also can be one of the business strategic tools that facilitate the organization to be less susceptible to external impacts. Knowledge can shape business strategy and improve competitiveness. This research has *suggested* that strategic management theory should be extended to cover 'knowledge management' as another one of domains of interest and as a key component of both adding value and as one means of ensuring competitive advantage.
Knowledge issues	
6. Organizations have problem with identifying the contents, location and the use of knowledge (Ioana 2002).	6. In this research the involvement of the researcher and a small group of the engineers has overcome the problems of identifying contents, location and use of knowledge. This is because the engineers were the group of people who would use the system. Therefore, they knew what was needed to be captured and stored and re-used. They knew where to find what they needed but it was in a form that was almost un-useable as it had never been classified and structured. Capturing only a specified area of knowledge helped both the researcher and the engineers not to capture irrelevant knowledge. This made the location of all relevant knowledge clear to all users in the Company. Knowing that made it useable. This research has *added* a new dimension to organizational knowledge capture in that the research

	process designed captures only what is necessary and does not try to capture every piece of knowledge in an organization.
7. Users require an integrated system that allows them to access organizational knowledge from various sources (Alavi & Leidner 1999).	7. The system created in this research was designed to capture both tacit and explicit knowledge in the cabinet build and testing process in the Company. It also integrated explicit knowledge from various formats and locations within the Company together into one place. The system created in this research allowed the engineers to have access to integrated organizational knowledge. In this research a new perspective was *added* on how various sources of organizational knowledge can be integrated into one place and be enabled for reuse. This is because the nature of the ontology allows that to happen.
8. Shadbolt and Milton (1999) mentioned that there are three main problems regarding implementation of knowledge management in organizations: • there are large amounts of knowledge to capture and store, • tacit knowledge is difficult to capture and store, and • domain knowledge is complex and difficult to communicate (Shadbolt & Milton 1999; Shadbolt, O'Hara & Crow 1999).	8. This research has addressed and overcome the problems with KM implementation mentioned by Shadbolt and Milton (1999). • This research captured only relevant knowledge related to the cabinet design/build/testing process, not the whole organization. Focusing in this way made the KM process strategic. • Ontology allowed the researcher to integrate, capture and store both tacit and explicit knowledge into the knowledge-based system. • The engineers collaboratively determined the structure of the knowledge-based system in an iterative manner. Therefore, the difficulty with system communication was overcome. The research *confirmed* previous research but also showed that knowledge management implementation problems can be *overcome* through more targeted implementation of knowledge management systems.
9. Expertise often embedded in tacit knowledge is difficult to transfer. To identify the knower is one of the best ways to make tacit knowledge reachable. (Alavi & Leidner 2001;	9. In this research the knowers were in a small team of engineers. It was their knowledge that the Company wanted and had identified. The knowers were used by the researcher to classify the knowledge in an ontology. The researcher attached the captured tacit knowledge with various objects. One of them was to its knower. This attachment was created in a

Ioana 2002; Schwartz 2006).	
10. Capturing tacit knowledge is difficult and often fails. (Dalkir 2005; Luthans, Rosenkrantz & Hennessey 1985; Matsumoto et al. 2005; Shadbolt & Milton 1999; Staab, S. et al. 2001).	10. In this research multiple techniques were used to collect tacit knowledge. These included a detailed study of existing artefacts, interviews, meetings, observation and shadowing. This research has confirmed that using multiple techniques can improve the effectiveness and degree of completeness of the knowledge capture process. The collection of data using multiple techniques, used in this research, showed that tacit knowledge capture can be improved and that the degree of tacit knowledge capture can be increased. This *challenges* previous empirical studies and adds a significant contribution to our understanding of tacit knowledge capture effectiveness. This is very important as so many businesses operate as knowledge organisations based on their knowledge workers. These professionals (engineers, doctors, lawyers, social workers etc) have the capacity to create new knowledge and store that with their existing knowledge. The research process adopted in this study, if applied in these contexts, offers organisations the ability to improve knowledge capture and sustain or improve performance.
11. Empirical research has shown that various techniques have been used in knowledge capture process in organizations. These included techniques such as interviews, observations, surveys, simulations, and artefact studies. (Dalkir 2005; Dow & Pallaschke 2010; Kanjanabootra, Corbitt & Nicholls	11. This researcher has extended that work and has shown that by deploying multi-layered, rather than singular, data collecting techniques during the knowledge capture process resulted in improving both the effectiveness of the knowledge capture process and the quality of the captured knowledge. The multi-layered data collection method has *added* new knowledge about how to improve the effectiveness of the knowledge capture process.

2010; Kanjanabootra, Corbitt & Nicholls 2011; Matsumoto et al. 2005; McDonald 2005; Mulder & Whiteley 2007; Staab, Steffen et al. 2009; Staab, S. et al. 2001)	
Ontology and research outcomes	
12. Ontology is an explicit specification which can be used to represented tacit knowledge used during a product design process (Barb, Chi-Ren & Sethi 2005; Fu et al. 2007; Gruber 1993, 1995; Hiekata, Yamato & Tsujimoto 2010; Studer, Benjamins & Fensel 1998).	12. In this research captured tacit and explicit knowledge was classified into class and subclasses to represent the cabinet testing process knowledge. This resulted in a more effective knowledge capture process, better organized and classified knowledge and a system that made it easier for the engineers to re-use that knowledge. The ontology developed in the research represented the knowledge in a clear and useable form. This research *discovered* that tacit knowledge can be captured and re-used if it has been designed to be attached with the physical objects the users create.
13. Ontology can be used to model the structure of knowledge as representation. The nature of the ontology allows users to create the structure of knowledge almost any way they want to (Ioana 2002; Studer, Benjamins & Fensel 1998; Sun & Chen 2008).	13. In this research, the researcher and the engineers have formed the structured knowledge classification put into an ontology by the researcher. The structure had components which related specifically to the Company's design, build and testing processes. The components were interlinked and integrated both tacit and explicit knowledge together. This resulted in an easier form for re-use by the engineers. One of the objectives of the research was to create a flexible and adaptable system. The ontology developed enabled that. This research has *confirmed* that the objected oriented nature of the ontology can be used to maximise the usefulness of the system designed through its enabling flexibility.

14. Bailey (2010) argued that if relevant knowledge such as product catalogues were studied before-hand, it will benefit to knowledge engineer more during the knowledge modelling process (Bailey 2010).	14. This research has shown that the artefact studies conducted prior to knowledge capture did enable the researcher to gain a better understanding about the domain knowledge. This resulted in more effective knowledge capture. In this research one additional aspect *added* was that to be able to study the existing organizational artefacts before the knowledge capture process can improve both the knowledge capture process and the knowledge modelling process.
15. Milton et al (2010) have argued that ontology has more benefits than just data logging.	15 This research has shown that the ontology is beneficial for classification of knowledge and a means to integrate all types of knowledge from various sources. The research has also shown that the ontology can be a valuable source to identify specific forms and elements of knowledge and information which can be extracted for further analysis. The use of HPM was possible because the specific knowledge required about the testing process could be precisely and accurately extracted from the system built on the ontology. This *confirmed* other empirical studies that the benefit of ontology as a knowledge representation is greater than we know.
16. Ontology provides a common understanding domain through knowledge representation and standards representation and allows experts to use ontology in various domains by providing terms and relationships in the modelled knowledge (Fensel 2001). Once knowledge can be modelled it can then be manipulated and reused (Gruninger & Fox 1995; Milton, S, Keen & Kurnia 2010; Staab et al. 2001; Studer, Benjamins & Fensel 1998).	16. In this research the Ontology allowed the researcher to break down knowledge element into small elements and structure them with an object oriented paradigm. This created a realistic knowledge representation for the user engineers. The ontology created helped increase knowledge query effectiveness and the search for existing knowledge by the engineers. Hence, the system facilitated better knowledge reuse. This *confirmed* other empirical studies on how ontology can be used to represent knowledge in ways close to the reality in the study.

Methodology outcomes	
17. One of the evaluation factors to measure the success of a system built through Design Science is the functionality of the system (Dalkir 2005; Nunamaker, Minder & Titus 1990; Venable 2006, 2010).	17. Using the Design Science process where the researcher and the engineers iteratively worked together meant that the knowledge-based system's functionality met the engineers' expectations. The research *confirmed* the utility of the evaluation process integral in the Design Science research; that the cyclical manner of the evaluation built by the researcher and the engineers throughout the system development process can improve the system itself.
18. If users are involved in research on knowledge collection the quality of the outcomes improves. This is because users are contributors and beneficiaries (Alavi & Leidner 1999)	18. In this research the engineer's participation has shaped the KMS's structure in the same way that they normally work. This result was a system that the engineers were familiar with. This research demonstrated to the experts/users that the artefact as an outcome is useful to them. Therefore they were willing to collaborate during the process. Because the KMS was designed by and treated as part of the work of the engineers and did not require additional knowledge, the users saw the benefits and used it. This research *confirmed* other empirical studies in Design Science research that the iterative manner used and that the participation of the engineers and the researcher working together, can both improve the quality of the system developed.
19. The ideal characteristics of a good action researcher is to be actively involved with the organization. (Baskerville & Wood-Harper 1996). If the researcher has domain knowledge the outcomes of the research will be more complete. (Baskerville & Wood-Harper 1996). Baily (2010) also argues that problems with knowledge capture can clearly be overcome if researcher has domain knowledge.	19. In this research the researcher was a practicing mechanical engineer who had domain knowledge of refrigeration. This meant that the researcher had a very good understanding of the engineering process being used, resulting in increased effectiveness and detail in the knowledge capture process. The research showed that one of the key reasons for the evaluated effectiveness of the knowledge-based system was because of the detail in the system, which it derived from the expertise of the researcher himself. The research has *confirmed* that the problems of capturing tacit knowledge identified in the research literature were overcome in this research partly because of the expert knowledge of the researcher and partly because of the adoption of multiple methods of collecting data used.

20. Using action research, where the researcher and research participants work together, the researcher can develop a better understanding of the subject being studied (Baskerville & Wood-Harper 1996; Rapoport 1970).	20. In this research adopting action research as part of Design Science, the researcher worked both collaboratively and iteratively with the engineers. This gave the researcher a detailed understanding of the refrigeration design, build, testing process used in the Company. The resulting KMS was evaluated and modified to ultimately meet the requirements of both the Company and the engineers. Each iteration improved the researcher's knowledge and improved the output, the knowledge-based system, with each iteration.
21. Previous studies have applied HPM with static business process (van der Aalst, Ton & Laura 2004; van der Aalst et al. 2003; van der Aalst, Weijters & Maruster 2004). Even in the industrial setting the research has still applied the HPM in static process (van der Aalst et al. 2007).	21. This research has shown that the HPM can be applied to industrial dynamic and changing processes. The result of applying HPM has shown that the cabinet testing process can be shortened. This research has *added* to our knowledge that HPM can be applied to dynamic business process contexts.
22. The iterative nature of Design Science, where feedback from evaluation process is sent onto building process, can increase the quality of the artefact developed (Baskerville & Wood-Harper 1996; Hevner & Chatterjee 2010; Hevner et al. 2004; Kanjanabootra, Corbitt & Nicholls 2010; Vaishnavi & Kuechler 2008).	22. This research showed that the iterative feedback from the engineers improved the quality of the artefacts, both the knowledge-based system and the results from HPM. The real test of quality in this research was confirmed in the evaluation where it was stated they met the requirements and needs of the engineers, CEO and COO. This *confirmed* one of the advantages of the Design Science research.

System implementation outcomes	
23. Empirical research has shown that implementing a KMS at the organizational level requires better IT infrastructure. This can be a significant cost to the organization (Alavi & Leidner 2001).	23. This research has shown that KMS implementation can be done cost effectively. In this research open source software was used and implemented on existing Company hardware. Therefore it was available at no additional cost. Furthermore, the research did not try to implement the KMS organization-wide. Therefore, it did not require an expensive new IT infrastructure. This conclusion *added* a new dimension in that knowledge management can be implemented in a cost effective manner which challenges previous empirical studies.
24. KMS implementation acts as a knowledge enabler which facilitates more knowledge sharing among individuals in a team (Alavi & Leidner 2001; Lilleoere & Hansen 2011).	24. In this research the interaction between the engineers in their product development meetings every morning has shown that there were knowledge sharing activities in place. However, the knowledge-based system has facilitated the engineers to capture their knowledge that has been shared in the meetings and made it available for re-use. This resulted in better knowledge enabling and more sharing among the engineers. This research *confirmed* that capturing knowledge and enabling it for sharing, facilitates better organizational knowledge sharing.
25. Previous research has shown that implementation of a knowledge management system should help the users rather than create more jobs. It should help users save time in undertaking their tasks (Alavi & Leidner 1999).	25. This research showed that implementation of the knowledge-based system was of significant value to the engineers. They reported the system helped them do their work more effectively and saved them time. One significant outcome of the research was the reduction in make-span time resulting from the system being in place and used. This is *new* to the application of both knowledge-based systems and HPM. This is because it was not only the researcher, but the users (engineers) and their use of the system which created the solution.

8.6 Limitations of the research

This research adopted a single case study method. This is because the research was designed to solve specific business strategic problems in an organization. This research then has a single research setting. The study focused on the phenomena that happen in the product development team in that company. This research did not aim to generalise or establish new theory. However, it aimed to gain real understanding of the strategic business problem in a refrigeration manufacturing company and understand how to build relevant solutions to their implementation. Together with applying a Design Science research methodology, the case study also acted like a case story. It was a story of participation and collaboration of researcher and the participants working together. However, the research only represents what this group did. Other groups, in other companies, will probably do things differently and the outcomes then may vary.

The other limitation of a single case study research is the research result cannot be generalised. The research purposes here were to solve an identified problem of business continuity and to reduce the make-span in only one manufacturing company. Therefore, the research did not state that implementing knowledge-based system in this way would solve all problems of business continuity in every organization. The situations are not that simple. There still are a number of other factors involved in helping organizations maintain their business continuity. They will vary by industry type and by location.

HPM was the mode of analysis used to address the make-span problem. It is only one of the available techniques that can be used to reduce make-span for this Company or any other company producing refrigerated display cabinets. This research did not argue that using HPM could reduce make-span of every manufacturing industry. Other solutions might produce different results.

One of the disadvantages of the case study method is that the research setting cannot be controlled. As shown in Chapter 7, during the time that this research was conducted, both the COE and COO left the Company. The researcher managed to deliver the first version of the knowledge-based system to the COO to demonstrate what the system could do, but it relied on the engineers to act because the new COO had not been involved. However, limited feedback was captured from the COO. Other unexpected problem was that CEO also left the Company. This time the researcher was not able to capture any feedback from the CEO about the whole system, even though he had been involved. Ideally, if both the CEO and COO had stayed at the Company until the researcher delivered the third version of the knowledge-based system, then better quality the feedback could have been achieved. The other thing that happened during the conduct of the research was that two of the original engineers left the Company. This affected the research in the same way as the managerial employees absence had as they all were research participants. However, adopting Design Science research where research and participants work together collaboratively meant that the resignation had little impact on the outcomes. This is because their research input has been collected from the earliest stage of the research.

When the researcher had started this research the Company's business was going well. The engineers were busy and there were new cabinets being tested all of the time. This helped the researcher to collect significant amounts of data to shape the research framework. Then, when the researcher had come to the point where the knowledge-based system had been developed to Version 2, the Company had experienced a reduction in orders for new products from their clients. The researcher had managed to collect data needed to construct the knowledge-based system version three and applied HPM to the captured knowledge. However, when the researcher had reached the final version of the knowledge-based system (Version 3), the researcher was informed by one of the engineers that the Company had gone into receivership and was about to close. The researcher then had made the last contacts with the engineers to let them evaluate the knowledge-based system version three and the results of HPM. The engineers had evaluated both outcomes of the research and the details were shown in Chapter 7. It must be stated that this meant a complete evaluation was not possible. The Company had encountered management problems during the research process before the final solutions were fully tested. In a single case study the research participants cannot be controlled. However, the Design Science research process adopted here was more enabling of changes because the process was not a single iteration or artefact but a process of iterations of artefact developments over time. Each cycle consisted of both building and evaluating process. This helped the researcher to detect changes in the processes. The researcher had the engineers to qualitatively evaluate both outcomes of the research, the knowledge-based system and solutions from HPM.

8.7 Future research

There are a numbers of suggestions for future research. These include,

- This research is an example of an application of Design Science Research to develop a specific knowledge-based system. The purposes were to solve the Company's business continuity issue and reduce their make-span. The KM application is sound and would be extendable to cover other types of manufacturing industries.
- This research has shown that multiple knowledge capture techniques are useful. Future research should adopt such techniques to increase the effectiveness of knowledge capture processes in organizations.
- The application of HPM also could be applied to other types of dynamic workflow logs. Industries often record their work logs. However, they rarely use what they have recorded strategically. The outcomes of this research would provide a useful model applied to other organizational workflow contexts.
- The previous research in HPM mostly applied this technique to static process, for example, business process, health care and public work. This research has shown that the technique is applicable to dynamic process such as cabinet testing processes. Future research could apply the technique to other dynamic processes.
- In future research, outcomes from HPM analysis should be quantitatively evaluated when applicable, especially in large scale operations. In this research, the Company's management problems, entry into receivership and eventually to cessation of operations, meant the researcher could only manage to qualitatively evaluate the outcomes of the HPM.
- In the future, the HPM technique also should be extending to cover the relation ship between set of more than two tasks.

- A Computing expert should extend the flexibility of the ontology application software. They can construct a knowledge-based system to extract workflow logs in XML format, so it can be used with available Heuristic Process Mining software.
- This research has developed Design Science an evaluation framework which could be applied to other Design Science research. The evaluation framework contains various evaluation aspects which cover all of the outcomes of Design Science Research.

8.8 Conclusion

This research has shown that knowledge management can be used to strengthen business strategy. In this research, strategic business problems were resolved by the application of knowledge-based systems collaboratively developed with users. The research has also shown that capturing knowledge and making it available for re-use can enable organizations to more readily adapt to changes in the external business environment in an effective way, provided that all other elements are considered. Whilst the knowledge-based theory of the firm argues for the recognition of the importance of knowledge and knowledge management in an organization’s strategy, this research has also shown that ignoring other strategy forces can negate that importance.

Ontology was used a basis for organization of specific corporate knowledge. This enabled the construction of a knowledge-based system to capture both the Company's explicit and tacit knowledge and use that to solve a business continuity problem. Ontology also allowed the researcher to extract captured tacit knowledge to identify and eliminate irrelevant tasks in the product development process. The analysis used reduced the complexities and numbers of tasks in that process.

The strategic use of KM has contributed to a better understanding of the relevance of a knowledge-based theory of the firm. Knowledge is of strategic importance and is a crucial part of organizational development. However, it is not an entity in itself, rather it is one significant and key resource that businesses must take account of to maintain business continuity.

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Appendix

Appendix A: Knowledge-based system overall structure - relationships

Appendix A Knowledge-based system overall structure