Automating the aetiological classification of descriptive injury data

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SCHOOL OF SAFETY SCIENCE

AUTOMATING THE AETIOLOGICAL CLASSIFICATION OF DESCRIPTIVE INJURY DATA

DEVELOPING A TAXONOMY FOR CLASSIFYING INJURY DATA AETIOLOGICALLY AND A KNOWLEDGE ACQUISITION SOFTWARE TOOL TO AUTOMATE THE CLASSIFICATION PROCESS

by

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Student No 2219172

A thesis in fulfilment of the requirements for the degree of Doctor of Philosophy

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Declaration of Originality

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Abstract 350 words maximum:

Injury now surpasses disease as the leading global cause of premature death and disability, claiming over 5.8 millions lives each year. However, unlike disease, which has been subjected to a rigorous epidemiologic approach, the field of injury prevention and control has been a relative newcomer to scientific investigation. With the distribution of injury now well described (i.e. 'who', 'what', 'where' and 'when'), the underlying hypothesis is that progress in understanding 'how' and 'why' lies in classifying injury occurrences aetiologically. The advancement of a means of classifying injury aetiology has so far been inhibited by two related limitations: 1. Structural limitation: The absence of a cohesive and validated aetiological taxonomy for injury, and; 2. Methodological limitation: The need to manually classify large numbers of injury cases to determine aetiological patterns. This work is directed at overcoming these impediments to injury research.

An aetiological taxonomy for injury was developed consistent with epidemiologic principles, along with clear conventions and a defined three-tier hierarchical structure. Validation testing revealed that the taxonomy could be applied with a high degree of accuracy (coder/gold standard agreement was 92.5-95.0%), and with high inter- and intra- coder reliability (93.0-96.3% and 93.5-96.3%). Practical application demonstrated the emergence of strong aetiological patterns which provided insight into causative sequences leading to injury, and led to the identification of effective control measures to reduce injury frequency and severity. However, limitations related to the inefficient and error-prone manual classification process (i.e. average 4.75 minute/case processing time and 5.0-7.5% error rate), revealed the need for an automated approach.

To overcome these limitations, a knowledge acquisition (KA) software tool was developed, tested and applied, based on an expert-systems technique known as ripple down rules (RDR). It was found that the KA system was able acquire tacit knowledge from a human expert and apply learned rules to efficiently and accurately classify large numbers of injury cases. Ultimately, coding error rates dropped to 3.1%, which, along with an average 2.50 minute processing time, compared favourably with results from manual classification. As such, the developed taxonomy and KA tool offer significant advantages to injury researchers who have a need to deduce useful patterns from injury data and test hypotheses regarding causation and prevention.

ABSTRACT

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However, unlike disease, which has been subjected to a rigorous epidemiologic approach, the field of injury prevention and control has been a relative newcomer to scientific investigation. With the distribution of injury now well described (i.e. 'who', 'what', 'where' and 'when'), the underlying hypothesis is that progress in understanding 'how' and 'why' lies in classifying injury occurrences aetiologically.

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This work is directed at overcoming these impediments to injury research.

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I owe much to you all.

Gareth W Shepherd

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1.0 INTRODUCTION

Injury prevention and control, as a science, begins with the observation, description and classification of injury data. The objective is defined in terms of injury 'prevention' and 'control', where: injury prevention is characterized by a reduction in incidence and prevalence, and; injury control denotes ongoing programs that seek to reduce the frequency and severity of injuries (Dictionary of Epidemiology, 2000).

The purpose of this work is to help advance the field of injury prevention and control by focussing on two vital, and related, research needs:

1. The need for a validated, cohesive classification system for coding injuries according to their aetiology (i.e. to help provide insight into how and why the injury occurred), and;

2. The need for a practical means to automate the manual process of classifying injury cases (i.e. to enable efficient and reliable classification of large populations of narrative-based injury data and determine aetiological patterns).

The underlying hypothesis is that future progress lies in understanding and classifying injury occurrences aetiologically, thereby enabling the identification of effective prevention and control measures (i.e. analytical epidemiology).

The work presented herein was completed during the period 2000 to 2005, and involved the Departments of Safety Science and Computer Science at the University of New South Wales (UNSW), as well as input and data from the National Occupational Safety Health and Safety Commission (NOHSC), National Coroners Information System (NCIS), Office of the Chief Electrical Inspector, and the United States Occupational Safety and Health Administration (OSHA).

2.0 CONTEXT

This section provides a brief historical perspective of the burden of disease and injury, as well as a review of the current injury toll, and an assessment of contemporary impediments facing the field of injury research.

2.1 The Burden of Disease and Injury

Injuries, like disease, have always been endemic in human populations. Control measures have long been adopted by societies and individuals; some basic and commonplace injury controls, such as footwear, have been used for millennia.

In many early societies, serious injury and disease were conceptualised in theological or mystic terms; that is, injury and ill-health were attributed to retribution from God, other super-natural causes, or unexplainable 'spontaneous generation'. Some form of individual mis-behaviour was seen as the underlying cause. For example, in response to outbreak of the bubonic plague in 1347, the French city of Rouen enacted regulations prohibiting individuals from gambling, cursing, drinking or engaging in other excesses which were thought to arouse the wrath of God (Nohl, 1926). Similar measures were applied throughout continental Europe, with the lack of effectiveness demonstrated by the death of an estimated 25 million people during the subsequent five year period - representing the largest human catastrophe of all time (Kelly, 2005).

Since this pre-scientific era, there has been much progress in the understanding, classification and control of disease phenomena. In particular, the emergence of germ (pathogenic) theory in the 18th Century and disease epidemiology in the 19th Century provided firm foundations for the modern scientific approach to public health (Collard, 1976).

Epidemiology evolved as a scientific means to study the patterns of disease in human populations and the factors that influence these patterns for the purposes of:

1. Elucidating the aetiology of disease;
2. Establishing working hypotheses from the above, and;
3. Developing and evaluating preventative strategies based on the above.

As a result of this epidemiologic approach, disease became increasingly understood as an ecological problem, rather than being considered as 'inexplicable' or viewed in theologically punitive terms (i.e. ultimately arising from pernicious individual behaviour).

For example, it was as a result of the epidemiological mindset that Wagner *et al* (1960) first established mesothelioma as a disease arising from exposure to crocidolite asbestos, based on analysing South African mine-worker population data for common aetiological patterns. This finding was remarkable in so far as he recognised the connection between exposure and a disease which had a latency period of up to 60 years.

As outlined in the Dictionary of Epidemiology (2000), the aetiology of disease is now defined in terms of interaction of host, agent and the environment (the so-called epidemiologic triad), with transmission of the agent occurring via inanimate vehicles (e.g. toys, food), animal vectors (e.g. mosquitoes) or airborne particulates (e.g. aerosols). Thus, an occurrence of Ross River fever may be understood in terms of the Ross River virus (infectious agent) being transferred to a susceptible human (host) within a particular environment, as a result of being bitten by an infected mosquito (vector).

By understanding and classifying disease occurrences in this manner, epidemiologists have been able to promote effective strategies to prevent or control the spread of infectious disease, such as vaccination programs and measures to pasteurise milk (Haddon, 1980). As a result of such interventions, the incidence of infectious disease worldwide has reduced dramatically over the past Century.

By way of example, **Figure 2.1** below depicts the average annual mortality in Australia from 1905-1999, comparing ‘Infectious diseases’, ‘All other accidents’ (e.g. workplace and home) and ‘Road traffic accidents’, as compiled by Dr Eric Wigglesworth AM (2001).

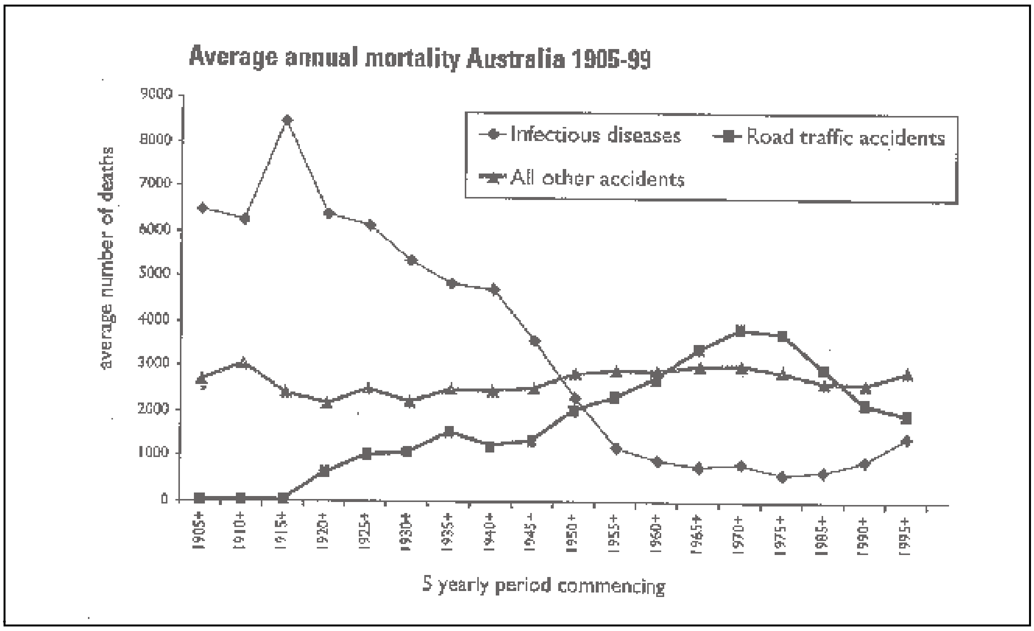


Figure 2.1 Average annual mortality in Australia, 1905-1999 (Wigglesworth, 2001).

These historical data reveal that the number of deaths due to infectious disease have reduced by over two thirds since Australia’s Federation. Between 1905 and 1909 there was an annual average of 6,478 deaths from diseases including tuberculosis, polio, smallpox, malaria, and diphtheria, with an overall death rate of close to 150 per 100,000 population per annum. In contrast, for the years 1995 to 1999, there was an annual average of 1,427 deaths from these diseases at the substantially lower rate of 8 per 100,000 population per annum.

In a WHO report on the global disease burden, it is pointed out that, as a consequence of the reduction in disease, modern society enjoys the highest levels of health and life expectancy in all of history (Murray, 1994). For example, the life expectancy for males and females in Australia has increased by about 40% since the year 1905 (Australian Institute of Health and Welfare, 2003), as per the following **Table 2.1**.

Year	Expectation of life (years)	
	Males	Females
1905	55	58
1999	75	81

Table 2.1 Changes in life expectancy during the twentieth century for Australian males and females (AIHW, 2003).

Today, with infectious disease no longer causing the majority of premature deaths among the population, injury has emerged to take its place as the dominant cause of premature death.

2.2 Current Injury Toll

While it is evident that medical research and disease epidemiology have enabled a substantial reduction in the toll of infectious disease, there has been no similar absolute reduction in deaths from unintentional injury. In fact, injury now accounts for over three times more lives lost than infectious disease (combining 'All other accidents' and 'Road traffic accidents' in the previous **Figure 2.1**). This is confirmed by examining hospital and government data; for example, Gillett *et al* (1993) showed that injury is the single leading reason for persons to present to hospital emergency departments. Further, death certificate data reveal injury to be the major cause of death of persons aged between 1-44 years (Australian Bureau of Statistics, 1995).

In Australia, injury was first recognised as a national health priority in 1986 and remains one of the key five national health priorities reflecting its impact on Australian society. The National Health and Medical Research Council document, *'Injury: from problem to solution'* (NHMRC, 1999), summarises the current state of the injury problem as follows:

> *"Throughout the 1990's injury has been responsible annually for more than 7,000 deaths and 14.7 percent of years of potential life lost, 400,000 hospitalisations, and direct medical costs of $2,607 million. Of particular concern is that the impact often*

> *occurs in the first half of the natural life span. On average, each fatal injury before the age of 75 results in the loss of 32 years of potential life lost compared with nine years for cancer and five for cardiovascular disease."*

The Australian historical trends noted above are broadly consistent for other high-income countries (such as the United States, Canada and the United Kingdom), where injury mortality rates are in the range 33-40 per 100,000 population per annum. As such, the average likelihood of a person being killed in any one year due to unintentional injury in these high-income countries is in the range 1:2,500 to 1:3,000. This likelihood is well below so-called 'acceptable' levels of risk as defined by organisations such as the Australian Nuclear Science and Technology Organisation (ANSTO, 1999) and the UK Health and Safety Executive (HSE, 2000), as can be seen in **Figure 2.2** below.

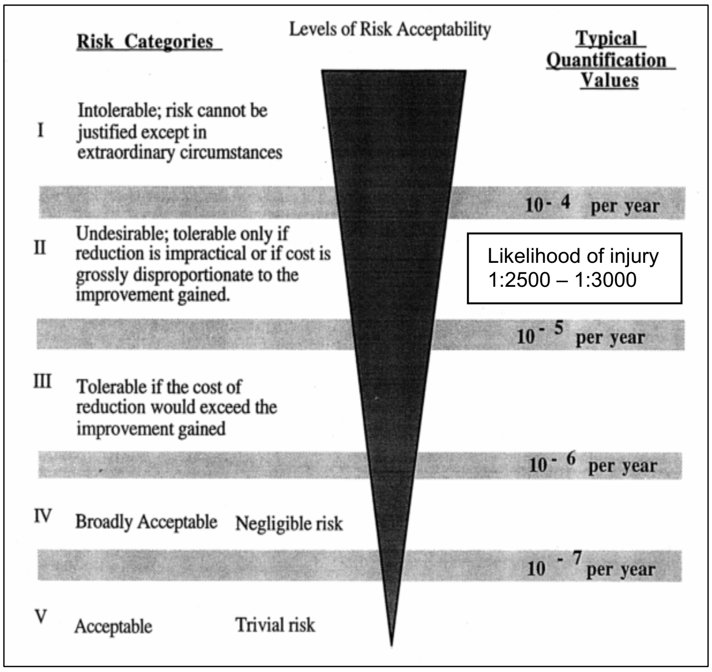


Figure 2.2 Levels of risk acceptability (so called 'Dagger diagram'), derived from the UK Health and Safety Executive (HSE) and the Australian Nuclear Science and Technology Organisation (ANSTO). Likelihood of injury data added by the author.

Figure 2.2 indicates that the current likelihood of injury for high income countries falls within 'Category II: Undesirable Risk', and as such is a problem that *"is tolerable only if reduction is impracticable or if the cost is disproportionate to the improvement gained"*. It is certainly not the case that the overall risk of injury is considered either 'Tolerable' (Category III) or 'Acceptable' (Categories IV and V) as defined by these accepted measures.

At a global level, injury now surpasses disease as the leading world-wide cause of death before age 60, claiming over 5.8 millions lives each year – the equivalent of 80 commercial airliner crashes, per day (World Health Organisation, 1999). Further, the toll of unintentional injury is predicted to continue rising, at least until the year 2020 (WHO, 1999).

Unintentional injury can be broadly categorised into road, home and work-related occurrences. Returning once again to the annual mortality chart for Australia 1905-1999 (**Figure 2.1**), it is noteworthy that the category 'All other accidents' (i.e. predominately at work or in the home) has now surpassed the toll from 'Road traffic accidents'. More precisely, the number of road traffic fatalities has reduced markedly while work and home injury deaths have not (in absolute terms); road deaths peaked at around 4,000 in 1970 and fell to just under 2,000 deaths per year in 1995 (despite a doubling of road users over this period). This halving of the number of road deaths is largely attributed to the introduction of safety measures such as seat-belts and improvements in the crash-worthiness of vehicle and roadway environments (Wigglesworth, 2001).

In relation to workplace injury, the Australian Industry Commission report entitled *'An Inquiry into Occupational Health & Safety' (1995),* revealed that 400,000 workplace injuries occurred during 1992-93, costing approximately $20 billion. This is well in excess of the estimated cost of road crashes in 1992-93 of $7 billion (National Committee on Transport, 1996). This cost also represents approximately 5% of the nation's gross domestic product, and is comparable to the $18.4 billion revenue generated by the Australian mining industry in the same year (Australian Bureau of Statistics, 1992-93). Over 80% of the cost of injury was found to be attributable to 13% of occurrences; those resulting in permanent injury or fatality.

The emergence of workplace injury as a dominant injury problem is a consistent trend globally, as summarised in the following extract from an International Labour Organization press release (ILO, 1999):

> *"In a speech to the introductory session of the Congress, Dr Jukka Takala, Chief of the ILO's Health and Safety programme, pointed out that the workplace hecatomb of 1.1 million deaths exceeds the average annual deaths from road accidents (999,000), war (502,000), violence (563,000) and HIV/AIDS (312,000).*
>
> *In addition, he said that by conservative estimates workers suffer approximately 250 million occupational accidents and 160 million occupational diseases each year. Deaths and injuries, he said, continue to take a particularly heavy toll in developing countries where large numbers of workers are concentrated in primary and extraction activities such as agriculture, logging, fishing and mining – some of the world's most hazardous industries.*
>
> *Also, according to ILO, some 600,000 lives would be saved every year if available safety practices and appropriate information were used."*

In a more recent ILO press release addressing workplace safety, Dr Takala added that at least 5,000 persons now die each day as a result of work-related accidents and illnesses (ILO, 2005).

In short, it is evident that progress in reducing the toll of unintentional injury (particularly workplace injury) has not paralleled achievements in the reduction of disease (since the 1900s) and, more recently, notable reductions in road trauma (since the 1970s).

2.3 Current Impediments to Injury Research

A commonly cited reason for the lack of progress in injury research is that, compared with the public health approach to disease, the application of applied scientific methods remains in its infancy (Haddon, 1980; Langley, 1988; Viner, 1991; Wigglesworth, 2001; Manuele, 2003).

One of the historical obstacles to progress was the widely held view that injury occurrences could not be prevented; a sentiment which prevailed well into the twentieth century (Nixon, 2000). Furthermore, unlike the study of disease, injury research has lacked a defined, cohesive, internally consistent conceptual framework for understanding and classifying injury occurrences. According to researchers such as Larsson and Hale (2000), there remains a limiting yet commonly-held paradigm that injury is the result of individual behavioural failure, as will be discussed.

Wigglesworth (2003) outlines two major existing impediments to progress in injury research: The first being the lack of any overall scientific conceptualisation, and the second being the poverty of available data. The problems are related, as the lack of an accepted means to conceptualise and classify injury leads to the existence of structurally flawed injury data-bases and classification systems, as will be described.

Currently, injury researchers use a myriad of databases worldwide for surveillance, classification and pattern analysis of injuries. These injury datasets are based upon sources such as: hospital admissions data; workers' compensation records; internal government or company records, and/or; Coroners' reports.

Injuries are usually coded according to the World Health Organisation's International Classification of Diseases Codes (ICD), which was introduced in 1948 based on a list of causes of death which had its origins in the 1850s (WHO, 1948). This coded information enables descriptive analysis of data such as by 'age', 'sex', 'activity', 'type of injury' and 'time of day' (i.e. classifying who, what, where and when). For example, the physical nature of an injury (e.g. broken leg, concussion) is captured by diagnostic codes known as 'N-codes' which provide important clinical information about the part of body injured.

In most developed countries, such as Australia, New Zealand, Europe and the United States, the ICD (or local derivations thereof) have become the basis for mandatory national standards for classifying injuries.

For example, Australian Hospital inpatient data is coded according to a local derivation of the ICD, known as ICD-AM (Australian Modification). Workers' compensation (i.e. WorkSafe) data, collected by the eight State and Territory Governments (as well as the former Joint Coal Board for injuries in the coal industry), are coded according to the NOHSC Type of Occurrence Classification System (TOOCS) which has been recently revised to align with the ICD (NOHSC, 2006). Previously, these NOHSC classifications (as published in the Australian Standard AS1885-1990) employed the Swedish model, defining separate 'Nature of Injury', 'Mechanism' and 'Agency' (or Source) categories (Andersson and Lagerlof, 1983). While these individual categories are well defined and useful in their own right, the overall approach was subject to longstanding criticism; for example, Skegg (1991) argued that the approach was flawed due to the lack of a theoretical basis, while Wait (1992) criticised the lack of utility of the overall classification in terms of elucidating aetiology, summarising the situation thus:

> *"Until such time as the details of an accident are recorded in a way that enhances understanding of the accident process, the benefit of recording information about accidents will be limited to the production of statistics with little meaning …"*

In New Zealand, the Accident Compensation Corporation (ACC) also codes work-related injuries based on the Australian modification of the ICD (Statistics NZ, 2003).

In the European Union, all member states code injury information on hospital discharges (and also death certificates) according to the ICD; procedures for the collection of this data are reported to be relatively homogenous between European countries (EU Task Force on Injury Data Base, 2006). The ICD data is recorded in the statistical information service of the European Union, known as Eurostat.

Similarly, in the United States, the ICD is used to code mortality data from death certificates as well as morbidity data from inpatient and outpatient records (with clinical modifications to meet the needs of American hospitals).

In summary, thousands of hospitals and government agencies around the world have been coding injury data according to the ICD classification for decades. Moreover, global adoption of the ICD has gathered pace in recent years, as countries supplant existing local coding systems with ICD derivations in order to achieve consistency and comparability in the reporting of injuries and disease (WHO, 1993).

The use of ICD codes is a useful and necessary first step in injury surveillance, and allows the distribution and trends of injury to be studied in detail (i.e. descriptive epidemiology). For example, the types of injury that occur with the greatest frequency and severity can be identified by age, gender, geographic region, industry and occupation (where applicable).

Typically, however, the coded data collected by these systems are of limited value in terms of characterising the causative determinants of the injury event; in particular, to gain insight into how and why the injury event occurred (i.e. analytical epidemiology).

A separate set of codes for 'external cause of injury' (known as 'E-codes') were introduced to the ICD in an attempt to distinguish various causation categories, such as ‘Drowning’, ‘Fall’, and ‘Hot object/substances’ (WHO, 1977). These E-codes have been renominated as ‘V-codes’ in the more recent revision known as ICD-10, without fundamental change (WHO, 1992).

The following **Table 2.2** provides data relating to 395,876 work-related injury and poisoning separations by external cause (E-code) for all Australian Hospitals, 1998-99 (Australian Institute of Health and Welfare, 2000).

The E-Code classification shown in **Table 2.2** reveals that key injury types relate to: falls (n=112,181 or 28.3%); complications of medical care (n=66,432 or 16.8%), and; exposure to mechanical forces (n=64,556 or 16.3%).

External Cause	Number
Falls	112,181
Complications of medical and surgical care	66,432
Exposure to mechanical forces	64,556
Transport accidents	49,318
Other external causes of accidental injury	33,656
Intentional self-harm	20,935
Assault	18,481
Accidental poisoning	13,951
Smoke, fire, flames, hot substances	5,816
Venomous plants, animals, forces of nature	4,642
Events of undermined intent	2,133
Electricity, radiation, extreme temperature/pressure	1,560
Other accidental threats to breathing	859
Accidental drowning and submersion	590
Legal intervention and operations of war	53
Total	**395,876**

Table 2.2 External cause classifications (based on World Health Organisation E-codes) for Australian work-place injury occurrences 1998-1999 (AIHW, 2000).

While such E-code classifications reveal high-level patterns which may help to target key areas for intervention, there is a lack of useful detail available regarding how the injury occurred or how the occurrence could be controlled. As such, the use of ICD external cause codes (E-codes) has been increasingly recognised as being inadequate for understanding injury aetiology and informing prevention and control activities (Baker, 1982; Viner, 1991; McDonald, 1995; Wigglesworth, 2003).

Langley (1999) summarises the present situation thus:

> *"Internationally, E-codes are the most widely used coding frame for categorising the circumstances of injury and poisoning. The government agencies responsible for health statistics in most member countries of the WHO are currently using E-codes to summarise the circumstances of injury.*
>
> *Despite their widespread use, these E-codes have been criticised for being inadequate for prevention purposes …*
>
> *Many agencies and individuals seek a more useful coding frame than ICD."*

Dr Stathakis of Monash University Accident Research Centre (MUARC), reviewed the most recent ICD-10 revision of the external cause codes in detail (Stathakis, 2000), noting that the revised E-codes still do not meet essential injury prevention and research needs, and calling for alternative injury coding systems to be developed.

There are two over-riding structural limitations with use of E-codes. First, the codes are largely arbitrarily defined and are not based on any scientific or fundamental concept of injury aetiology (as will be discussed). While some of the classifications such as 'falls of people' are inherently sound and useful, others such as 'exposure to mechanical forces' include such diverse injury mechanisms as 'cave in', 'being struck by a hockey ball', 'exposure to noise', and 'explosion of a pressurised boiler'. Moreover, ICD E-codes embody each of the following diverse concepts: intent (e.g. 'suicide'); type of location (e.g. 'public highway'); occupation (e.g. 'crew member of a commercial aircraft'); context of person when injured (e.g. 'commuting to work'); type of object involved in producing injury (e.g. 'powered lawn-mower'); and the injury mechanism (e.g. 'immersion' and 'poisoning'). In a paper on the history of the ICD, Bowker (1996) opines that there is no single organising principle underlying the ICD; in fact, given this limitation, he describes the ICD as a nomenclature rather than a classification.

The second major limitation is that ICD E-codes are uni-dimensional; that is, are based on a series of single-level classifications. This allows coding of a number of disparate data items for a single occurrence (e.g. intent and nature of injury). However, by classifying the same injury case into multiple unrelated codes, it no longer becomes possible to maintain critical associations between the components of data. Driscoll *et al* (2003) points out that this lack of flexibility significantly limits the utility of the ICD approach to examine the many specific questions of interest that were not anticipated at the time the coding system was developed. This limitation embodies the classic reductionist trap; that is, use of ICD E-codes reduces complex injury information into separate individual data-sets, but in the process the original identity of the occurrence is lost, particularly as it relates to the causal sequence leading to injury.

There have been some recent attempts to overcome the limitations of E-codes. For example, a new International Classification of External Causes of Injury (ICECI) has been developed by injury researchers to complement the ICD-10 edition. The ICECI offers a multi-dimensional and modular coding structure, comprising seven ‘core modules’: ‘mechanism of injury’; ‘objects/substances producing injury’; ‘place of occurrence’; ‘activity’ when injured; ‘human intent’; use of ‘alcohol’, and; ‘drug use’ (ICECI, 2004). The core modules are designed to provide an overview of external causes of injury cases. For example, ‘mechanism’ records how the injury came about, and ‘objects/substances’ records what types of entities (or sources) were involved in the process. The benefit of the ICECI is that these modules follow a hierarchical structure which allows the user to choose from up to three levels of detail for data collection and reporting.

While this new classification offers substantial improvements to ICD E-codes by enabling more detailed and flexible classification of injury causation, the approach is ultimately limited by the constraint of maintaining structural compatibility with the original E-code system, as described below by the ICECI Maintenance Group (2004):

> *“A major factor underlying the development of the ICECI has been dissatisfaction with some aspects of the ICD External Causes chapter [E-codes] for certain purposes related to injury prevention.*
>
> *It was not possible to develop a version of ICECI which mapped directly to categories in the External Causes chapter at fine level without forcing the ICECI to take on characteristics of the External Causes chapter which had prompted development of the new approach. However, it was recognised by the ICECI development group that maximal comparability with ICD was a necessary design criterion.”*

The need for comparability and complementarity with the ICD is due to the long-standing and entrenched use of E-codes for injury surveillance by governments and hospital emergency departments (as was discussed previously). For example, comparative studies (by country, time period etc.) require continuity of recording and classification systems.

It appears that this need for comparability is longstanding; Bowker (1996) quotes the preface to the fifth revision of the ICD, thus: *"The Conference endeavoured to make no changes in the contents, number and even the numbering itself of various items, so that statistics based on the successive lists should be as comparable as possible, and employees of the registration and statistical services should have their habits of work changed as little as possible. Many possible improvements in matters of form and order were abandoned in order to achieve this practical object."* (League of Nations, 1938).

Today, existing legislative requirements to code injuries against E-codes (or derivations thereof) are a further barrier to comprehensive improvements. In short, wholesale changes to E-codes, as required by injury researchers, appear to be precluded by the need to maintain structural consistency with historical surveillance systems.

The limitations of ICD codes and need for a useful, unambiguous and conceptually clear means to classify injury occurrences is summarised by Viner (1991):

> *"The definitions and classifications foisted on the world by the WHO [i.e. ICD codes], even in their most recent form, conform with no modern model of accidents and in practice are effectively unusable because they do not relate to the reality of what happens during the injury process. They satisfy none of the basic requirements of classifications and can at best, by giving us an example of the worst, help us to understand what these should be:*
>
> *- the model used should represent the pinnacle of understanding in the field;*
> *- the classifications should stimulate measurement and research;*
> *- the items should be objectively factual to the greatest extent that is possible and any judgement required should be removed by the use of conventions which are capable of practical application;*
> *- the classifications should be unambiguous, that is there should be no requirement for personal judgement to be made to select the appropriate classification. The rules should be clearly stated. This requires a statement of convention which has some rational basis;*
> *- the classifications should be practically useful, that is they should assist in the identification of control measures, suggesting the need to use as a basis a model which is of value in this regard.*
>
> *These and other deficiencies in the collection of accident data have stultified research*

> *for at least a quarter of a century. The field is at the brink of being exposed to the full rigour of the scientific method rather than any significant distance down that path."*

As a result of the failure of the ICD approach to provide detailed insight into injury aetiology, injury researchers who wish to deduce aetiological patterns currently need to manually review and classify injury case narratives (which are available alongside coded data in many injury databases). A variety of classification systems unrelated to ICD can then be applied, such as taxonomies based on 'damaging energy type', 'systems/process models' or 'human error' (as will be discussed). The value of using injury narratives to complement coded data is well known, as summarised by the ICECI Maintenance Group (2004):

> *"Inclusion of a description of the way an injury occurred, usually recorded as text in natural language, adds to the usefulness of injury surveillance systems. Detailed (and consequently lengthy) structured descriptions are particularly valuable. An example is the written findings provided by some officials, such as Coroners, who inquire into the circumstances of certain deaths. However, even short descriptions, containing only a few words, can provide information which complements and enhances the value of coded data."*

The manual classification of descriptive injury data to yield insight into injury patterns is an accepted and commonly adopted research methodology; however, detailed insight into an injury problem can require the manual classification of large numbers of cases (i.e. hundreds or thousands of narrative records). This is a laborious and time-intensive process, and incorrect classification can occur. Errors can arise out of ambiguities and inaccuracies related to the classification systems (i.e. systemic errors) as well as human error related to the reliability of the coding task (i.e. random errors). Moreover, the manual classification process must be repeated if another dataset or classification system is selected, or if reliability testing needs to be conducted (e.g. to quantify inter- and intra-rater coding error rates).

The application of computer technology to assist with the manual classification process has thus far been limited to simple data input, storage and retrieval functions (e.g. basic word searches or use of relational databases). Sophisticated technologies such as expert systems and knowledge acquisition techniques have not yet been applied to the problem of classifying injury data aetiologically.

2.4 Summary

Injury research, particularly as it pertains to classifying injury aetiologically, rather than just descriptively, has so far been inhibited by two related limitations:

1. Structural limitation: The absence of a cohesive and validated aetiological taxonomy for injury, and;

2. Methodological limitation: The need to manually classify large numbers of injury cases to determine aetiological patterns (a time-consuming and error-prone task, which must be repeated if a new data-source or different classification system is selected).

These limitations represent a significant impediment for those in the injury prevention and control field (e.g. in the academic, corporate and government domain) who have a need to accurately and reliably deduce useful aetiological patterns from populations of text-based injury data.

The work presented herein is directed at overcoming these limitations to injury research.

The following **Section 3** of this dissertation provides background to the application of the scientific method to understand and classify injury aetiology. **Section 4** outlines the advancement, testing and practical application of an aetiological taxonomy for injury. **Section 5** describes the development, testing and application of a knowledge acquisition software tool designed to automate the classification of text-based injury data.

3.0 BACKGROUND

This section provides an overview of attempts to apply the scientific method to understand and classify injury aetiology, including: the Heinrichian approach; foundations of the epidemiology of injury; advancement of the energy-damage concept, and; summary of modern 'incident-causation' models.

3.1 The Heinrich Doctrine

The most well known early attempt to document an understanding the injury sequence was that of H.W. Heinrich who published the first edition of *Industrial Accident Prevention* in 1941, based on work he completed in the 1930s studying tens of thousands of accident report forms while working for an American insurance company.

Heinrich proposed the 'domino theory' of injury causation based on four edicts: 1. Injuries result only from accidents; 2. Accidents are caused by unsafe acts of unsafe conditions; 3. Unsafe acts and conditions are caused by faults of persons, and; 4. Faults of persons are created by an environment or acquired by inheritance (Heinrich, 1941).

This led Heinrich, famously, to postulate that "*A total of 88% of all industrial accidents … are caused primarily by the unsafe acts of persons*" (with the remaining 10% caused by unsafe conditions and 2% due to acts of God). Heinrich concluded that human failure was at the centre of the injury problem, and that methods of control should be directed towards preventing 'unsafe acts'.

While much of Heinrich's statistical work was of a breakthrough nature in studying injury trends, the unsafe act/condition concept is now widely considered to be such a gross simplification as to limit understanding (Johnson, 1973; McDonald, 1974; Harvey, 1985; Kletz, 1991; Culvenor and Else, 1994; Manuele, 2003). In particular, the use of subjective, judgemental and emotive terminology, the absence of an overall conceptual basis for injury, and the rudimentary cause-effect bias implicit in the 'dominoes' model limit its scientific and practical value.

As such, Heinrich's work is considered to mark the boundary between the pre-scientific era and the growth of intellectual endeavour in the field of safety research (Viner, 1991).

The need to apply a scientific approach to the study of injury and shift from away from judgemental and limiting cause-effect thinking which focuses on 'unsafe acts', draws a historical parallel with the previously discussed shift in the understanding of disease from individual misdemeanour to an ecological paradigm.

3.2 Beginnings of a Scientific Concept of Injury

In 1917, Cornell physiologist Hugh De Haven ruptured his liver, pancreas, and gall bladder and broke two legs in an airplane crash as a cadet in the Royal Flying Corps. The other pilot walked away uninjured. During his convalescence De Haven began to challenge the dominant paradigm that injuries are an inevitable outcome of impacts and accidents.

Over the subsequent two decades, De Haven studied injury thresholds in body mechanical energy exchanges. He found that the extent of injury depends on the interacting characteristics of the susceptible person, the mechanical energy, and features of the impact environment (De Haven, 1942; 1944).

De Haven's work was of immediate and ongoing practical benefit in terms of improving the crashworthiness of occupant environments, particularly with a view to energy absorption and dissipation. His research revealed injury as a phenomena which is both predictable (i.e. non-random) and preventable. While these concepts are well accepted today, at the time this represented a significant advance which is said to have marked the beginning of injury science (Winston, 2000).

3.3 The Epidemiology of Injury

In parallel with Heinrich's and De Haven's work during the 1930s and 1940s, the science of disease epidemiology was progressing rapidly, and contributing to dramatic reductions in the occurrence of infectious disease (as was discussed in **Section 2**).

In 1949, John E. Gordon, Professor of Epidemiology at Harvard School of Public Heath, was the first to realise that biologic principles that govern disease hold equally well for injuries. He suggested that the study of injuries, being characterised by point epidemics, seasonal variation, long-term trends, and determined by ecologic interactions, would benefit from the application of epidemiology (Gordon, 1949).

In his seminal paper, *'The Epidemiology of Accidents'*, Gordon (1949) outlined the beginnings of a conceptual model of injury thus:

> *"An established and satisfactory equilibrium or adjustment between man and his environment leads to the situation called health. A significant disturbance of that equilibrium is the basis for disease or injury. The disturbance may occur either through principal action of the agent, because of a characteristic of the host, or as a function of the environment, but most often all of the three."*

Gordon also emphasised the need to classify and analyse injury data to reveal patterns for prevention and control:

> *"Neither disease or injury in a community can be effectively prevented or controlled without knowledge of when and under what conditions cases are occurring. The method is fundamentally that so well developed for diseases …*
>
> *An analysis of collected data according to the pattern described is believed to be helpful in understanding the origin of accidents, since it provides a framework into which endless scattered observations can be fitted. It involves first recognition of the agent involved, second a determination of the mechanism by which that agent comes into play, and thirdly a definition of cause in terms of combined effect originating from host, agent, and the environment."*

Gordon went on to show that the host-agent-environment model of classical epidemiology accommodates injury epidemiology. Moreover, he revealed that host factors (including age, gender and genetic susceptibility) and environment factors (such as physical - ambient temperature or socio-economic – rural/urban) are often common to both injury and disease phenomena.

However, Gordon also erroneously identified as ‘agents’ such components as a hot iron in a burn injury, powerlines in an electrocution case, and a faulty ladder in a fall-related injury. By way of definition, the concept of an ‘agent’ (in its classic epidemiologic sense) refers to the environmental entity whose action is necessary to produce the consequence of interest and without which it cannot occur. As such, Gordon’s faulty ladder cannot be considered the agent, as the fall (and subsequent injury) can still occur from a non-faulty ladder. It is neither the conceptual nor functional equivalent of the Ross River virus necessary for disease. Just as theoretical and practical problems would emerge if no aetiological distinctions are made between the mosquito (vector) and Ross River virus (agent), so to the faulty ladder, hot iron, and powerlines must be considered as distinct from the underlying agents.

3.4 The Energy-Damage Concept

James J. Gibson, an experimental psychologist, was the first to outline a clear concept for the specific agents of injury (Gibson, 1961), thus rectifying Gordon’s conceptual oversight:

> *“Man … responds … to the flux of energies which surround him – gravitational and mechanical, radiant, thermal, chemical. Some limited fields and ranges of energy provide stimuli for his sense organs; others induce physiological adjustments; still others produce injury...*
>
> *Injuries to a living organism can be produced only by some energy interchange. Consequently, a most effective way of classifying sources of injury is according to the forms of physical energy involved. The analysis can thus be exhaustive and*

> *conceptually clear. Physical energy is either mechanical, thermal, radiant, chemical, or electrical."*

Based on Gibson's work, the aetiologic 'agent' of injury can be clearly conceptualised as the type of energy which went outside tolerable limits of the susceptible structure. To pursue the previous example: thermal energy is the agent of burns; electrical energy is the agent of electrocution, and; gravitational energy is the agent of fall injury. Moreover, the susceptible person in each case will suffer injury or disease based on a certain threshold being exceeded (e.g. tissue resistance to heat flow or electric current).

Gibson (1961) also produced the following preliminary classification of energy types:

> *"Mechanical energy:*
> - *active impact, e.g. due to falling (vertical motion) or colliding*
> - *passive impact, e.g. due to being struck by an object*
> - *interference with breathing, e.g. through 'encountering the wrong medium'*
> - *tool and machine forces*
> - *machine failures, e.g. tyres blowing out, flywheel failures*
> - *animal forces, e.g. due to biting and clawing*
> - *weapon-induced forces*
>
> *Thermal energy - extreme of prolonged heat gain or loss*
> *Radiant energy - e.g. ultraviolet, atomic radiation*
> *Chemical energy – i.e. poisons*
> *Electrical energy – e.g. lightning and reticulated electricity."*

The emerging energy-damage concept was advanced significantly by renowned American epidemiologist William Haddon, Jr. (Haddon, 1967), who summarised the conceptual basis for injury, as follows:

> *"A major class of ecologic phenomena involves the transfer of energy in such ways and in amounts, and at such rapid rates, that inanimate or animate structures are damaged. The harmful interactions with people and property of hurricanes, earthquakes, projectiles, moving vehicles, ionizing radiation, lightning, conflagrations, and the cuts and bruises of daily life illustrate this."*

Haddon (1967) pointed out that, while most injuries occur due to an excess of energy (as per De Haven's work), injuries can also occur as a result of interruptions to normal energy exchanges; for example frostbite (lack of thermal energy), and asphyxia (lack of oxygen). Thus, Haddon was able to extend Gibson's concept of injury, revealing that physical injuries are characterised by an exchange of energy which goes outside (i.e. above *or* below) tolerable limits of the susceptible structure (e.g. human tissue).

This understanding has led to the contemporary definition for injury as: A unit of bodily damage resulting from the transference to the body of amounts of energy in excess of the injury threshold *or from interference with normal energy exchanges* (Wigglesworth, 1972).

Once again there is a clear analogy to disease aetiology; for example, an excess of sunlight can lead to skin diseases (e.g. skin cancer) and an excess of food can lead to heart-disease, while the lack of sunlight or food can result in various nutritional deficiency diseases. Further, in many cases, the aetiologic agents are identical for injury and disease; for example, respiratory arrest due to acute exposure to toxic gas may be labelled injury (e.g. toxic asphyxiation) whereas exposure to low concentrations of the same agent, over an extended time period, may be referred to as disease (e.g. pot-room asthma).

In fact, it became clear to Haddon (1980) that the distinction between injury and disease is based not on fundamental differences in agency, but on differences in time between exposure to the agent and onset of damage manifestation (i.e. the latency period). This finding gives theoretical support for extending disease epidemiology concepts and approaches to the study of injury.

In addition to the conceptual value of considering energy as the 'agent' of injury, the energy concept offers considerable practical benefits, both in terms of classifying injury phenomena as well as identifying control measures aimed at managing the energy exchange. For example, Haddon outlined a hierarchy of control strategies available to counter injurious energy transfers in his well-known paper '*On the Escape of Tigers: An Ecologic Note'*, first published in the Massachusetts Institute of Technology's review in 1970:

"The Strategies

I. To prevent the initial marshalling of the form of energy (e.g. don't climb to a height – work from ground level).
II. To reduce the amount of energy marshalled (e.g. reduce speeds of vehicles, reduce lead content in paint, lower voltages in appliances).
III. To prevent the release of energy (e.g. bolting mine roofs, not arming weapons).
IV. To modify the rate or spatial distribution of release of energy from its source (e.g. brakes, pressure relief valves).
V. To separate in space or time the energy being released from the susceptible structure (e.g. walkways around hazards, machine guarding, traffic lights).
VI. To separate the energy being released from the susceptible structure by interposition of a material barrier (e.g. gloves, child-resistant containers).
VII. To modify the contact surface, subsurface, or basic structure which can be impacted (e.g. crumple zones in cars, narrow crib spacings in cots).
VIII. To strengthen the living or nonliving structure which might be damaged by the energy transfer (e.g. immunization, making structures more earthquake resistant, strengthening muscles before strenuous work).
IX. To move rapidly in detection and evaluation of damage and to counter its continuation and energy transfer (e.g. smoke detectors, emergency alarms).
X. To stabilise, repair and rehabilitate the object of the damage (e.g. post-traumatic cosmetic surgery, fire sprinklers)."

These ten strategies can also be considered in terms of the three classic prevention categories applied in public health, that is: Primary prevention (prevent the injury/disease before it occurs - Strategies I to VIII); Secondary prevention (prevent recurrences or exacerbations of an existing injury/disease - Strategies VIII and IX), and; Tertiary prevention (reduce the severity of the injury/disease – Strategies IX and X). Notably, Haddon's ten strategies do not centre on exhaustively determining causation, per se. Instead, the analytic focus is on control, not cause. This approach yields a variety of practical and conceptual benefits, and as such, the 'hierarchy of control' concept has been adopted widely; for example, it is a central item in a multitude of government regulations and industry standards throughout Australia, and in many places in the world (Culvenor, 1997).

To illustrate the application of the ten strategies, consider a hypothetical case of electrocution of a 10 year old child who inserted a metallic paper-clip into a household power-outlet. A range of potential controls can be readily conceptualised to prevent or control the exchange of electrical energy (and therefore injury), including: manufacture only plastic paper-clips (Strategy I); use lower voltage or DC power points in homes (II); lengthen the power point slots to maximise safe penetration depth (III); fit an earth-leakage circuit breaker (i.e. safety switch) to the household circuit (IV); locate general purpose outlets out of children's reach (V); use protected/guarded power outlets (VI); supervise the child at all times (IX); ensure adult householders know cardio-pulmonary resuscitation (X).

In terms of selecting the most effective controls, Baker (1982) stressed that priority should be placed on proven 'passive' measures (i.e. independent of human behaviour) rather than 'active measures' (which require some specific individual behaviour). For example: vaccination for poliomyelitis is more effective than changing children's behaviour; purifying water is more effective than individual boiling, and; the use of earth-leakage devices (as in the above case study) is more effective than widespread training and supervision of children. This is not to de-emphasise controls directed at individuals; the point is, simply, that efficacy should become the objective measure.

To extend the previous example, consider that there are forty such electrocution cases, all classified as occurring due to 'electrical energy – metal object in power plug'. While each case will likely have vastly different preceding events, all incident sequences will effectively converge at the point in which the damaging energy exchange takes place. As such, any identified control measure which prevents the energy exchange in one case, will prevent injury/death in all cases, regardless of the antecedent events. Thus, an earth-leakage (or residual current) device can be selected as a key control to interrupt electrical flow, even without specific knowledge about why the child placed a metal object in a power plug (just as water purification controls contamination even without knowing the specific causes of the contamination).

In short, it is proposed that one of the key advantages of classifying injury according to the energy involved is that Haddon's ten strategies can be applied to identify control strategies, with a focus on those measures which can prevent or control the energy exchange (e.g.

'passive' engineering controls such as the use of earth-leakage devices, pool-fences, machine guarding, fire sprinkler systems, child-resistant containers, and seat-belts). These benefits are explored by way of case studies later in this document.

The main limitation of the energy-damage construct is that it is based on physical and physiological injuries, and requires extension to accommodate psychological injuries such as mental stress. Prima facie, the process is strikingly similar: psychological stress can be considered to occur as a neurological response to an external stressor, just as injury (and pain) occurs as a neurological response to an external physical stressor. As such, it may be practical to include a 'psychological stressor' or 'psychosocial energy' category in an injury classification, or if semantic issues prove insurmountable, to define the 'agent' as a source of potentially damaging energy *or information* (Viner, 1991).

For example, if a case involves workplace bullying where the protagonist punches one employee (causing physical injury) and verbally threatens another (resulting in mental stress), the cases could be classified as follows:

1. Person struck causing physical injury: Biomechanical (human) energy – physically struck by – another person (fist).
2. Person abused causing non-physical injury (e.g. mental stress): Psychosocial energy – abused/threatened – another person (verbal abuse).

However, a complication is that psychological stress may be attributable to a variety of chemical, noise and/or psycho-social stressors and the severity of outcome depends on the recipient's psychological and neurological response. Further work is required to resolve the issue at a conceptual level.

3.5 Incident Models

Arising from the epidemiologic principles described above, a chronological sequence can be applied to injury causation to form a useful model for analyzing incidents (that is, occurrences which resulted, or could have resulted, in injury or ill-health). Haddon (1980) did so with the establishment of the 'Haddon Matrix' which has two dimensions:

1. Factors - human, vehicle, and environment;
2. Time phases - pre-event, event, post-event.

Over the last two decades, this matrix model has formed the conceptual basis for the analysis of motor vehicle crashes (National Committee on Transport, 1996). The *energy model* has also been translated, in a myriad of derivations, to the analysis of occupational and home incidents. For example, Andersson and Menckel (1995) provided a detailed summary of eleven commonly employed injury models, observing that they all incorporated a time dimension, along with human, agent, and environment factors. The various dimensions were illustrated graphically in a composite model for injury prevention, reproduced as **Figure 3.1** below.

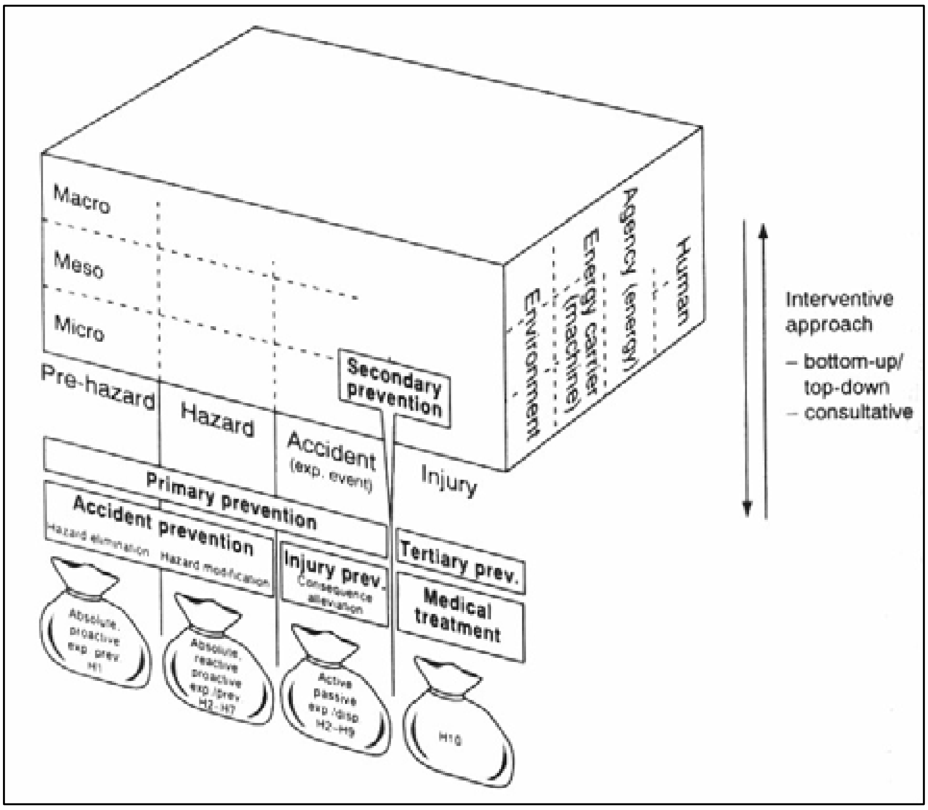


Figure 3.1 A composite model for injury prevention (Andersson and Menckel, 1995). The 'sacks' contain concepts related on other dimensions than time, with H1 to H10 referring to Haddon's ten strategies.

This composite model extends the original Haddon matrix and presents a three-dimensional view of injury aetiology:

1. Causative Factors – human (host), vehicle (energy carrier), agency (energy), and environment;
2. Time phases – pre-hazard, hazard, accident (exposure to energy), and injury;
3. Intervention level – micro (individual), meso (group), macro (organisation/society).

As described in the text *Injury and Violence Prevention* (Gielan and Sleet, 2003), the energy concept forms the basis for the current scientific understanding of injury, and is widely-accepted as a useful means to conceptualise control measures.

However, researchers such as Kjellén (1993) and Rasmussen (1997) point out that the aforementioned *energy model,* while providing conceptual clarity and a useful focus on proximal causative factors, has weaknesses in terms of providing insight into upstream factors (such as organisational and societal issues). The identification of high level antecedent factors is particularly important when analysing complex individual incidents/accidents (as opposed to classifying large numbers of injury reports). What follows is an overview of the range of analytical models which have been developed for the purposes of detailed post-incident investigations.

The earliest formal incident investigation methodologies emerged from systems theory, and thus are known collectively as *systems models*; notable examples include fault tree models (Leplat, 1978) and the Management Oversight and Risk Tree (MORT) analysis technique (Johnson, 1975). Such models highlight the logical relationship between antecedents, including organisational systems issues, and require training to be used correctly (Ferry, 1981). As such, these models are best suited to investigating complex, large scale disasters (e.g. air-crash investigations, and catastrophic events like Bhopal and the Challenger explosion).

An alternative approach involves *process models*, where incidents are analysed in terms of a multi-factorial chronological sequence (as opposed to a graphical fault/event tree). This includes the 'multi-linear events sequencing' approach of Benner (1975) and the Swedish ISA system (Lagerlof and Andersson, 1979), whereby the investigator/team systematically work back from the incident event in order to identify causal antecedents and pertinent preventative actions. Kjellén (1984) introduced the concept of analysing incidents in terms of 'deviations' from the accepted norm (including irregular workloads, production disturbances, unsafe acts, errors etc). There is a link with the energy model in that deviations that describe the loss of control of energies are characterised by the type of energy involved (Kjellén and Hovden, 1993). Preventative actions are the aimed at: reducing the probability of deviations; reducing the consequences of deviations, and; reducing the time from occurrence of deviations to their identification and correction. Such models are useful for a wide range of incident investigations, regardless of the severity and complexity of the event, and are best applied in complement to systems models (Torsteinsmd et al, 2001).

The literature pertaining to the incident investigation process is large and is comprehensively reviewed elsewhere. For example , a complete assessment of the 15 most common variations of the systems and process incident investigation models (and composites thereof) is provided by the US Department of Energy report *'Conducting Accident Investigations'* (1999); importantly, the authors conclude that the models are not incompatible with one another, each simply stresses different aspects. The common underlying principle is that the incident investigation process is reduced into a large number of 'break-down events' which are further scrutinised in order to identify causal factors and potential control measures. By definition, the application of these models is 'open-ended'; that is, the number of causal factors identified is not limited or pre-defined.

As a result, such systems and process models are well placed for post-incident investigations, but have little utility in terms of classifying large numbers of brief incident reports to discern aetiological patterns (which is the focus of this thesis). This point is emphasised in the paper *'The classification of accident data'* (Lortie *et al*, 1999), as follows:

> *"An understanding of the underlying causes of accidents is essential for their prevention… Several models have been proposed to extensively analyse accident circumstances in order to develop pertinent preventative actions. However, these models rely on detailed post-accident investigations, while prevention strategies in industry are often based on the retrospective analysis of brief accident reports, usually completed following the injury."*

The remaining family of incident models to be examined can be collectively described as *information-psychology (or 'human error') models*. The focus here is on the role of human behaviour or, more specifically, human error in incident sequences; thus adding a useful alternative perspective to the investigative process. These models include: the task-demand model of Waller (1973); Surry's decision model (1974); Rasmussen's cognitive performance approach (1982), and; James Reason's swiss-cheese and resident pathogen models (1990; 2000). An attempt to quantify the probability of operator errors arising from so-called 'error producing conditions' such as 'unfamiliarity with the task' was made by Williams (1988), leading to the Human Error Assessment and Reduction Technique (HEART). These multifactorial human error models built upon the seminal research of Hale and Hale (1970) which debunked the longstanding twin myths of accident proneness and uni-causality.

In contrast to the aforementioned systems and process approaches, these models are generally 'closed-ended'; that is, there are a finite number of pre-defined categories of human error. Thus, as for the energy model, the human error approach lends itself not only to individual incident analysis, but also to incident classification (as will be discussed).

Most recent attempts to classify human errors are based on Professor James Reason's 'resident pathogen model', which has been widely adopted in the analysis of occupational, nuclear and aviation incidents. The underlying premise is that latent failures in technical systems are analogous to resident pathogens in the human body, which combine with local triggering factors to cause incidents (see **Figure 3.2** below).

According to Reason's model, an incident sequence progresses as a result of swiss-cheese like holes in the defences, comprising ‘active failures’ and ‘latent conditions’, which are described as follows.

Active failures are unsafe acts committed by people who are directly connected with the incident (e.g. operators, pilots). They take a variety of forms: slips, lapses, fumbles, mistakes, and procedural violations. Active failures have a direct and usually short-lived impact on the integrity of the defences. For example, the Chernobyl operators mistakenly violated plant procedures and switched off successive safety systems, thus creating the immediate trigger for the catastrophic explosion in the core.

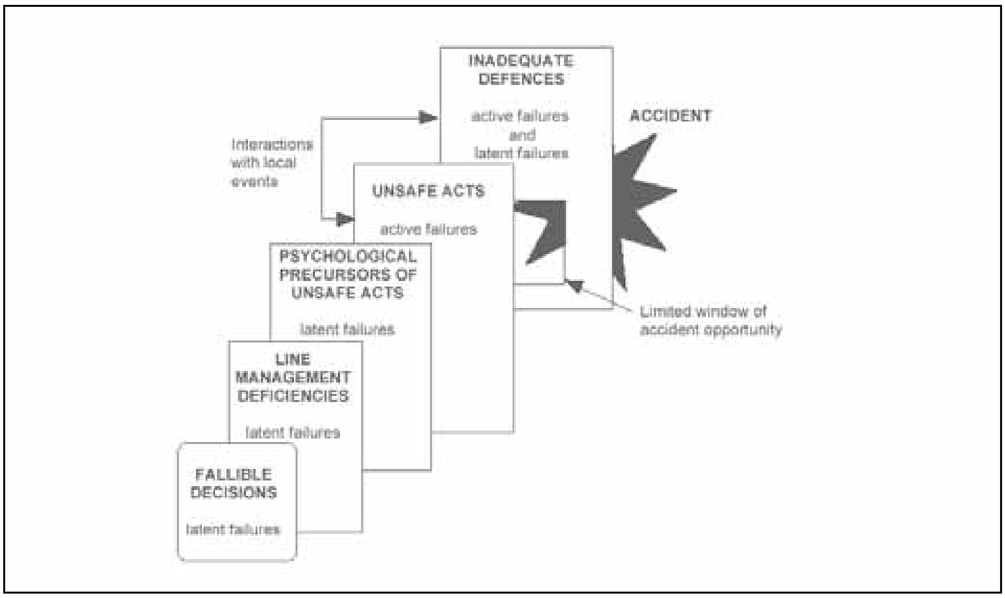


Figure 3.2 Latent Pathogen Model for Accident Causation (Reason, 1990).

Latent conditions are resident pathogens within the system which may remain dormant for many years. They arise from decisions made by designers, builders, procedure writers, and top level management. All such strategic decisions have the potential for introducing pathogens into the system. Latent conditions have two kinds of adverse effect: they can translate into error provoking conditions within the local workplace (for example, time pressure, understaffing, inadequate equipment, fatigue, and inexperience) and they can create long-lasting holes or weaknesses in the defences (untrustworthy alarms and indicators, unworkable procedures, design and construction deficiencies, etc).

Arising from such models, a number of human error classifications have been developed to categorise the: Type of mistake (e.g. rule-based, skill-based or knowledge-based) after Rasmussen (1982); Intent (e.g. errors versus violations) as described by Senders (1991), and; Latency of the error (e.g. immediate active failures versus latent conditions) as outlined by Reason (1997). There are many existing derivations of the human error model; an industry-specific example is that of RAIT (Railway Accident Investigation Tool), where 'railway problem factors' such as time pressures and lack of supervision are identified as causal factors (Reason, 2000).

The most widely adopted generic classification is that of the Human Factors Analysis and Classification System (HFACS), which defines and categorises human error at four levels of failure: 1. unsafe acts of operators; 2. preconditions for unsafe acts; 3. unsafe supervision, and; 4. organizational influences. HFACS is derived from Reason's Generic Error Modelling System (GEMS), which, in turn, was based heavily on Rasmussen's skill, rule, and knowledge based error categories (Reason, 1990). The HFACS framework has been used in the commercial, aviation, and military sectors to systematically examine underlying human causal factors (Shappell and Wiegmann, 2000); for example it has been adopted by the US Federal Aviation Administration (FAA) and the US Military. **Figure 3.3** depicts the categories of errors and violations forming part of HFACS.

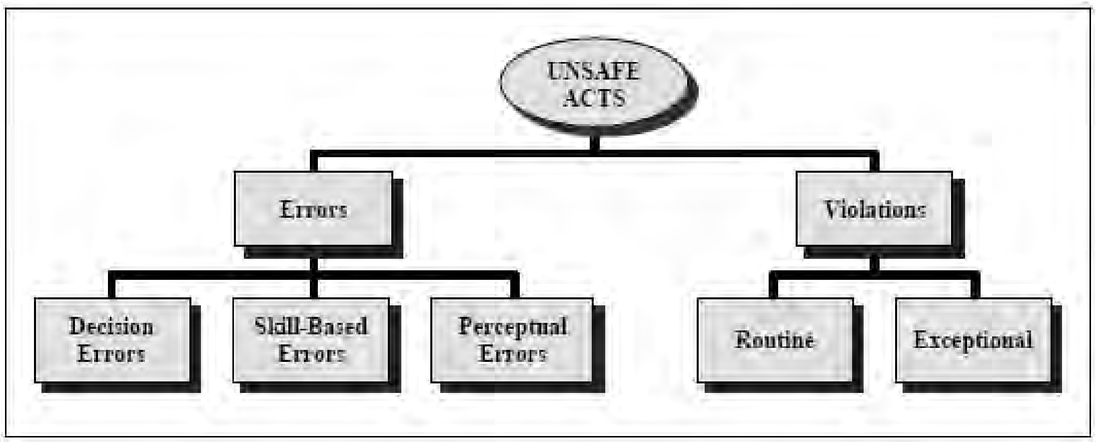


Figure 3.3 Classification of 'Unsafe Acts' from the Human Factors Analysis and Classification System (HFACS).

Such 'human error' approaches are critical to understanding and classifying failures relating to local human factors, as well as higher-level organisational factors and management deficiencies. This information can then form the basis of interventions such as improved human factors design (at the micro-level) and/or strategies focussed on such things as management decision making and organisational culture (at the macro-level). A key advantage is that organisational and cultural reasons can be identified for why physical controls were not put in place or used (e.g. why was the protective gas mask not worn?).

For example, in a study of train incidents, Reinach and Viale (2006) demonstrated that HFACS is a useful approach to guide analysis and: *"enabled the capture of both low-lying fruit of operator acts (Reason's active failures) and the higher-hanging fruit – the preconditions for operator acts, supervisory factors and organisational factors (i.e. latent factors and conditions)."*

However, while these models are useful to help identify relevant human factors, their aetiological focus is, by definition, limited primarily to human behaviours and errors. Moreover, it is often the case that underlying such approaches is the Heinrichian construct of 'unsafe acts', which, as discussed, has been discredited due to significant limitations. For instance, the unsafe acts concept features prominently in the James Reason and HFAC models, as can be seen in the previous **Figures 3.2** and **3.3**.

In a recent critical review, Dr Andrew Hopkins of Australian National University outlined limitations of the Reason model, including that it highlights unsafe acts as the immediate cause of injury and does not allow for the possibility that latent failures may cause defence failures directly, even in the absence of unsafe acts (Hopkins, 2003). More generally, Larsson and Hale (2000) point out that the common paradigm of injury being the result of individual behavioural failure has resulted in archaic, low-grade, individualistic, and inefficient controls.

By way of example, according to the Reason approach, the previous case of electrocution of a child (who inserted a metallic paper-clip into a household power-outlet), can be considered in terms of: active failures (e.g. unsafe act/error of the child, unsafe act/supervisory lapse of the parent), and; latent conditions (e.g. lack of experience of the child with electrical safety, availability of metal paper-clips, weakness of defences to prevent contact with electricity). It is evident that this focus on human error and behaviour does not yield detailed insight into effective countermeasures (such as 'passive' engineering controls like an earth-leakage safety switch) to the same extent of the Haddon 'energy' approach. As stated by the Australian Industry Commission (1995): *"Only very limited, if any, control is possible by focussing on the behaviour of those who may be injured"*.

Practical limitations associated with the subjective classification of human error have also been reported by a number of authors (Dekker, 2003; Manuele, 2003; Hollnagel, 2001). For example, in a seminal paper entitled '*A Critical Essay on Error Classification',* Dr Sidney Dekker (2003) showed that many assumptions underlying error classifications remain untested and that error classifications can deepen investigative biases. Likewise, in the textbook '*On the Practice of Safety'*, Manuele (2003) outlines the practical difficulty in adequately defining and objectively classifying 'unsafe acts' and other forms of human error.

Hollnagel (2001) outlines a study involving the coding of 28 incident reports by three experienced analysts against an established human error model with which the analysts were familiar. The average inter-coder reliability was found to be only 42%, well below the level of 75% that is deemed to represent an excellent agreement beyond chance (Landis and Koch, 1977). These poor reliability results were attributed to ambiguities of the model as well as 'contextual' variations between observers:

> *"The lesson is that a classification always implies a context, but that the context of one observer may be quite different from that of another, and different again from that of the person [who is involved in the incident]. It is furthermore impossible in a conceptual framework to define an absolute or reference context relative to which actions can unequivocally be classified as right or wrong.*

> *Since the context implied by most human error taxonomies actually is very sparse because the supporting theories of human action usually are insufficiently articulated, it follows that it is both principally and practically impossible to use such taxonomies to classify 'errors' in a reliable fashion."*

Another study, involving the coding of 119 aircrew-related accidents by two experts using the HFACS framework, yielded higher reliability results; the observed inter-coder agreement was determined to be 71% (Wiegmann and Shappell, 2001). While this result is significantly better than that achieved by Hollnagel (2001), the implied residual error rate of 29% remains excessive (particularly given that the study involved two coders who were experts in the HFACS approach). As will be discussed, it is desirable to reduce manual coding error rates to below 5% (this implies a target inter-coder reliability of 95%).

In sum, a range of approaches can be taken to the problem of understanding and classifying injury aetiology. While each approach will have strengths and weaknesses, there is no inherently 'right' or 'wrong' approach or model; the test is whether the resulting classification system can be applied reliably in practice, and is 'useful' with respect to discerning aetiological patterns and helping identify efficacious control measures. Moreover, injury occurrences are complex phenomena, and it is unlikely that any single approach will prove completely satisfactory in isolation.

3.6 Classifying Injury Aetiology

Based on the discussion above, it is hypothesised that a logical and meaningful starting point for an aetiological classification should be the fundamental causative agent of injury; that is, damaging energy. This ensures that the basis of the classification system is conceptually sound, rather than being based on arbitrary descriptors (such as the flawed ICD E-codes) or based on judgmental cause-effect constructs (such as the idea of 'unsafe acts').

As Haddon (1973) pointed out:

> *"An important landmark is reached in the evolution of a scientific field when classification of its subject matter is based on the relevant, fundamental processes involved rather than on descriptions of the appearances of the phenomenon of interest."*

Moreover, in a recent critical evaluation of the range of available injury classification systems, Viner *et al* (2003) conclude that the energy concept is arguably the only underlying concept with relatively wide acceptance amongst injury researchers.

The beginnings of a functional energy classification have been established by a number of researchers by extending J.J. Gibson's preliminary classification to include the following list of 12 energy types (Haddon, 1967; Baker, 1982; Viner, 1991; McDonald, 1995; Wigglesworth, 2001):

Chemical (toxic, allergenic, corrosive, reactive)
Microbiological (infection, pathogen, mutagen, parasitic)
Electrical
Radiation (electromagnetic, ionising and non-ionising)
Thermal (fire, heat or cold)
Vibration
Noise (acoustic)
Explosion
Gravitational potential: Falls of people, Falls of objects
Kinetic: Vehicle, Machine, Object
Biomechanical (muscular effort of humans and animals)
Atmospheric pressure (oxygen toxicity, suffocation, drowning)

As can be observed, there are a limited number of energy types with which human beings interact; this provides a finite and logical boundary for the first level of an aetiological classification for injury.

The energy classification shown above is commonly referred to in tertiary safety science and injury epidemiology syllabi. It has also been applied in practice by a number of researchers in the manual classification of text-based injury datasets (Ernst, 1996;

McDonald, 1997; Hale and Swuste, 1997; Manuele, 2003).

However, further work is required before the energy classification can become a viable and widely accepted methodological tool for classifying injury aetiology. In particular:

1. While the first level of the energy classification is reasonably well defined, subsequent levels are currently subjectively determined by individual researchers, rather than being subject to standardization.

2. The existing classification has not been subject to validation testing. For example, there are no studies available which assess whether each injury case can be coded unambiguously into a single classification category, and to quantify coding accuracy and reliability amongst different coders.

3. Although the conceptual utility of the energy-damage approach is widely supported, there are few published assessments of the practical outcomes of applying the energy classification (in terms of yielding patterns useful for injury prevention and control).

4. Finally, given the widespread and entrenched historical use of ICD classifications to code injury events, any alternate classification system will need to be applied retrospectively (with injury narratives being coded manually). As discussed previously, this constraint has proved to be a strong disincentive to the development and application of alternate injury classifications. Thus automation will be required for any new classification system to be of widespread, practical use.

The challenge is to overcome these limitations. This should yield progress towards the development of a more comprehensive method for classifying injury occurrences aetiologically.

The need for such progress was summarised by Wigglesworth in a paper entitled *Injury Control – Part of Risk Management* (1997):

> *"To meet the scientific requirement … present accident classifications (which are based on an elderly WHO system) need revision to bring them in line with modern scholarship. Ideally they should be based on an analysis of the type of energy delivered.*
>
> *Whatever the type of energy, an approach which sequentially attempts to identify, and to quantify, to evaluate and then to control the risk of unplanned energy delivery is an appropriate and modern framework for the important task of injury control."*

The following section of this dissertation outlines the advancement of an aetiological classification for injury, building on the existing body of research.

4.0 ADVANCING A TAXONOMY FOR CLASSIFYING INJURY DATA AETIOLOGICALLY

This section outlines the formation, testing and practical application of a taxonomy for classifying injury aetiologically; that is, according to the energy type which was released resulting in injury.

4.1 Defining a Cohesive Classification Structure

In order to meet the need for a cohesive and unambiguous injury taxonomy, it is necessary to first define a conceptually clear classification *structure.*

With the first level already established as the type of energy involved, it is proposed that subsequent classification levels should elucidate 'how' the process leading to injury unfolded (i.e. provide insight into aetiology). A logical three-level structure has been put forward by Viner (1991), as follows:

Classification Level	Basis of classification
I	Energy type (e.g. chemical energy)
II	A structure based on mechanisms (e.g. ingested, inhaled)
III	Circumstances and Conditions (toxic gas, fumes etc)

Levels I and II of the classification appear sound, and satisfy the need to capture both agent and mechanism data, or as Gordon (1949) espoused: "*understanding the origin of accidents … involves first recognition of the agent involved, second a determination of the mechanism*".

Viner (1991) suggested that level III should be based on a description of the 'circumstances or conditions' of each injury case. However, this definition is unnecessarily broad and lacks clarity in comparison with the logical basis for levels I and II. It is proposed that progress lies in adopting, as level III, the epidemiologic concept of transmission vehicles and vectors to define the 'source' of the energy transfer. Thus, just as the mosquito is a transmission vector for the infectious disease agent, so too are electrical powerlines the vehicles of electrical energy, and motor-cars the vehicles of kinetic energy. In this fashion, the source of the energy transfer can be considered as distinct from the underlying agent and the mechanism of transfer.

By assimilating the above concepts, injury aetiology can be clearly conceptualised in terms of transfer of a distinct energy *type* (level I) by way of a specific *mechanism* (level II) from an energy *sourc*e (level III). For example, burns result from a transfer of thermal energy (energy type) by way of contact with hot liquid (mechanism), originating from boiling tap water (source).

As such, a conceptual taxonomic structure is proposed which consists of a standardised hierarchy, defined by the following three discrete taxon levels:

Level I: Energy type – describes the type of energy of which control was lost, resulting in energy being released or transferred, leading to injury. These energy types are finite and, based on previous research, include: gravitational energy (falls of people and falls of objects); kinetic energy (moving vehicles, objects, and mechanical machinery); electrical energy; thermal energy; chemical energy; radiation energy; biomechanical energy (muscular energy of humans or animals); and; microbiological energy (e.g. infection).

Level II: Mechanism – describes the means by which (i.e. how) the energy was released, transmitted or transferred (having regard to interactions of the human, vehicle/vector and the environment). Such mechanisms can be categorised using easily understood descriptive terms, such as: fell from a height (for gravitational energy); crash/collision or run-over (kinetic energy – vehicles); struck/crushed by (machinery); punctured/cut by (projectiles); burnt by (thermal energy); inhaled/ingested/absorbed (chemical energy); stung/bitten by infected animal (microbiological energy); et cetera.

Level III: Energy source – describes the origin or source (i.e. the object, substance or entity) which conveyed the energy. For example, in the case of electrical energy, sources include: overhead powerlines; fixed wiring; tools/equipment and appliances; underground powerlines, and; electrical storms/lightning. For the case of thermal energy, sources include: fire/flame (e.g. bushfire); hot liquid/gas (e.g. hot drink); hot objects (e.g. bar heater), and; excessively hot/cold ambient temperatures (e.g. hyperthermia/hypothermia).

This three tiered structure is analogous to the classic epidemiological model for infectious disease, whereby disease occurs as a result of transmission of an agent (e.g. influenza virus) by way of a mechanism of transmission (e.g. sneezing/airborne droplet spread), originating from the source/carrier (e.g. infected person). This alignment with established principles of disease epidemiology provides strong theoretical support for the proposed framework.

The following **Figure 4.1** depicts the underlying conceptual structure for the proposed injury taxonomy, in terms of a combined fault/event tree; also known as an occurrence-consequence diagram after Viner (1991) and Lees (1995).

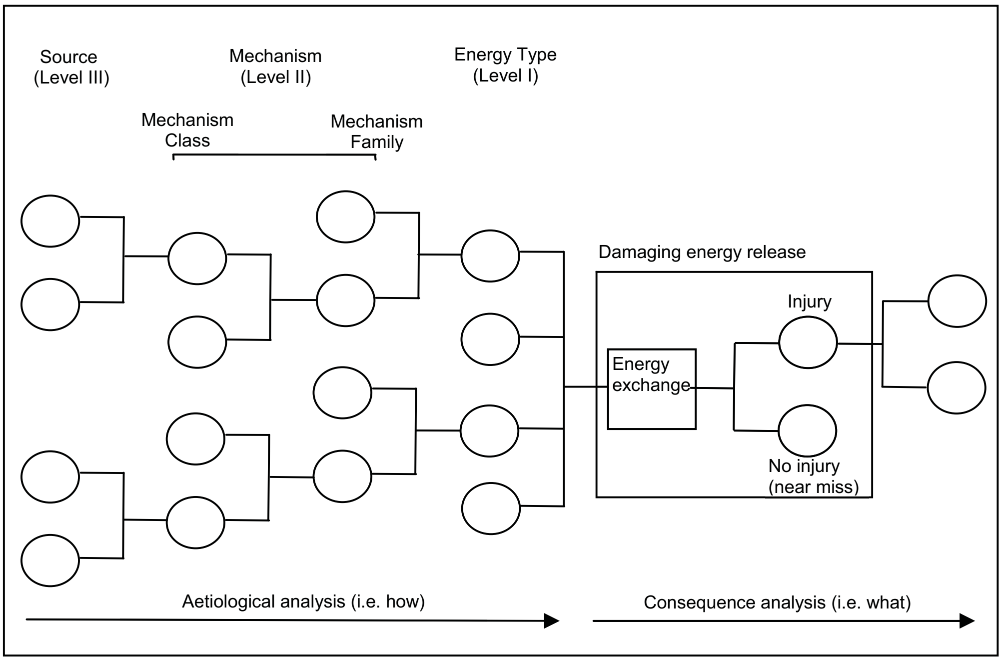


Figure 4.1 An occurrence-consequence diagram to visualize the proposed conceptual structure for classifying injury aetiology.

A key benefit of adopting this type of multi-level (or taxonomic) approach is that critical associations between data are retained. This enables more insight to be gained into the process leading to injury (i.e. how it occurred) such that control measures can be identified and directed at preventing and controlling the energy transfer relating to each of the three levels.

Taxonomy is one of the oldest and time honoured of the scientific methods; amongst the more well-known applications include the periodic table of elements (in chemistry), and the genetic classification of animals and plants into species, family, phylum et cetera (in zoology). Taxonomic classification is based on observation, description, and recognition of common patterns and individual differences. The concept of applying the taxonomic approach to classify injury is summarised by McDonald (1995) who points out that a classification system needs to be developed out of the phenomena that are being classified, and that data should be organised into a useful form to enable people to make decisions about action to be taken. He goes on to state that: *"Compilation of data into preconceived and disconnected tabulations is far less helpful."*

With the taxonomic structure defined, it is necessary to clearly outline the individual *classification categories* (or taxons). With respect to energy type (level I), categories can be comprehensively compiled by extending the work of injury researchers described in **Section 3**. The mechanism (level II) and source (level III) categories can be clearly defined and standardised by adapting the established International Classification of External Causes of Injuries (ICECI) catalogue of injury mechanisms and underlying objects/sources (known as Module C2 - Mechanism of Injury, and Module C3 - Object/Substance Producing Injury).

The individual classification categories of the proposed taxonomy are presented by way of a detailed matrix in **Appendix I**. In addition, **Figure 4.2** on the following page shows a partial breakdown of the complete taxonomic structure, sampled from the full matrix (for visualisation purposes only).

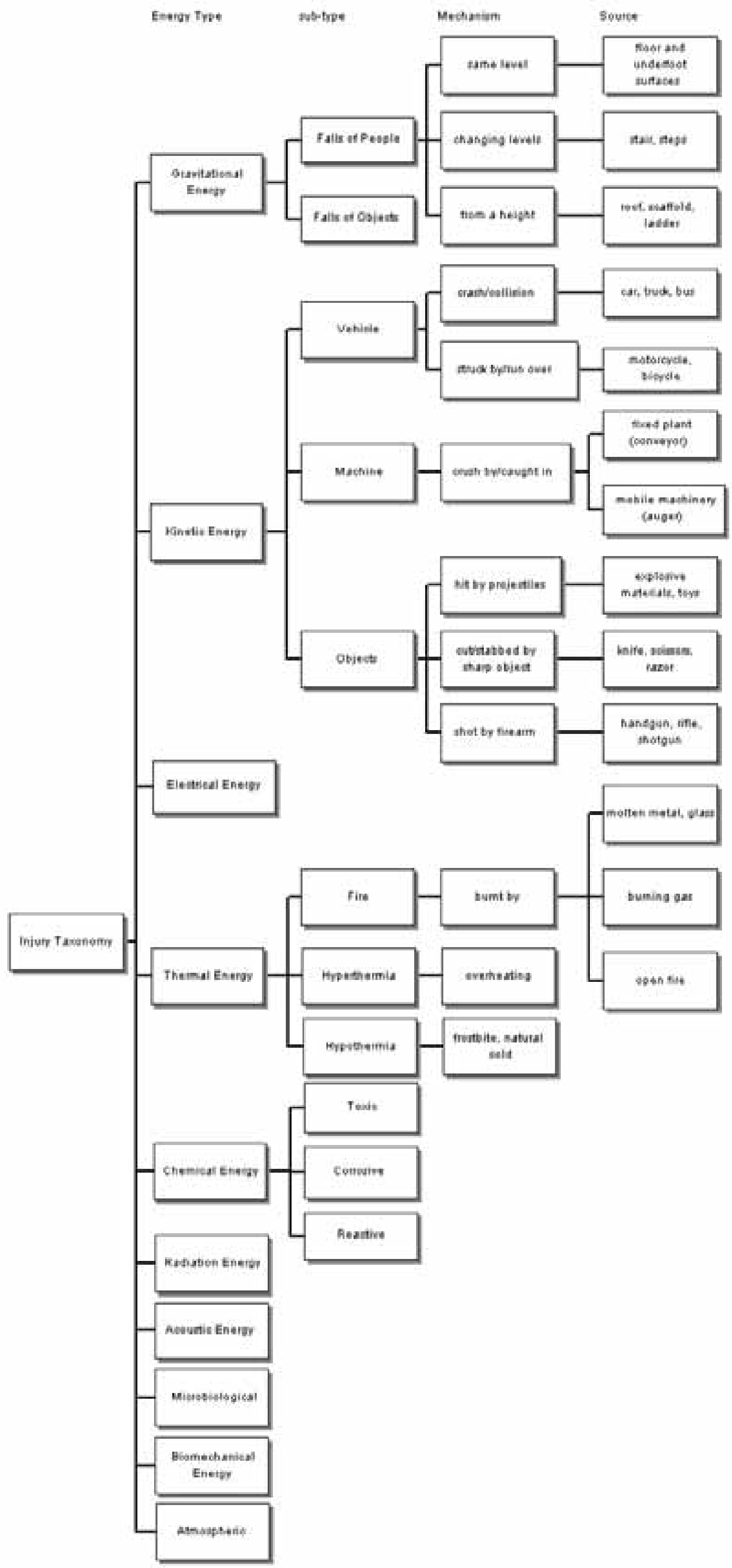


Figure 4.2: Partial (sample) breakdown of the injury taxonomy, extracted from Appendix I.

One of the key advantages of a detailed taxonomy is that it provides an economical and holistic description of the full variety of the phenomena under study, with patterns naturally emerging based on the relative numbers of cases in each group. Further, once an injury case is classified into its appropriate group, a lot is already known about it because of the known characteristics of cases in closely related groupings.

By way of example, the previously described case of electrocution of a child who inserted a paper-clip into a household power-outlet could be classified in terms of 'energy type - mechanism – source' as: *'Electrical Energy – Contact with live conductors (via metal object) – Power point'*. As such, the incident can be grouped with other similar occurrences (e.g. incidents involving insertion of objects like nail-files, wires, coins and keys into power points). As more incidents are grouped into this specific category, the relative frequency of this type of incident becomes known, allowing the researcher to study the incident-type in more detail (e.g. by applying Haddon's hierarchy of control strategies). As before, the use of an earth-leakage circuit breaker was identified as a key control as it effectively prevents the energy transfer (regardless of the preceding sequence).

While the taxonomy is presented as a static and uni-directional structure, it is pointed out that the three classification levels can be transposed depending on the research need. For example, it may be desirable to classify injury cases by a specific 'source' which may be of particular interest (e.g. injuries involving a mobile crane, baby pram or trampoline). In such cases, an appropriate taxonomic structure may be 'source – energy type – mechanism'. Note that the while the structure is adaptable to the research need, the individual classification categories do not change and critical associations between data are retained. The analogy is classifying disease according to the mosquito carrier, rather than by disease agent.

In sum, the following key features of the proposed injury taxonomy have been adopted in order to help overcome the previously outlined limitations of existing classification systems:

1. Clear conceptual basis – the first level of the classification structure is based on the

fundamental aetiological agent of injury (that is, energy), as opposed to arbitrarily defined E-codes or judgmental cause-effect constructs such as ‘unsafe acts’. This should also allow for application of Haddon’s ten energy management strategies (as described above).

2. Taxonomic classification structure – the three level ‘energy-mechanism-source’ hierarchy is designed to provide a cohesive multi-dimensional view, such that, for each classified injury case, a working level of detail regarding causation can be retained. This can be compared to traditional classification systems where the original identity of the data is lost in the process of coding injury cases into unrelated uni-dimensional codes (see **Section 2.3**). As above, this multi-dimensional view also allows flexibility in how the data is analysed (e.g. by source, mechanism or by energy, depending on the research need).

To ensure that the proposed injury taxonomy is unambiguous, such that each injury case has only one correct position within the structure, it is necessary to define a clear set of conventions for the classification of cases which involve multiple energy types, mechanisms and/or energy sources.

It is proposed that the key *reference point* for the set of conventions be defined as the point of initial loss of control which precipitated the dominant incident sequence. For example, the point at which a driver loses control of a vehicle (kinetic energy), the point at which a person slips and loses balance (gravitational energy), or the point at which contact is made with overhead powerlines (electrical energy). Further, it is proposed that the *consequence of interest* be specified as the principal injury (i.e. the highest severity outcome). In this fashion, the classification system is anchored by the principal phenomena of interest – i.e. the loss of control event which led to the dominant outcome.

The resulting set of classification conventions can be expressed as follows:

1. The energy type is defined as the energy of which control was lost, precipitating the dominant injury sequence. For example, if a person falls off a ladder from a height

causing severe injury, this convention calls for the energy type to be classified as 'gravitational energy', as this is the key energy type released by the fall from the ladder (before being transformed into kinetic energy during the fall).

2. Where multiple energy types, mechanisms or sources are involved, classification is based on the underlying energy type, mechanism or source which resulted in the most severe injury (i.e. the most significant energy type, mechanism or source). In the example above, if the person received a mild electric shock from a faulty tool prior to falling off the ladder, the energy type would remain 'gravitational energy' as the dominant injury resulted from the fall (rather than from the electric shock). In this fashion controls can be identified which are focussed on the key energy exchange which ultimately resulted in injury. Any other energy-transfer events (i.e. the electric shock event which precipitated the fall) can be classified into mechanism family and class sub-categories.
3. If the injuries are equally severe (or indeterminable), select the underlying mechanism and energy source that appears first in the chronological sequence.
4. If it is not possible to determine the energy type, code as 'not classifiable'.
5. If it is not possible to distinguish between mechanisms or sources, code the case by energy type (level I) and classify levels II and III as 'unspecified mechanism' and/or 'unspecified source', as appropriate.

The proposed taxonomy and set of conventions were outlined in a paper entitled '*Injury Aetiology: an ecological energy model*', delivered by the author at the WHO 5th World Conference on Injury Prevention and Control (Shepherd and Cross, 2000).

The hypothesis is that the proposed taxonomy, with its defined cohesive structure and clear set of conventions, can be applied with high coding accuracy and reliability. Further, it is hypothesised that classifying injury cases according to the energy type, mechanism and source will yield practical insight into key injury problems.

The objective of this work, then, is twofold. First, to test the proposed taxonomic classification system for coding accuracy and reliability. Second, to apply the taxonomy in practice to key injury problems, trial its adaptability to different databases, and assess the utility of the resulting classification patterns.

The following sections of this report outline: the research method adopted (**Section 4.2**); the results of testing and application of the taxonomy (**Section 4.3**), and; a detailed discussion of the findings (**Section 4.4**).

4.2 Test Method

The following subsections describe the methodology adopted in the testing and subsequent practical application of the proposed injury taxonomy. The testing process is depicted in **Figure 4.3** below.

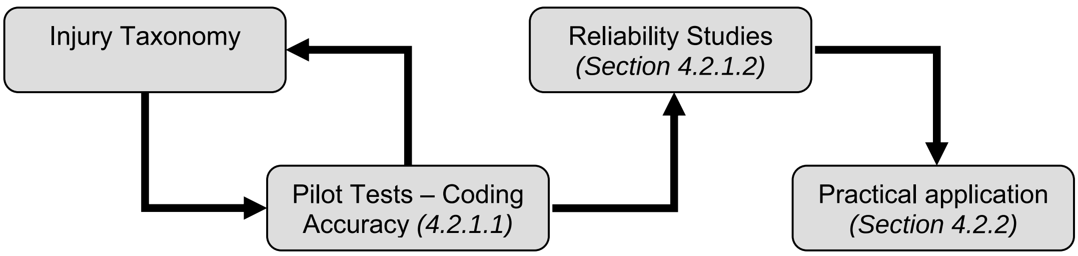


Figure 4.3: Research and Development process for Injury Taxonomy

4.2.1 Testing of Injury Taxonomy

The injury taxonomy was subjected to a series of tests to quantify the coding accuracy and reliability (including intra-coder and inter-coder reliability), as follows.

A test dataset comprising 400 randomly sampled occupational fatality cases for the years 1989-1992 was sourced from the National Occupational Health and Safety Commission (NOHSC, 1998). These data derive from Coroners' records of unintentional death, as investigated by Australian State and Territory Coroners.

The NOHSC injury cases contained between 3 and 10 lines of text narrative and represented a wide variety of unintentional work-related circumstances. A representative sample case extracted from the NOHSC dataset is as follows:

> *The deceased was a 50 year old male plant operator who died of a crush injury to the abdomen when he was run over a by scraper at a road construction site. The roller operator, who was travelling in the opposite direction with the grader adjacent to him, looked back and saw the deceased bending over on the roadway, probably picking up a rock, such action being part of his job. The deceased obviously did not see the scraper and the noise was too loud to allow the deceased to distinguish the sound of the approaching grader, nor the roller operator to warn the scraper operator or the deceased.*

The 400 cases were manually reviewed and coded, as per the test regime outlined below. Manual coding was completed against the 'Energy Type – Mechanism – Source' taxonomy for each case. For example, the above case was classified as 'Kinetic energy (mobile machinery) – Run over by – Scraper'. Selection of the appropriate classification category was based on semantics of the injury description, as interpreted by the coder's decision-making rules. In this case the words *"run over by scraper"* in the context of *"died from crush injury"* led to the classification conclusion.

4.2.1.1 Testing for Accuracy

The accuracy of a result or procedure refers to the conformity between test results and the accepted values. In the current context, the coding accuracy associated with the proposed taxonomy can be measured in terms of coding agreement between independent coders and an accepted 'expert record'. The expert record is also known as an expert-generated 'gold standard' in qualitative statistical research terminology (Hripcsak, 2005).

To establish the accepted expert record, the 400 injury cases comprising the test dataset were reviewed and classified by the author over a period of four days. This classification process was repeated 8-weeks later, with results compared to develop an accurate gold standard. The 8-week time period was selected to maximise independence of the recoding process, and minimise any recollection bias. This process also allowed for testing and minor refinement of the proposed injury taxonomy and associated conventions in practice. The expert record was verified during subsequent inter-coder reliability tests (with a consensus arrived upon in the case of any divergent coding).

Four study participants were selected to be trained as coders and apply the taxonomy to the test dataset. The four subjects were chosen at random from a secretarial staff listing (drawn from the author's workplace). The subjects were diverse in terms of age and gender, and had no prior knowledge nor experience in either injury classification or the energy-damage model (i.e. they were 'novices' with respect to the classification task, the energy concept, and accident analysis in general).

The study participants were provided with the proposed injury taxonomy, coding rules and conventions, as well background material for their review. They subsequently attended a 4-hour group training session seven days later, with a detailed presentation of the injury taxonomy, coding rules and conventions provided by the author (as per the previous discussion).

The four trained coders were then asked to review and independently classify the 400 injury cases against the proposed injury taxonomy. In addition, the subjects were instructed to identify any ambiguous cases, and record as 'not classifiable'. Classification data were entered by the coder as each case was individually processed and classified. The coding time was recorded for each case. The process was completed over a period of four days. The four coders were then asked to recode the same dataset 8-weeks later.

The classifications submitted by each coder were then compared to the expert record to determine the accuracy in applying the injury taxonomy. Outcome metrics included percent agreement and the kappa statistic (as described below).

4.2.1.2 Testing for Reliability

Reliability refers to the extent to which a test or procedure yields the same result on repeated trials (Carmines and Zeller, 1979). For the purposes of this testing, reliability can be defined as the inter-coder and intra-coder agreement in applying the injury taxonomy.

The kappa coefficient, expressed as a percentage, was used as a quantitative measure of reliability. This statistic provides a more rigorous metric than the standard 'percent agreement' as kappa accounts for the fact that some degree of agreement is to be expected by chance alone. The estimated kappa was calculated as $[(p_o - p_e)/(1-p_e) \times 100]$, where p_o is the observed agreement and p_e is the expected agreement based on chance (Fleiss, 1981). Their difference, $(p_o - p_e)$, represents the obtained excess agreement beyond chance, while the maximum possible excess agreement beyond chance is represented by the quantity $(1-p_e)$. The ratio of these two, the kappa statistic, can therefore be interpreted as the percent agreement among coders beyond that which is expected by chance.

The kappa statistics were used to compare codes assigned by multiple coders (to determine inter-coder reliability) and compare codes assigned by the same coder (to determine intra-coder reliability). The inter-coder kappa statistic was calculated based on agreement by all four coders. Landis and Koch (1977) suggest that kappa values greater than 75% may be taken to represent excellent agreement beyond chance, values below 40% to represent poor agreement beyond chance, and values between 40% and 75% to represent fair to good agreement beyond chance. Standard errors of kappas were calculated using a statistical method, as described by Fleiss *et al* (1979), which accounts for different sets of coders classifying the same cases. Standard errors were used to compute 95% confidence intervals (CIs) for all kappa statistics.

4.2.2 Practical application of the Injury Taxonomy

Following experimental testing and refinement, the proposed injury taxonomy was applied to manually classify case-narratives relating to a number of key work-related injury problems. The purpose was twofold:

1. To assess the quality of outcomes of practical application of the taxonomy (in terms of yielding injury patterns useful for prevention and control);
2. To trial the adaptability of the taxonomy to different injury databases (i.e. outside the NOHSC test dataset).

Three discrete research projects were conducted to apply the taxonomy in practice. Each project was based on a key workplace injury problem area and was independently commissioned by either a research or corporate entity, with the objective being to determine aetiological patterns useful for prevention and control. A combined total of 1045 fatality text narratives were obtained and manually classified by the author (GW Shepherd), as follows:

Case Study I: Crane fatalities in the Construction Industry, 1985-1995 (n=525). This study was initiated by Bechtel, one of the worlds largest construction firms (comprising 40,000 employees), which requested an in-depth study of crane fatalities in order to better focus their preventative strategies for this key fatality problem. By way of background, best estimates suggested that cranes were the source of 25-33% of casualties in the construction industry (MacCollum, 1993). Existing data relating to crane fatalities was available in tabulated form, describing the problem in terms of age of deceased, time of incident, work activity, occupation etc. However, there was no detailed information available regarding the aetiological patterns of crane fatalities (i.e. how they occurred).

In order to obtain quality data for manual review and classification, an approach was made by the author to the US Occupational Safety and Health Administration (OSHA), which provided 525 crane-related fatality narratives for the period 1985-1995. These narratives were extracted from fatality inspection reports stored on OSHA's Integrated Management Information System (IMIS), which has similar characteristics to the NOHSC dataset described earlier. The underlying assumption is that the pattern of crane fatalities in the

US will be similar to the pattern of Australian crane fatalities. This assumption cannot yet be tested as the sample size in Australia is small (approximately 5 crane fatalities occur per year), though some general comparisons of work-related fatality surveillance in the US and Australia reveal strong similarities (Stout *et al*, 1990).

Case Study II: Australian work-related electrical fatalities, 1989-1999 (n=243). This work was commissioned by Australian company Leighton Contractors Pty Ltd, to elucidate the pattern of work-related electrical fatalities in Australia. Existing data revealed that around 10% of all Australian workplace fatalities pertain to electrical energy (NOHSC, 1998); however, the detailed pattern of electrical fatalities was not known. An approach was made to the Office of the Chief Electrical Inspector in Victoria who assimilated national data and provided case narratives of 451 electrical fatalities, representing all Australian electrical deaths reported for the period 1989-1999. All 451 cases were manually reviewed, with 243 (54%) found to be work-related (i.e. occurred either at work or during work activities, including self-employed tradespeople).

Case Study III: US fatalities involving portable ladders, 1984-1998 (n=277). Following the crane and electrical fatality studies, the author was commissioned by the International Society for Fall Protection (ISFP), to determine the pattern of fatal injury associated with portable ladders. As before, the prevalence of injury relating to the ubiquitous portable ladder was well known, but detail regarding causative mechanisms was lacking. OSHA data was obtained regarding 277 fatality narratives involving portable ladders reported for the years 1984-1998. The Australian National Coroners Information Service (NCIS) dataset was also accessed in order to compare Australian and US data; however the NCIS dataset (which contains coded and text-based injury data reported since January 2001) did not contain sufficient numbers of ladder related cases for statistically significant outcomes.

For all three studies, individual fatality narratives were manually reviewed and classified according to the injury taxonomy. Detailed taxonomic classifications were produced and the resulting patterns analysed in terms of identifying key problem areas, as well as possible prevention and control measures. These outcomes are detailed in the following Results and Discussion sections.

4.3 Results

Outcomes of testing and practical application of the injury taxonomy are outlined in **Sections 4.3.1** and **4.3.2** respectively.

4.3.1 Outcomes of Testing of the Injury Taxonomy

For the NOHSC injury cases comprising the test dataset (n=400), the percent agreement between the four coders and the gold standard for the three taxon levels (i.e. energy type, mechanism and energy source) are recorded in **Table 4.1** below.

Taxon level	Expert/Coder A	Expert/Coder B	Expert/Coder C	Expert/Coder D	**Expert /Overall**	**Inter-coder**
	% Agreement	% Agreement	% Agreement	% Agreement	**Average %**	**% Agreement**
Energy Type (Level I)	95.0	97.8	95.5	97.5	**96.5**	**97.5**
Mechanism (Level II)	92.3	96.3	94.2	94.4	**94.3**	**96.3**
Source (Level III)	95.8	94.5	91.5	94.5	**94.1**	**95.0**

Table 4.1: Percent agreement among coders and between coders and the expert record (400 randomly sampled injury cases, NOHSC).

As can be seen, the average percent agreement between coders and the expert record ranged from 94.1% to 96.5%. This indicates that the coding accuracy is high for the injury taxonomy. Further, it was found that there was strong agreement in terms of cases deemed to be ‘not classifiable’. The expert record contained 13 cases (3.3% of sample) deemed not classifiable due to poor quality case descriptions which lacked sufficient information. These unclassifiable cases were identified by all four coders with an overall 94.2% accuracy. In other words the coding error rate for ‘not classifiable’ cases was 5.8%.

Table 4.1 also shows that the inter-coder agreement is high, ranging from to 95.0% to 97.5%. However, as described in the methodology, a better measure of reliability is provided by the kappa statistic (i.e. a measure of percent agreement beyond that which can be expected by chance alone). As such, **Table 4.2** below contains expert/coder and inter-coder outcomes in terms of the average kappa (in percent).

Taxon level	Expert/Coder A	Expert/Coder B	Expert/Coder C	Expert/Coder D	**Expert/Overall**	**Inter-coder**
	Kappa (95% CI)	Kappa (95% CI)	Kappa (95% CI)	Kappa (95% CI)	**Average Kappa**	**Kappa (95% CI)**
Energy Type (Level I)	98.0 (96.5-99.5)	92.0 (90.2-93.8)	96.0 (94.6-97.4)	94.0 (91.9-97.1)	**95.0** (91.9-97.1)	**96.3** (94.9-97.7)
Mechanism (Level II)	94.5 (91.0-98.0)	94.5 (91.2-98.2)	95.8 (92.3-99.3)	91.5 (90.0-93.0)	**94.1** (92.1-96.1)	**94.3** (91.2-97.8)
Source (Level III)	93.5 (91.3-95.7)	95.0 (91.8-97.0)	90.0 (88.3-91.9)	91.5 (89.6-93.4)	**92.5** (90.8-95.4)	**93.0** (91.2-94.8)

Table 4.2: Kappa statistics among coders and between coders and the expert record (400 randomly sampled injury cases, NOHSC).

Table 4.2 indicates that the overall expert/coder kappa statistics (i.e. coding accuracy) are in the range 92.5% to 95.0%, slightly less than the percent agreement results (as would be expected once agreement due to chance is accounted for). The inter-coder reliability results are in the range 93% to 96.3% for all three categories. Both sets of results are well in excess of the 75% threshold which is considered to represent 'excellent' agreement beyond chance (Landis and Koch, 1997). The lowest kappa recorded was 93% for classification of the source (level III), where a total 28 classifications (from the 400 case dataset) were not agreed upon by all four coders.

Intra-coder reliability for the NOHSC dataset, as measured again by average kappas, was also found to be well above the 75% threshold for all three classification categories (see **Table 4.3**).

The median coding time for classifying cases from the NOHSC dataset, as measured in 30 second increments, was 3.5 minutes (see **Table 4.4**). The average coding time was significantly slower (mean = 4.75 minutes, 95% CI = [4.7%, 5.1%], range = 1-16 minutes).

Taxon level	Expert/Coder A	Expert/Coder B	Expert/Coder C	Expert/Coder D	**Expert/Overall**	**Intra-coder**
	Kappa (95% CI)	Kappa (95% CI)	Kappa (95% CI)	Kappa (95% CI)	**Average Kappa**	**Kappa (95% CI)**
Energy Type (Level I)	97.0 (96.5-99.5)	91.5 (90.2-93.8)	96.0 (94.6-97.4)	93.5 (91.9-97.1)	**94.5** (91.0-98.0)	**96.3** (94.9-97.7)
Mechanism (Level II)	93.5 (90.0-97.0)	95.5 (92.2-99.2)	95.8 (92.3-99.3)	91.5 (90.0-93.0)	**94.1** (92.0-97.2)	**95.0** (91.8-97.0)
Source (Level III)	94.0 (91.8-96.2)	95.0 (91.9-97.1)	91.5 (88.3-94.7)	91.5 (89.6-93.4)	**93.0** (91.3-95.7)	**93.5** (90.0-97.0)

Table 4.3: Kappa statistics for intra-coder reliability (400 randomly sampled injury cases from NOHSC, coded twice by the same coder at different times).

Coding time (in minutes)	Number of Injury Cases	Percent Distribution
1 minute	1	0.3
1.5 minutes	2	0.5
2 minutes	14	3.5
2.5 minutes	37	9.3
3 minutes	68	17.0
3.5 minutes	109	27.3
4 minutes	96	24.0
4.5 minutes	45	11.3
5 minutes	17	4.3
5.5 minutes	3	0.8
6 minutes	3	0.8
6.5 minutes	1	0.3
7 minutes +	4	1.0
Total	**400**	**100.0%**

Table 4.4: Classification coding time (400 randomly sampled injury cases, NOHSC).

Overall, these results support the hypothesis that the proposed taxonomy can be applied to classify injury cases with a high degree of coding accuracy and reliability. The results are examined in further detail in the Discussion section of this report.

4.3.2 Outcomes of practical application of the Injury Taxonomy

With the testing and refinement process complete, the injury taxonomy was applied in practice to manually classify three discrete injury datasets.

It was found that for all three case studies a vast majority of fatality narratives (98.2%) could be unambiguously coded into a single taxonomic category. In all of the remaining 'not classifiable' cases, ambiguity arose from lack of quality detail conveyed by the case narratives, as opposed to classification system or convention ambiguity. The average coding time was found to be 4.65 minutes/case, similar to the test results reported earlier.

The practical outcomes of each of the three independent case studies are presented in detail as **Appendices II, III and IV** based on the following published work:

Case Study I: Crane fatalities in the Construction Industry, 1985-1995 (n=525). Outcomes of the classification of 525 US Crane Fatalities were published in the Journal of Safety Science in a paper entitled *Crane Fatalities – A taxonomic analysis* (Shepherd, Kahler and Cross, 2000), which is provided in its entirety as **Appendix II**.

Case Study II: Australian electrical fatalities, 1989-1999 (n=243). Outcomes of this work were published in a study entitled *The Pattern of Electrical Fatalities* (Shepherd and Kahler, 2001). This journal paper is presented in full as **Appendix III**. The results were also presented at the 91st National Safety Council Congress and published in the proceedings thereof (Shepherd, 2003).

Case Study III: US fatalities involving portable ladders, 1984-1998 (n=277). Practical outcomes of this taxonomic study are presented in **Appendix IV**, based on a paper entitled *Ergonomic Design Interventions – A case study involving portable ladders* (Shepherd, Cross *et al*, 2006). These results were also presented at the 3rd International Fall Protection Symposium (Shepherd 2000) and at the 37th Annual Ergonomics Conference (Shepherd, Cross and Kahler, 2001).

The following section of this report contains a detailed examination of the results from the three case studies.

4.4 Discussion

This section discusses the outcomes of the testing and application of the proposed injury taxonomy, as well as its strengths and weaknesses, and potential avenues for future development.

4.4.1 Outcomes from testing (NOHSC data, n=400)

Overall, the test results support the hypothesis that the proposed injury taxonomy and conventions can be accurately and reliably applied to classify text-based injury data.

Importantly, it was found that the three-tiered taxonomy could be independently applied by four trained coders with high coding accuracy (kappa ranging from 92.5% to 95.0%, as measured by coder/expert agreement). In other words, the coding error rate was in the range 7.5% to 5.0%, suggesting that there is little ambiguity associated with the proposed injury taxonomy and conventions. There was also strong agreement in terms of cases coded as ‘non-classifiable’ (a 5.8% error rate was experienced). Importantly, the trained coders were initially ‘novices’ and thus results are unlikely to have been dependent on prior expertise or experience on the part of the coders.

These results compare favourably with previous studies which assess coding accuracy. For example, the US Centres for Disease Control’s (CDC) assessment of the ICECI classification system (CDC, 2000) revealed that observed agreement between coders and the pre-determined expert record (i.e. accuracy) was in the range 80.6% to 94.1%. In relation to human error classifications, published inter-rater reliability results vary from 42% (Hollnagel, 2001) to 71% (Wiegmann and Shappell, 2001), as detailed earlier.

Further, the tests demonstrate that the injury taxonomy can be applied with high reliability (as measured by kappa), both in terms of inter-coder reliability (93.0-96.3%) and intra-coder reliability (93.5-96.3%). As before, kappa statistics greater than 75% indicate an 'excellent' agreement, taking into account agreement expected by chance alone.

Figure 4.4 summarises the results based on data presented in the previous **Tables 4.2** and **4.3**, showing the average kappa statistic, with 95% confidence interval, for the three classification categories (i.e. energy type, mechanism and source).

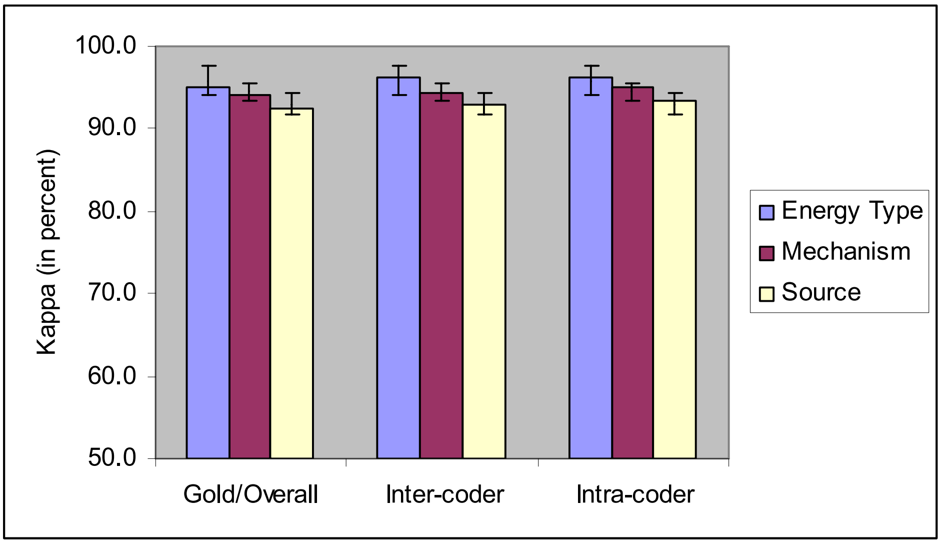


Figure 4.4 Average kappa statistics, with 95% confidence interval, between coders and the expert record ('gold standard'), inter-coder and intra-coder by classification categories (NOHSC data, n=400).

The similarity between the three sets of reliability results (expert/overall, inter- and intra-coder) indicates that coding errors are random in nature, as opposed to being systemic or inherent to the taxonomy. Systemic errors would manifest as a significant divergence between results, for instance: if the agreement between coders and the expert record (expert/overall) was poor while inter-coder agreement was excellent, it would indicate that the coders are classifying inaccurately but reliably, pointing to systemic error. Similarly, divergence in inter- and intra-coder agreement would indicate some form of non-random error.

The observed coding error rate of 5.0% to 7.5% is therefore considered to be predominately random (not systemic) in nature, and due to human (coder) error. Further evidence of this is that there was little intra-coder agreement in terms of errant classifications. In other words, individual coder's errant classifications were generally not repeated when the same cases were recoded 8 weeks later, though new errors were introduced. Likewise there was little inter-coder agreement as to errant classifications, again pointing to errors being independent and random in nature.

Despite the observed error rate comparing favourably with other published studies of manual coding accuracy, it is highly desirable that error rates be reduced further, to at least below 5% (i.e. to achieve 95% accuracy). This is to ensure that valid and statistically significant results emerge in terms of patterns of injury.

With respect to coding time, the results revealed that manual classification of the 400 NOHSC cases required an average of 4.75 minutes/case. As such, each coder expended an average of 31.7 hours (4 working days) to code just 400 cases. The time consuming nature of the manual classification process is a major methodological limitation, as was discussed earlier. Further, it is predictable that coding error could increase with the number of cases processed, due to the repetitive nature of the task.

4.4.2 Outcomes of practical application

The detailed outcomes of practical application of the taxonomy to three separate injury case studies are discussed as follows.

4.4.2.1 Case Study I – Crane fatalities in the Construction Industry, 1985-1995 (n=525)

A high-level breakdown of the crane fatality taxonomy is depicted below as **Figure 4.5** (derived from the complete taxonomy presented in **Appendix II).**

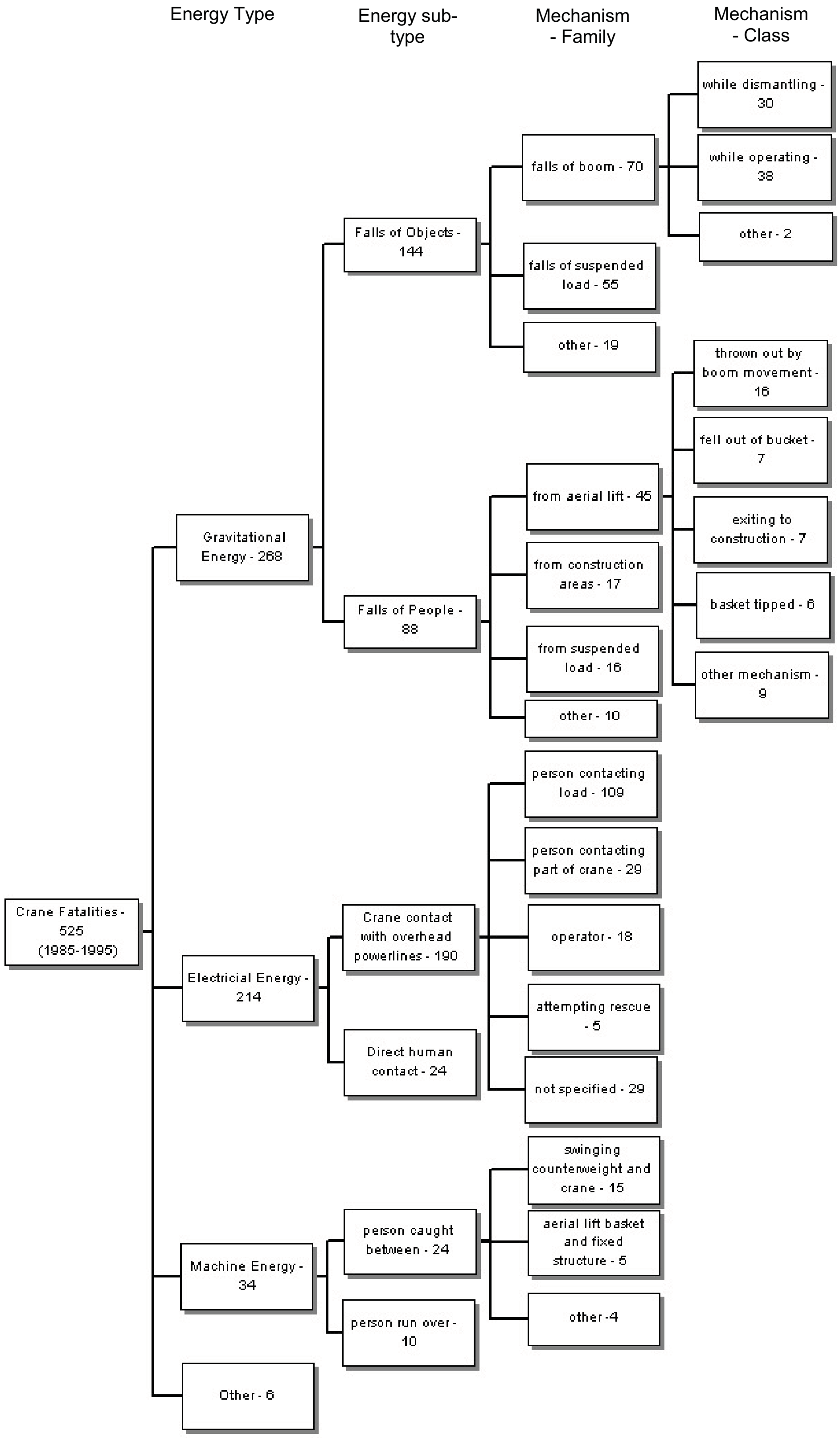


Figure 4.5 Taxonomy of 525 Crane Fatalities (United States OSHA data).

As can be seen, strong patterns emerge from classifying the crane fatality data according to the injury taxonomy, with most of the fatality problem attributable to just a few energy types. In particular, Electrical Energy and Gravitational Energy are highly represented, accounting for 92% of the crane fatality problem. This is consistent with the core concept in epidemiology that injury distributions are highly non-random (Haddon, 1980).

The emergent patterns were found to help identify focus areas for intervention targeting, as well as assisting in the identification of potential control measures. For example, examining further detail of the crane taxonomy reveals that the most common fatality mechanism is related to crane contact with overhead powerlines (190 cases or 36%), with at least 109 of these (57%) involving the person handling/guiding the load (i.e. the 'dogger'). **Figure 4.6** below provides a diagrammatic representation of this dominant crane fatality mechanism.

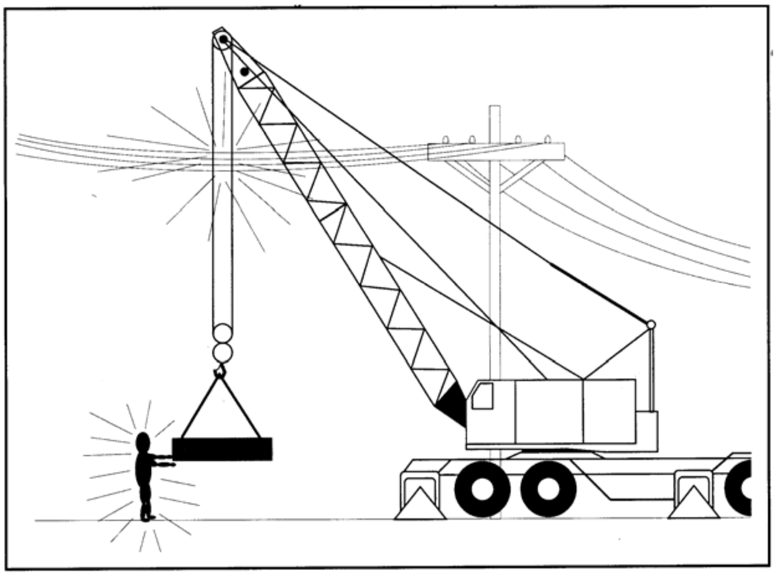


Figure 4.6 Dominant fatality mechanism identified as crane contact with overhead powerlines, with victim contacting the load (n=109).

The high representation of electrical incident is consistent with previous studies of crane fatalities based on tabulated data (Paques, 1993); however, the taxonomy revealed additional levels of detail which allowed for more insight to be gained regarding the causative sequence. For instance, the abovementioned finding that the majority of electrocutions involve the person guiding the load (as opposed to the crane operator or bystanders). As outlined in the following discussion, this new information is of considerable benefit when considering preventive strategies.

Control measures for incidents involving cranes striking overhead powerlines have for decades focussed on training (i.e. 'look up and live'), as well as procedures to maintain minimum distances from electrical lines and apparatus. The situation is reflected in documents such as the *Crane Safety Manual for Operators and Users* (Australian Crane Association, 1993), which states:

> *"People are the biggest influence on safe working conditions. The single most important factor in preventing injury on the job is having competent and reliable personnel, who are safety conscious.*
>
> *Power line contact is the largest single cause of fatalities associated with cranes. Operators – before setting up or operating on any project LOOK FOR POWERLINES and if present EXERCISE EXTREME CAUTION.*
>
> *BEWARE – the greatest danger is people's bodies acting as conductors between crane/load and the ground."*

In support of such training and procedural controls, stringent legislative requirements to maintain safe clearance from live powerlines apply in the United States as well as in Australia and many other western countries.

The following **Figure 4.7** provides a photograph and newspaper headline of an actual case involving crane contact with overhead powerlines (which resulted in two fatalities).

Two die as crane hits power lines on Chevron Is

BUILDING workers watched in horror yesterday as two of their mates were electrocuted in a freak crane accident.

A cable of the crane touched high-voltage power lines at a construction site in Purli Street.

Figure 4.7 Fatal incident involving crane boom contact with overhead power-lines (Gold Coast Bulletin, August 14th 2001). Two workers guiding the load were killed. Note that the smoke evident in the photograph is the result of burning crane-boom hydraulics.

When reviewing individual cases, such as the one above, it is evident that many of the powerline contact cases involved situations where either unplanned or inadvertent boom/load-line movement caused contact (e.g. boom movement due to crane support destabilising, load-line swinging in the wind, *et cetera*). Most of the remaining situations involved the crane operator mis-perceiving the proximity of powerlines, a task which is problematic even in experimental settings. For example, as outlined in a research paper entitled *Problems in the Perceptions of Overhead Powerlines* (Cunlitz *et al*, 1985), powerlines represent an impoverished visual stimulus where accurate clearance and distance judgements appear not to be possible. The authors point out that it is not appropriate to blame careless operators when careful operators have difficulty in making such judgements.

It is therefore argued that procedural controls such as 'maintaining safe clearances' are essential, but limited, as such controls do not effectively manage the energy involved in causing injury, nor the propensity for human error to be involved in the release of this energy.

To better manage this key crane fatality type, a hierarchy of energy management strategies can be identified (after Haddon, 1980) aimed at interrupting the path of electrical energy from the powerlines to the crane boom, load, and ultimately to the person on the ground:

1. Prevent marshalling of energy: De-energise the powerlines.
2. Prevent release of energy (powerlines/crane): Use insulating line sheaths (tiger-tails) on the powerlines; Separate crane from powerlines by in excess of 6 metres; Provide an insulated boom cover; Provide audible proximity alarm in the crane cab.
3. Prevent transfer of energy (crane/load): Use of insulated link/crane hook as an insulating barrier.
4. Prevent transfer of energy (load/person): Use non-conductive tag-lines (to connect to the load) as an insulating barrier.

Most of these controls have been identified as viable preventative strategies for crane activities, although they have not been supported by legislative import or emphasised to the same extent as procedural controls to maintain 'safe clearance'.

The use of an insulated link (measure 3), however, has not been previously adopted by the mobile crane or construction industry as a potential control measure. This is not because insulated links do not exist or are not practical. In fact, insulating links have been available for a long period of time (US Patent Office, 1958) and are used in industrial environments such as aluminium smelters and for military applications such as missile transportation (where avoiding electrification of the load is critical). There are also no technical constraints as suitable links are: readily available from three manufacturers in the United States alone; load rated up to 160 tonne, and; electrically rated to insulate 50kV in wet or dry weather (versus 11kV for most powerlines). The US dollar cost of between $20,000 and $50,000 (depending on load rating required) is also reasonable in comparison with the unit cost of a large mobile crane (upwards of $1 million). The concept of use of an insulating link is demonstrated in **Figure 4.8** below.

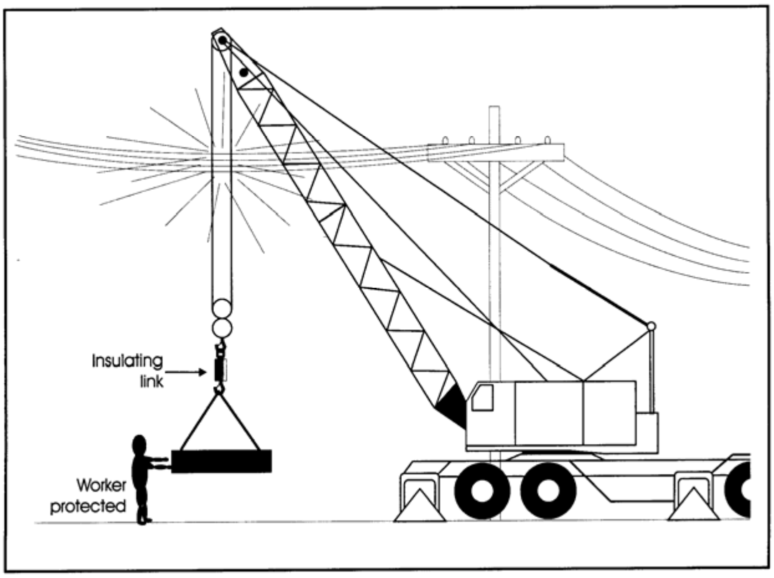


Figure 4.8 Use of an insulated link (hook) to interrupt the energy transfer, protecting the person handling the load.

While the other three energy-management strategies are also effective in preventing the transfer of energy, the advantage of the insulated link is that it could be fitted to all mobile cranes (as standard), automatically managing up to 20% of the crane fatality problem. Of course, insulated links cannot be considered a panacea as other controls are necessary to protect the crane operator and any persons contacting other parts of the crane (apart from the load). Nevertheless, if used in addition to a stronger focus on, say, the use of insulating line sheaths and proximity alarms, then up to 36% of the crane fatality problem could potentially be managed.

The need to apply such passive or 'fail-safe' control measures (to supplement controls which rely on specific behavioural inputs) has been made many times in the past; for example, Jarasunas (1984) points out:

> *"The experience of more than 60 years of organised accident prevention has demonstrated that it is unwise to place principal reliance on co-operation, training or*

> *constant attention on the part of the employee."*

The need to adopt such an approach in the crane/construction context is described by MacCollum (1993), one of the worlds leading crane safety engineers:

> "*Serious injury or death that occurs repeatedly from similar circumstances should be considered epidemic. These occurrences should be examined to identify hazards so that appropriate prevention measures can be initiated in the same diligent manner that the medical profession examines a disease or infection to develop a vaccine or antibiotic for its prevention or control. Unfortunately, at the work site, many occurrences are often labelled as 'freak occurrences' because operating personnel are sometimes totally unaware of similar repetitive occurrences because of their wide dispersal."*

As an aside, the media and other popular channels of information tend to reinforce the mythology of the freak occurrence. The following quote from the newspaper article depicted earlier serves as an example (Gold Coast Bulletin, August 14th 2001): *"Building workers watched in horror yesterday as two of their mates were electrocuted in a freak crane accident"*. As the taxonomy revealed, far from this being a 'freak' occurrence, around 36% of crane fatalities occur due to contact with overhead powerlines.

In regards to other key crane fatality problems identified by the taxonomy, a similar process was adopted resulting in control measures being recommended to manage the energy exchange and prevent future occurrences (see **Appendix II**). For example, 88 (17%) crane fatalities were due to falls of people from a height (e.g. from aerial lift, crane or load) and can be managed via use of appropriate fall protection systems to prevent release of gravitational energy where the height exceeds 1 metre. Similarly, 55 (10%) crane fatalities were associated with falls of objects (e.g. falls of crane boom or suspended load) which are preventable by ensuring gravitational energy is not marshalled in the first place (i.e. that loads and the crane are not suspended over people at any time), or that safety hooks, anti-two blocking devices, and falling object protective structures are used as a barrier to prevent the release of energy.

In summary, it was found that the injury taxonomy can assist in yielding insight into the extent, nature and patterns of crane fatalities as well as identifying key areas requiring focus. For example, the present case study revealed that the three fatality mechanisms discussed above accounted for 63% of the problem. Further, it was shown that the taxonomy allows for the practical identification of control measures which are focussed on managing the energy exchange.

4.4.2.2 Case Study II – Australian electrical fatalities, 1989-1999 (n=243)

The complete taxonomic classification of 243 electrical fatalities involving Australian workers is documented in **Appendix III**. A second level breakdown of the taxonomy is depicted in **Figure 4.9** below. The next level of detail can be provided with reference to the taxon numbers.

In this case, the application of the taxonomy is based on one energy type (i.e. Electrical energy - electrocution), and the taxonomy is presented in terms of 'Energy type – Source – Mechanism' to better understand the patterns of electrical fatalities by energy source (such as overhead powerlines, fixed wiring, underground power, etc).

As before, it is evident that patterns emerge with respect to electrical fatalities. In particular, the complete electrical fatality taxonomy indicates that 85% of the problem can be managed with focus on the following four sources: 1. Overhead powerlines (35%); 2. Fixed wiring - direct contact with exposed live conductors or cable (24%); 3. Tools, equipment and appliances (14%), and; 4. Flexible electrical cord and fittings (12%).

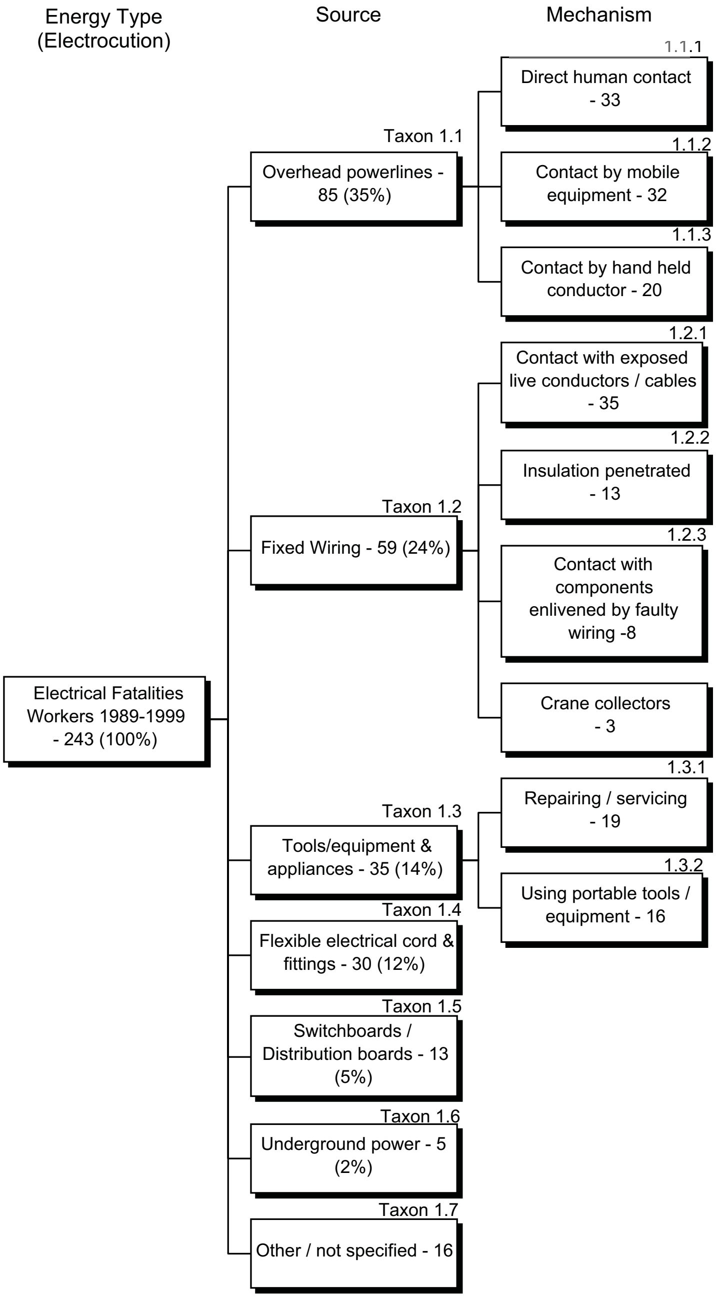


Figure 4.9 Taxonomy of 243 Australian work-related Electrical Fatalities, 1989-1999.

As for the previous crane study, the taxonomy provides a significantly greater level of detail regarding the aetiology of electrical fatalities than existing published studies based on tabulated data (such as the NOHSC Work-related Fatalities Study), as outlined in the overall study reproduced in **Appendix III**. For example, the following **Figure 4.10**, extracted from **Appendix III**, shows the detailed breakdown for energy source 'Flexible Electrical Cord and Fittings'. Most of these cases (96%) pertain to extension cords.

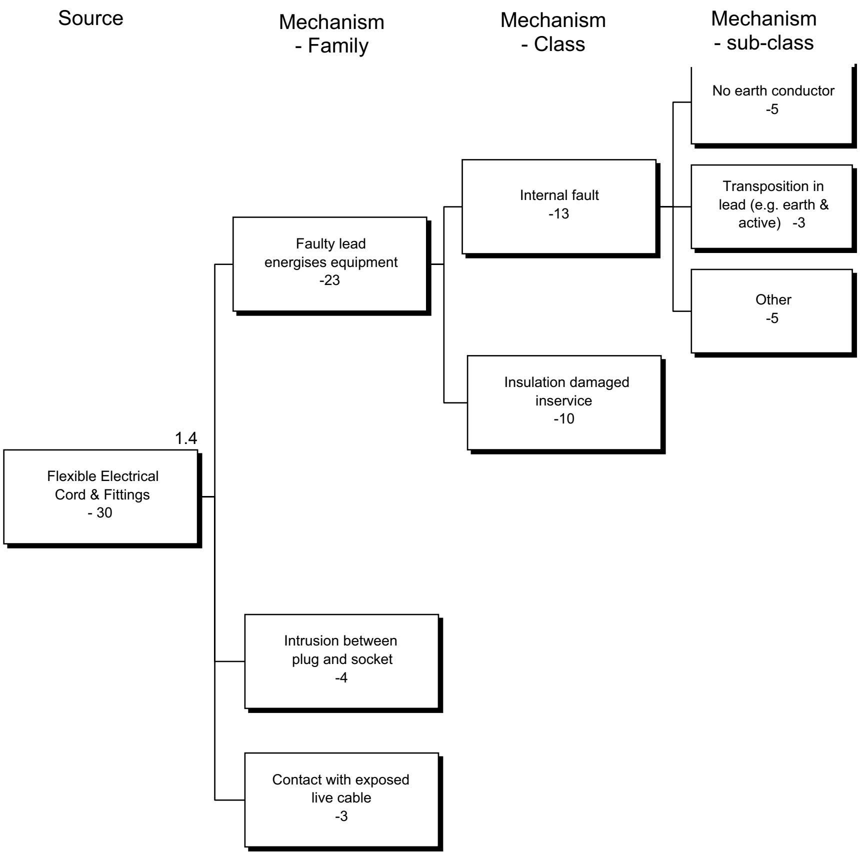


Figure 4.10 Breakdown for Taxon 1.4, Flexible Electrical Cord & Fittings (n=30 Cases).

Figure 4.10 reveals that a majority of the 30 fatalities relating to electrical cords occurred either as a result of faulty leads (13 cases), leads becoming damaged while in use (10 cases), or intrusion of a metal object between plug and socket (4 cases). The need for control measures has been recognised over the last ten years, with Australian State and Territory Governments enacting legislation to mandate testing and tagging of electrical cords as per Australian Standard AS3000 (2000). It is likely that such measures will help manage incidents involving faulty leads (13 cases or 5% of the overall problem).

However, testing and tagging cannot be relied upon to prevent the remaining 14 cases (6% of the overall problem) which involve electrical leads being damaged whilst in service (e.g.

live cord inadvertently cut into) or plug/socket intrusion (e.g. scaffold energised after kick-board penetrated the small gap between a live cord/plug connection).

Traditionally, control measures for these residual hazards rely on awareness and safe work procedures for using electrical cords in the workplace. For example, the following quotation is drawn from a safety guide produced by the Queensland Department of Mines and Energy (2000):

> *"Extension cords can pose a real danger in some work situations, if damage is ignored, neglected or unknown. This danger can be eliminated if you simply look around and check the surroundings of your work location before starting work."*

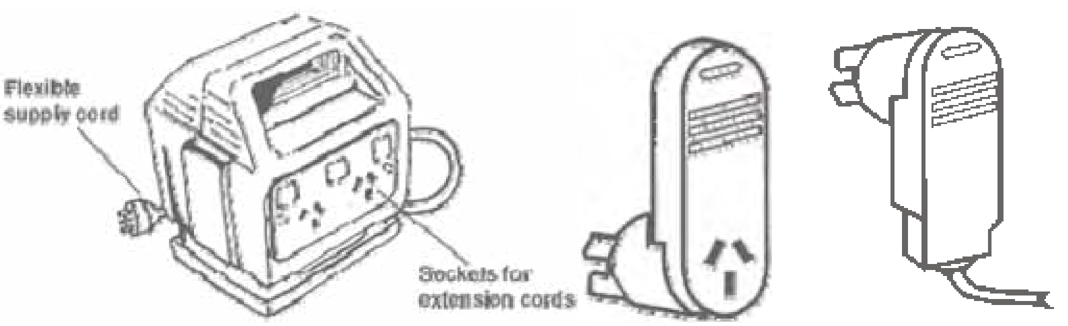
Such control strategies are focussed on trying to illicit a desirable behaviour. The implicit assumption is that the human error is the predominant cause and thus is the prime focus of control. As outlined earlier, such measures are limited as they do not control the underlying hazard (i.e. the energy source). The need for an alternative approach is supported by injury researchers such as Trevor Kletz (2000):

> *"Incident statistics show that over 50% and sometimes as high as 90% of incidents are due to human failing; this is comforting to manager, it implies that there is little or nothing they can do to stop most incidents. To say that incidents are due to human failing is not so much untrue as unhelpful. It does not lead to any constructive action."*

A key benefit of the electrical fatality taxonomy is that it focuses attention not on human error or behaviours, but on the marshalling and release of electrical energy. This is a useful approach as human error cannot be eliminated (or human behaviour reliably controlled) whereas the marshalling and release of energy can be effectively controlled (producing an error-tolerant system).

Based on the taxonomic breakdown of fatalities associated with electrical cords (as per **Figure 4.10**), a hierarchy of energy management strategies or barriers can be identified (as for the crane study), which are aimed at interrupting the path of electrical energy from the cord or fitting to the person:

1. Prevent marshalling of energy: Use non-electrical (e.g. battery/pneumatic) or DC appliances.
2. Prevent release of energy (extension cord/person): Install an earth leakage circuit breaker such as a residual current device (RCD) onto extension cords and/or use a portable RCD connected to the output side of a socket. RCDs detect earth leakage and break the circuit preventing unwanted electrical energy exchange (see **Figure 4.11**).
3. Prevent release of energy (plug pins/person): Prevent intrusion between a connected plug and socket by providing a physical barrier (shroud) on the socket. These shrouded sockets are designed so that when the plug begins to withdraw from the socket it disconnects before a gap appears between the plug and socket.



Portable RCD unit suitable for use with extension cords and portable power tools | Portable RCD plug adaptor | Plug adaptor wired to an extension cord

Figure 4.11 Depiction of various types of Residual Current Devices (RCDs).

Review of the case descriptions confirm that the provision of operational RCDs onto extension cords and/or sockets of flexible cords would have prevented 29 of the 30 'Flexible Electrical Cord' fatality cases referred to above (taxon 1.4). Further, at least 16 cases involving the use of 'Tools/Equipment & Appliances' (taxon 1.3.2) are preventable via use of a portable RCD. In total, at least 44 cases (19%) of electrical fatalities can be managed with this single control measure.

RCDs have been available for many years and in recent times legislators in Australia, the US and other western countries have legislated for the mandatory use of portable RCDs on construction worksites. The recommended next step is to mandate improvements in extension cord design to include an RCD as an integral, fixed component of extension cords. Likewise, it is recommended that the protective shroud discussed above be incorporated into mandatory product design standards for extension cords.

Similar analyses were conducted for all other taxons, leading to recommendations being made which are focussed on key exposures (see **Appendix III**).

An unexpected result discerned from the overall pattern of electrical fatalities was that low voltage energy sources (i.e. 240 volt) accounted for a majority of fatalities (57%). For reference, **Figure 4.12** shows the number of fatalities by voltage. It appears that, contrary to popular belief, the problem of work-related electrocution is not a high-voltage problem, but is predominately a 240 volt problem. Further, it is unlikely to be due to a lack of training, since most victims were qualified electricians doing routine work. This provides further support for the need to focus on 'passive' control measures such as inbuilt RCDs on power-cords and other recommendations made in the complete study.

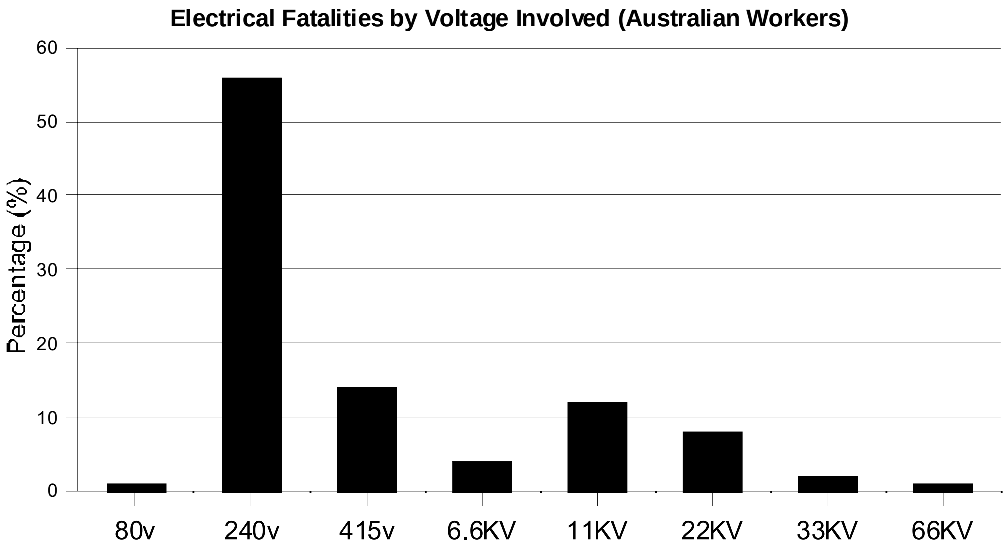


Figure 4.12: Breakdown of electrical fatalities by voltage involved (Australian workers, n = 243).

In sum, as for the crane study, it was found that the taxonomy provided useful insight into the patterns and determinants of electrical fatalities, as well as helping to highlight potential intervention strategies.

4.4.2.3 Case Study III – United States fatalities involving portable ladders, 1984-1998 (n=277)

Following the crane and electrical fatality studies, the author was commissioned by the International Society for Fall Protection (ISFP), to determine the pattern of fatal injury associated with portable ladders.

Prior to this work, the prevalence of injury relating to the ubiquitous portable ladder was well known, but detail regarding the pattern of incidents and causative mechanisms was lacking. In particular, there were no prior studies available which analysed the aetiology of fatal incidents involving portable ladders. The taxonomy was generated by the author after obtaining and classifying OSHA data regarding 277 detailed fatality narratives involving portable ladders reported for the years 1984-1998 (see complete paper in **Appendix IV**).

A high level breakdown of the resultant ladder fatality taxonomy is reproduced below as **Figure 4.13**. Once again it was found that strong patterns emerged from application of the injury taxonomy. In particular, it can be seen that the following four mechanisms account for over 70% of the problem:

1. Electrocution of person whilst handling or working from ladder – 86 cases (31% of the problem, with the majority involving a conductive ladder contacting overhead powerlines during handling).
2. Person fell with ladder due to sliding of support – 42 cases (15% of the problem, with the majority associated with outward sliding of the ladder feet, and a small number involving lateral sliding of the top support).
3. Person fell during transition onto/off ladders (e.g. from roofs) – 40 fatalities (14% of the problem, with the majority involving an unsecured ladder displacing during transition and/or the person losing balance).

4. Person fell from ladder after overbalancing/slipping – 34 fatalities (12% of the problem, with the majority involving the person's hand or foot slipping off the ladder rung or otherwise mis-stepping and losing balance).

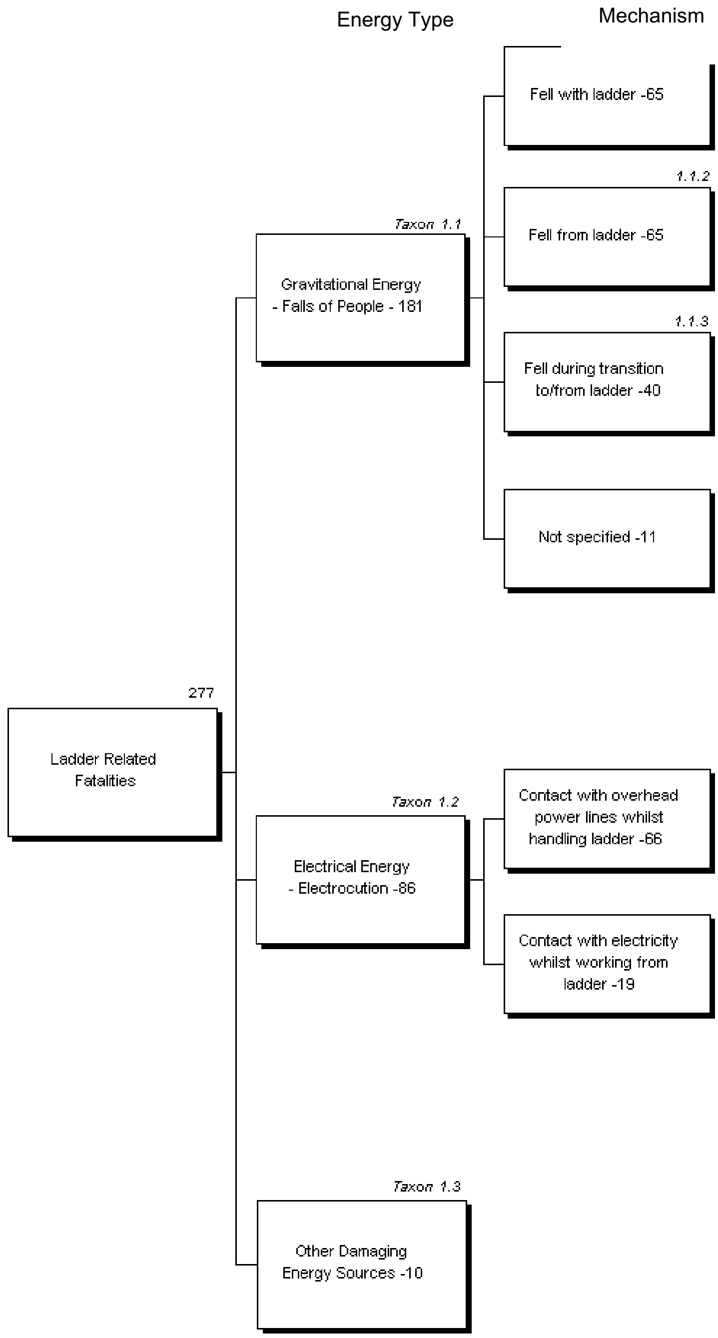


Figure 4.13 Taxonomy of 277 Portable Ladder Fatalities (US OSHA data).

As for the previous studies, the aetiological detail provided by the taxonomy was used to identify ladder design features which could be enhanced to interrupt the release and transfer of energy. As a result, a number of specific design features were recommended, as depicted in the following **Figure 4.14**.

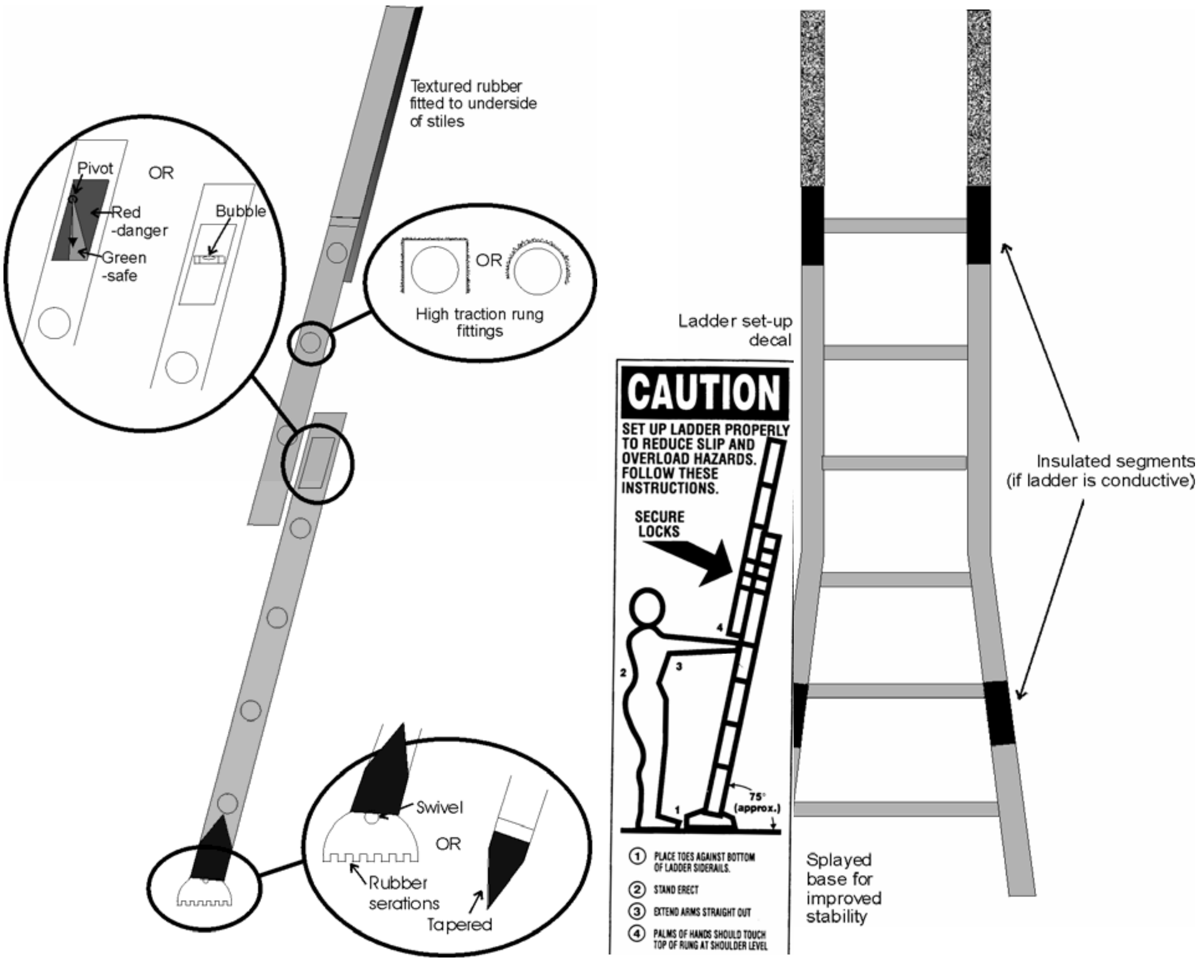


Figure 4.14 Graphical depiction of suggested portable ladder design features (based on ladder taxonomy findings). Not to scale.

The design features include: an inbuilt ladder inclinometer (to help operators confirm the correct angle after set-up in accordance with the instruction decal); high friction rubber contact surfaces fitted to the underside of stiles (to reduce lateral sliding of the top support), and; a swivel mechanism for the ladder feet incorporating a high friction serrated surface (for hard base surfaces) as well as a tapered surface (for securing the ladder in soft bases). Inbuilt insulated segments (e.g. carbon fibre) are also recommended for conductive ladders.

As for the previous case studies, this practical application of the injury taxonomy supports the hypothesis that patterns emerge which are useful in terms of providing a basis for further study, and yielding practical insight into where preventative strategies should be focussed.

4.4.3 Strengths and Weaknesses of the Injury Taxonomy

A key strength of the proposed injury taxonomy, as demonstrated by the validation testing, is that it can be applied with a high degree of accuracy (coder/expert agreement was 92.5-95.0%), and with high inter- and intra-coder reliability (93.0-96.3% and 93.5-96.3%, respectively). These results indicate an excellent agreement beyond chance, and compare favourably with reliability results of existing classification systems based on the ICD or human error approaches.

Application of the injury taxonomy to three key work-related injury problems (i.e. 525 crane deaths, 243 electrocutions and 277 ladder fatalities), enabled the logical classification of all 1045 fatality narratives (with an overall 98.2% of cases able to be coded unambiguously into a single taxonomic category). As such, the taxonomy can be deemed to be adaptable and comprehensive, at least in terms of the three diverse text datasets in question; specifically: Australian NOHSC fatality data (based on Coroner's reports); United States OSHA data (based on fatality inspection reports), and; Australian electrical fatality narratives (based on Electrical Inspector records).

Notably, strong aetiological patterns were revealed in all three case studies (overall, 76% of cases arose from less than 20% of taxons); this is consistent with the core epidemiological concept that injury distributions are highly non-random. Moreover, for each case study, new levels of detail were revealed from the taxonomic pattern of incidents that were not available from tabulated data in existing published research (and thus outcomes were publishable in their own right). In particular, it was found that the three-tiered taxonomic structure (capturing energy type, mechanism, and energy source) provided useful insight into the aetiological sequence leading to injury. For the crane study, one example is the finding that a majority of deaths were associated with cranes contacting overhead wires and involved the person holding the load, rather than involving the operator or bystanders. For the ladder study, a variety of new insights were revealed regarding the aetiological pattern of ladder falls; for example, of 181 ladder falls, 36% involved the person 'falling with the ladder' (mainly due to outward sliding of the ladder feet), while a further 22% of deaths involved 'falling while transitioning onto/off the ladder' (predominately from roofs).

As such, application of the proposed injury taxonomy in practice was found to overcome some of the limitations of existing classifications systems. Firstly, the taxonomy, with its defined structure and clear conceptual basis (centred on 'energy' as the agent of injury), overcomes the conceptual limitation of the ICD E-codes (and derivations thereof) which lack an underlying organising principle (as was discussed previously in **Section 2.3**). Secondly, the taxonomic structure (which is multi-axial and hierarchical) helps overcome the reductionist classification trap which afflicts uni-dimensional coding systems; as, rather than deconstructing injury information into disconnected tabulations of data, the output is a three level taxonomy where aetiological associations between components of data are retained.

While the practical benefits of this are difficult to quantify, it was found that the resulting taxonomic patterns and new aetiological insights gained were of assistance both in terms of identifying target areas for further analysis, as well as identifying potential interventions suitably focussed on the key injurious energy transfers (e.g. by applying Haddon's 10 energy management strategies). For example, the adoption of an 'energy transfer' frame of reference, and the knowledge that the most common crane fatality involves electrocution of the person guiding the load, led to the logical conceptualisation of controls aimed at interrupting this energy flow (such as de-energising powerlines, using insulated line sheaths, insulated hooks and/or non-conductive taglines). As was discussed, the insulated hook was identified as a potential control measure using this approach, despite it being previously overlooked by the construction industry. Likewise, the ladder study led to the conceptualisation of a variety of innovative enhancements to interrupt the release and transfer of energy. Of course, the specific control measures identified depend not only on the conceptual frame of reference adopted, but also on the individual researcher's background and experience. In this regard, it would be considered beneficial for multiple researchers (from different backgrounds) to be involved in the control measure identification and assessment process.

Overall, then, the injury taxonomy appears to satisfy the basic requirements of an effective classification system as outlined in **Section 2.3**, namely:

1. The model used represents the pinnacle of understanding in the field (i.e. is based on the energy-damage concept, which is fundamental to injury aetiology);
2. The classifications help stimulate further measurement and research (in each case study key focus areas were identified and a range of countermeasures were conceptualised for further investigation and practical implementation);
3. The classification categories are based on a cohesive and conceptually clear multi-level structure (this is satisfied by the defined Energy Type – Mechanism – Source structure);
4. Subjective judgement is minimised through the use of clear classification conventions which are capable of reliable, practical application (as demonstrated by high inter- and intra-coder reliability results).
5. The classifications are practically useful in that they assist in the identification of control measures which are focussed on preventing and controlling the exchange of energy (and thus injury occurrences).

As a result, it is proposed that the injury taxonomy can provide a meaningful starting point for understanding injury aetiology. For instance, in relation to the electrical fatality study, once it is recognised that most electrocutions pertaining to 'fixed wiring' involved 'contact with exposed live conductors' (240 volts), and most of these occurred whilst working in the ceiling space, the relevant sequences leading to this outcome can be scrutinized further. This detailed causal analysis should include a study of human factors, as well as higher-level organisational factors and systems issues. This can be achieved by applying a variety of incident investigation approaches such as those outlined in the literature review (assuming highly detailed incident descriptions are available). For example, by applying James Reason's latent pathogen model, 'latent conditions' such as undue time and management pressures and poor safety culture may be identified, as well as 'active failures' such as decision making errors (e.g. why the household power wasn't isolated prior to working in the ceiling space).

In this fashion, pattern analysis according to the aetiologic agent (i.e. energy) can logically precede analysis of common incident archetypes. This approach is equivalent to that adopted by disease epidemiologists who first determine patterns of the underlying agent, then study the host, environment and vehicle/vector inter-relationships.

As such, it is recommended that the proposed taxonomy be applied in complement to existing analytical approaches such as the *process*, *systems* and *human-error* models discussed previously; the taxonomy is neither presented for use in isolation nor with any pretensions of finality. To best understand the complex and multi-factorial nature of injury causation, a pluralistic approach is likely to be required. To this end, it is suggested that future development work could focus on integrating the proposed injury taxonomy with these existing approaches.

It is also important to note that the case studies presented in this report are based solely on fatal injuries. The elucidation of patterns of fatalities is considered a necessary first step for injury prevention and control; however, it is recognised that a larger injury problem arises from non-fatal permanent (i.e. severe) injury (Industry Commission, 1995), and that the pattern of fatalities is likely to be different than the pattern of non-fatal permanent injury (McDonald, 1995). As such, future work lies in conducting taxonomic classifications of non-fatal permanent injuries. This calls for the availability and taxonomic analysis of descriptive (narrative) permanent injury data, to complement fatal injury studies; for example, using workers' compensation statistics and/or severe occupational injury information systems such as the TSI in Sweden (Torsteinsrud *et al*, 2001).

This work also revealed that a variety of quality injury datasets are available worldwide which contain detailed case narratives, at least in relation to fatalities. Moreover, it was found that around 3 to 4 lines of text narrative provide sufficient information to unambiguously code injury cases.

However, it was also demonstrated that a key methodological limitation is the current need to manually process injury cases. The time intensive nature of the manual coding process (average coding time 4.75 mins/case for the NOHSC dataset) is exacerbated by the need to classify large numbers of cases to yield reliable patterns. For example, it takes a period of four days for one injury researcher to classify just 400 cases. The process is also inflexible, in that if a new taxonomy or new dataset is selected, the process must be repeated. Finally, while coding error rates of 5-7.5% were reasonable relative to other published studies, it is desirable to decrease error rates to below 5%.

These methodological constraints associated with the manual classification process, severely restrict the practical application of the injury taxonomy (or any other non-ICD classification systems) by injury researchers. As such, injury researchers must currently either rely on existing coded data (e.g. ICD data, which as discussed does not provide the detail necessary), or obtain descriptive data and manually classify (which is time and labour intensive, and prone to error).

A number of injury researchers have called for progress in terms of overcoming the limitations of existing methods for analysing injury data. For example, in a paper entitled *Methodological Considerations in the Analysis of Injury Data*, Bangdiwala (2000) concludes with the following statement:

> *"The potential for injury epidemiology is unrealised at present. The injury research*

> *community – working closely with methodologists that fully comprehend the specific issues in the nature of injury data – is challenged to continue tackling the important methodological issues in order to advance the field and to be able to deal more efficiently with limited resources with this grave problem affecting the entire world."*

It is suggested that progress towards overcoming one such methodological issue is to automate the manual classification process using computing technology.

4.5 Summary

In summary, this work has demonstrated that the proposed injury taxonomy can be applied as an accurate, reliable and useful tool for classifying injury cases.

However, automation is required to allow efficient classification of text data and reduce human error resulting from the manual classification process. The following section of this dissertation outlines the development, testing and application of such an automated tool.

5.0 DEVELOPING A KNOWLEDGE ACQUISITION SOFTWARE TOOL TO AUTOMATE THE CLASSIFICATION PROCESS

This section outlines the development, testing and application of a knowledge acquisition tool to automate the classification of injury data and overcome current methodological limits associated with manual classification of large injury datasets.

5.1 Introduction

Knowledge Acquisition (KA) refers to a suite of techniques, developed from the areas of artificial intelligence and expert systems, which aim to elicit knowledge from a human 'expert' and capture it in a 'knowledge based system'. The advantage is that once the knowledge base is elicited, the system can efficiently and reliably simulate the reasoning of an expert, benefiting other experts and novice users. Further, hypotheses regarding aetiological patterns or interventions can be efficiently tested using computer-based classifications.

KA technology has been successfully applied to fields such as medicine and pathology; one commonly cited example is a medical expert system known as 'Mycin', which was designed to assist physicians with the diagnosis and treatment of bacterial infection (Buchanan et al, 1988). Mycin uses a rule-based approach to the interpretation of thyroid assays to help the treating physician determine whether a patient has a bacterial infection, which organism is responsible, which drug may be appropriate for the infection, and which drug may be used on the specific patient.

While KA has a variety of such industrial applications, it is yet to be applied as a methodological aid to the field of injury prevention and control.

The present need is for a KA software tool which can elicit expert knowledge of the taxonomic injury classification ('domain knowledge') as well as deducing the experts' classification reasoning ('rule-based knowledge'). The hypothesis is that if the experts' knowledge base can be acquired, the classification process can be automated – removing human inefficiency and error from the classification process. Further, the tool should be adaptable to different injury databases and classification systems, such that injury researchers can apply the tool to efficiently and reliably classify any English text based injury dataset.

The objective of this work, then, is to develop, test and apply such a software tool for classifying injury cases. This goes well beyond use of computing technology as a passive storage device or basic search engine tool (e.g. keyword searches and relational databases).

In order to meet this objective, a prototype knowledge acquisition software tool was developed, tested and trialled at the University of New South Wales over a five year period from 2001 to 2005.

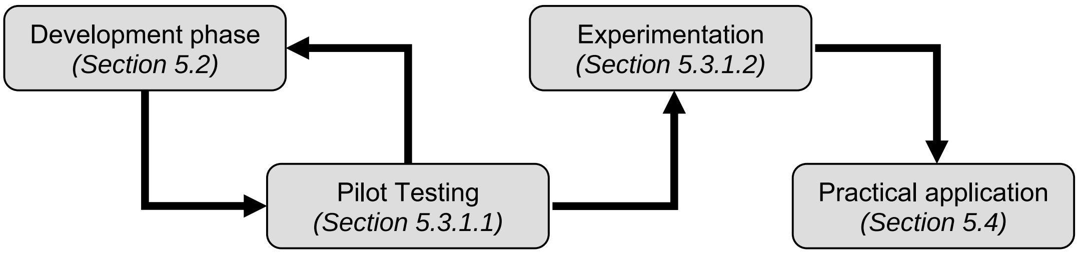


Figure 5.1: Research and development process for KA Software tool (dubbed 'Injury Knowledge Manager').

The research and development process, depicted by **Figure 5.1**, is outlined in detail in the following sections of this dissertation.

5.2 Development of Prototype KA Software Tool

The author received expert Java programming assistance from researchers at UNSW School of Computer Science in the writing of the source code (under the direction of Professor Paul Compton). All other aspects of the development (e.g. pilot testing, experimentation, and practical application) were completed exclusively by the author. The Java™ programming language was selected as it is platform independent, highly portable and has a strong Graphical User Interface (GUI) which promotes ease of use. Sun Microsystems provides the Java 2 Runtime Environment as a free, redistributable environment.

5.2.1 Development Method

The following subsections outline the methodology adopted in the development of the software tool, including: design of the expert interface; method to acquire domain knowledge (that is, knowledge of the expert's classification system), and; method to acquire rule-based knowledge (via the KA algorithm).

5.2.1.1 Expert Interface

The software was programmed to create various user-friendly interfaces along with a back-end consisting of the actual knowledge acquisition system. The program was designed to flow as follows: Set-up main window (called the *Display Case* window); read-in all cases from the data file, then; display the first case in the *Display Case* window for user input.

The user interface (front end) was designed to comprise of three interactive GUIs:

1. *Display Case* – a main window to display data cases individually and allow the user to open a data file and scroll through all the cases. Standard functions such as save, open, and exit functions were included.
2. *Add Concept* – a pop-up window to allow the expert to input the classification categories (i.e. add concepts to define the domain).
3. *Make a new Rule* – a pop-up window to allow the expert to select relevant features of each data case that define its place in the classification tree (i.e. generate rules to build the knowledge base).

The expert interface was designed so as not to require any consultation between the expert and the program developer (also known as the 'knowledge engineer').

5.2.1.2 Method to Acquire Domain Knowledge

For the present application, the domain equates to the classification system the expert chooses to adopt in classifying a dataset of injury cases. The domain taxonomy is thus a hierarchical tree where each classification category (or concept) is represented as a taxon (or node) on the taxonomy.

The software was programmed to accommodate different injury taxonomies. This was achieved by designing the *Add Concept* interface to allow direct input of the desired injury classification system by the expert. In other words, the program was designed to elicit domain knowledge directly from the expert, rather than being pre-programmed to any one particular injury domain.

A save/open function was provided so that an existing classification system can be saved (e.g. for later application to new injury cases) or a fresh session opened (e.g. to reclassify cases according to an alternate injury taxonomy).

Likewise, the program was developed to accept different sources of data (i.e. injury cases) by having the functionality to import different injury datasets.

5.2.1.3 Method to Acquire Rule-based Knowledge

The back-end of the software was developed to acquire a set of classification rules from the expert via application of a specialised KA methodology known as ripple-down rules (RDR).

Compton and Jansen introduced the RDR technique to enable the acquisition and maintenance of large rule-based systems (Compton and Jansen, 1990a; 1990b). The underlying concept is that a domain experts' knowledge base can be acquired by incremental transfer and refinement of rule-based knowledge within a well-defined context. Unlike most knowledge acquisition, RDR does not rely on the expert to specify what they know. Instead, tacit knowledge becomes codified by the RDR system while the domain expert demonstrates their expertise.

RDR systems have been put into routine use with a number of domains. A key application of RDR is PEIRS (Pathology Expert Interpretive Reporting System), a large medical expert system used to interpret chemical pathology reports at St Vincent's Hospital Sydney (Compton, Edwards *et al.* 1993). PEIRS has been in use for over ten years.

The RDR approach allows for modelling of an experts reasoning process by developing a network of production rules, otherwise known as IF-THEN rules. The "IF" component of the rule specifies the features (or conditions) which must be present in order to lead to the conclusion (i.e. classification category) referred to by the "THEN" part. For example:

1. IF *burn* THEN *thermal energy*

This simple rule states that if the feature *burn* is found in the case, then it should be classified as belonging to the *thermal energy* category.

The KA program was designed to allow the expert to select keywords and the order of the keywords as features in the text cases. As such, a rule can contain any number and any order of features connected by "AND" or "<" operators respectively.

All the features specified by the rule must be present for the rule to fire and the conclusion to be accepted. However, the conclusion may not be valid for all cases. For example, Rule 1 above may fire, but other features may lead to a different conclusion, such as for an injury case involving *burn* due to prolonged exposure to the sun. In this case, the conclusion needs to be altered to *radiation energy - solar* as per the following rule:

2. IF *burn* AND *sun* THEN *radiation energy - solar*

In the above example, the RDR system provides a means for the expert to generate a new rule linking the relevant case features to the new conclusion.

In technical terms, this new rule is called a refinement (or exception) rule and is attached as an 'if-true' branch to the original rule. If a new case leads to the original rule *and* the refinement rule firing, then the conclusion of the refinement rule is returned. If the user disagrees with the conclusion then another refinement rule is generated and again attached to the 'if-true' branch of the first refinement rule. The case which prompts addition of the new rule is stored in association with the rule as a 'cornerstone case' to maintain the context of the knowledge base.

On the other hand, if a case does not contain any features to fire existing rules, the RDR system yields the default (null) classification. The user then inputs relevant features and nominates the correct conclusion for this case, thus generating a new rule. This new rule is attached to the 'if-false' branch of the previous rule which did not fire.

As such, the RDR system is designed to build up a large number of rules as more and more cases are processed. The resulting RDR structure becomes a tree-like network of rules with hierarchical structured exceptions, connected by 'if-true' and 'if-false' branches. The 'if-true' branch is followed when a rule fires, and the 'if-false' branch is followed when a rule doesn't fire.

More precisely, RDRs can be defined as the quadruple < R, C, X, S > where R is the parent rule, C is an arbitrary conclusion (in this case either true or false), X are the refinement rules (also known as children rules) and S are the succeeding RDRs (known as sibling rules).

A simple RDR structure is depicted in **Figure 5.2** below, with boxes marking rules, and edges labelled ‘if-true’ and ‘if-false’ pointing to the refinement rule and the succeeding RDRs respectively.

In this example, a case containing the feature *burn* will be classified as *thermal energy*, unless it is *sun burn* or *chemical burn*. However, the RDRs also state that burns from hot chemicals (e.g. scalding burns from contact with hot gas) will be classified as *thermal energy*.

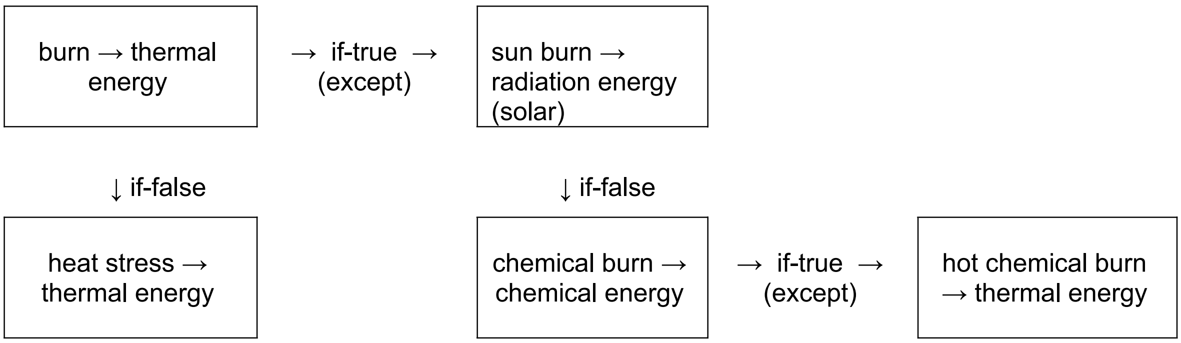


Figure 5.2: Example of ripple-down rule (RDR) structure.

In this fashion, each RDR defines a relatively small and, at least in principle, independent piece of knowledge acquired from the expert. The advantage of RDR over other knowledge acquisition methods and conventional production rule development lies in its refinement structure. It allows the expert to define a coarse definition for a conclusion and then provide refinements later. Further, the RDR system ensures that no knowledge is ever lost; rules cannot be removed, rules are only added. The new rules either cover cases not yet handled by the system, or act as refinements to correct errant conclusions.

Importantly, knowledge (i.e. any new rule) is validated at the time of acquisition. If an expert thinks the interpretation of a case is incorrect, then they must input some feature of the case which distinguishes it from a case which is correctly interpreted by the RDR pathway. A new rule is valid only if it correctly deals with the case for which it is added and will not result in the system mishandling any previous cases.

This combination of the acquisition and validation processes, inherent to RDR, contrasts with the conventional approach of building an expert system and then attempting to validate it.

Further, the expert simply adds rules to the bottom of a path and cannot embed any control knowledge affecting the way inferencing proceeds (Compton, 1990). In fact the program is designed such that nothing other than domain expertise is required to build a knowledge base.

In summary, the present KA system for classifying injury cases was designed to adopt an RDR approach, whereby:

- Knowledge is added to the knowledge base to deal with specific cases, building up a network of rules as more and more cases are processed by the expert.
- Rules are boolean expressions which link features of a case to a specific conclusion (classification category). All the features of a rule must be present for the conclusion to be accepted.
- The knowledge base evolves incrementally, while being used to process real cases. When a misclassification occurs, new rules are added by the expert. The new rules either apply to cases not yet handled by the system, or act as refinement rules.
- RDRs form a tree-like structure consisting of ‘if-true’ and ‘if-false’ branches. The conclusion returned by the system is that which is associated with the last rule to fire in the sequence.
- A new rule is deemed valid only if it will correctly deal with the case for which it is added, and will not result in the system mishandling at least the other cases which have been used for knowledge acquisition.

5.2.1.4 Knowledge Acquiring Algorithm

The algorithm outlined below was developed to enable the software to acquire RDRs for each classification category in the domain.

1. Define and input the classification categories and dataset.

   Category (Class) set $C = \{ C_{0,} C_{1,} C_{2,} C_{3,} \ldots, C_n\}, C_{0\ =\ unknown\ class}$

   Dataset $D = \{d_{0,} d_{1,} d_{2,} d_{3,} \ldots, d_i\}$

2. Initialize the concept C_0 with the positive default RDR. Set $C = \{C_0\}$.

3. If there is a new data case *d*, present the system with *d*, otherwise loop back to $d_{0.}$

4. If the RDR is empty, return the default conclusion C_0 for the data case. Return to step 3.

5. If the RDR is not empty, check features of the cases for applicability against consecutive rules in the rule-base:
a) if a rule does not hold, evaluate the next 'if-false' rule;
b) if a rule holds, any connected 'if-true' rule is evaluated recursively in the same manner.

6. Return the conclusion C_i corresponding to the last rule to fire. This conclusion is returned if and only if all the all the exceptions to this rule do not hold.

7. If the expert agrees with the classification C_i of the system, return to step 3, otherwise proceed to step 8.

8. If the expert disagrees with the classification proposed by the RDR system, prompt the expert to specify the correct concept $C_j \in C$ and proceed to step 9.

9. Prompt the expert to select features (keywords and/or order of the keywords) in the data

case which justify the new conclusion C_j about this case. The expert can select any conjunction of features that are true for the case as long as at least one of these differentiates the case from previous classifications. This case is then stored by the system as a cornerstone case, as it is the case providing the context for the new conclusion.

10. The existing RDRs, R_i and R_j, are refined according to the following algorithm:

$$R_i = R_i \leftarrow (-, \mathit{Features}(d)),\ R_j = R_j \leftarrow (+, \mathit{Features}(d))$$

These refinement rules are added to the knowledge base. The RDR system ensures that all knowledge is stored in context by storing the rule (containing the justification and conclusion), with the cornerstone case.

11. Return to step 3.

5.2.2 Outcomes of Development of KA Software

The developed knowledge acquisition software tool was dubbed *Injury Knowledge Manager* (IKM). A detailed user manual and further technical documentation are contained as **Appendices V** and **VI** respectively.

The following subsections outline key outcomes relating to: the expert interface; domain knowledge acquisition, and; rule-based knowledge acquisition.

5.2.2.1 Description of Expert Interface

The Injury Knowledge Managers' user interface (display case window) is depicted in **Figure 5.3** below. This is the main environment developed to display the data cases individually and allow the user to sequentially analyse and classify each case.

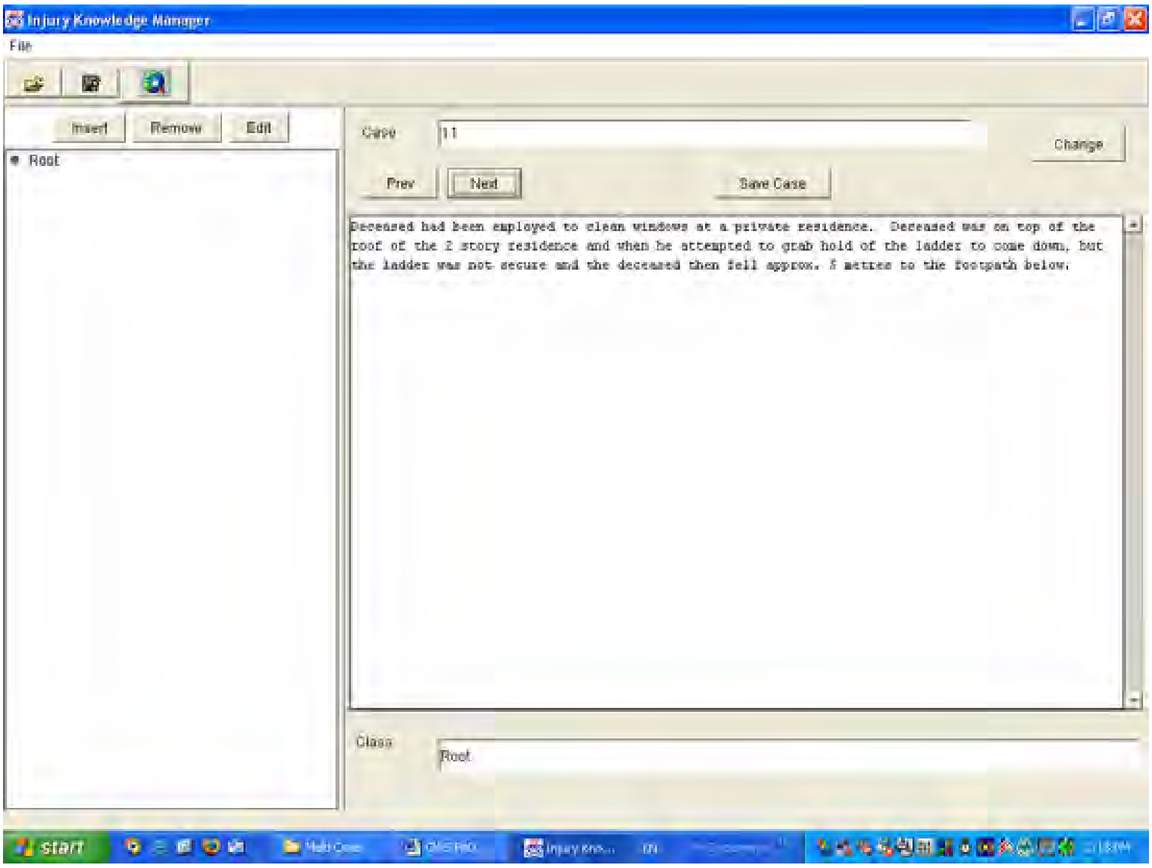


Figure 5.3: The main knowledge acquisition screen of Injury Knowledge Manager which allows the expert to add classification categories, review cases and change existing classifications.

The right-hand side of the window is used for case analysis. It contains the following features:

- *Case* box – displays current case number.
- *Case text* box – contains the current case description.
- *Prev* button – causes previous case to be displayed. If the first case is being displayed this will loop to the last case.
- *Next* button – causes next case to be displayed. If the last case is being displayed this will loop to the first case.
- *Save Case* button – to save any required edits to the current case (e.g. any typographical errors).
- *Change* button – to change an incorrect classification. This function will be discussed in more detail later.

- *Class* box – displays the KA system's classification of the case. The default value is labelled "Root" to denote the root of the taxonomy. It also lists all parent classifications, thus showing the user the relevant branch of the classification tree.

5.2.2.2 Acquiring Domain Knowledge

The display case window also provides for display and input of the desired injury classification system (domain), by way of the left-hand panel. To add to the domain, the user simply clicks *Insert* and enters details, as seen in the *Add Concept* pop-up window in **Figure 5.4** below.

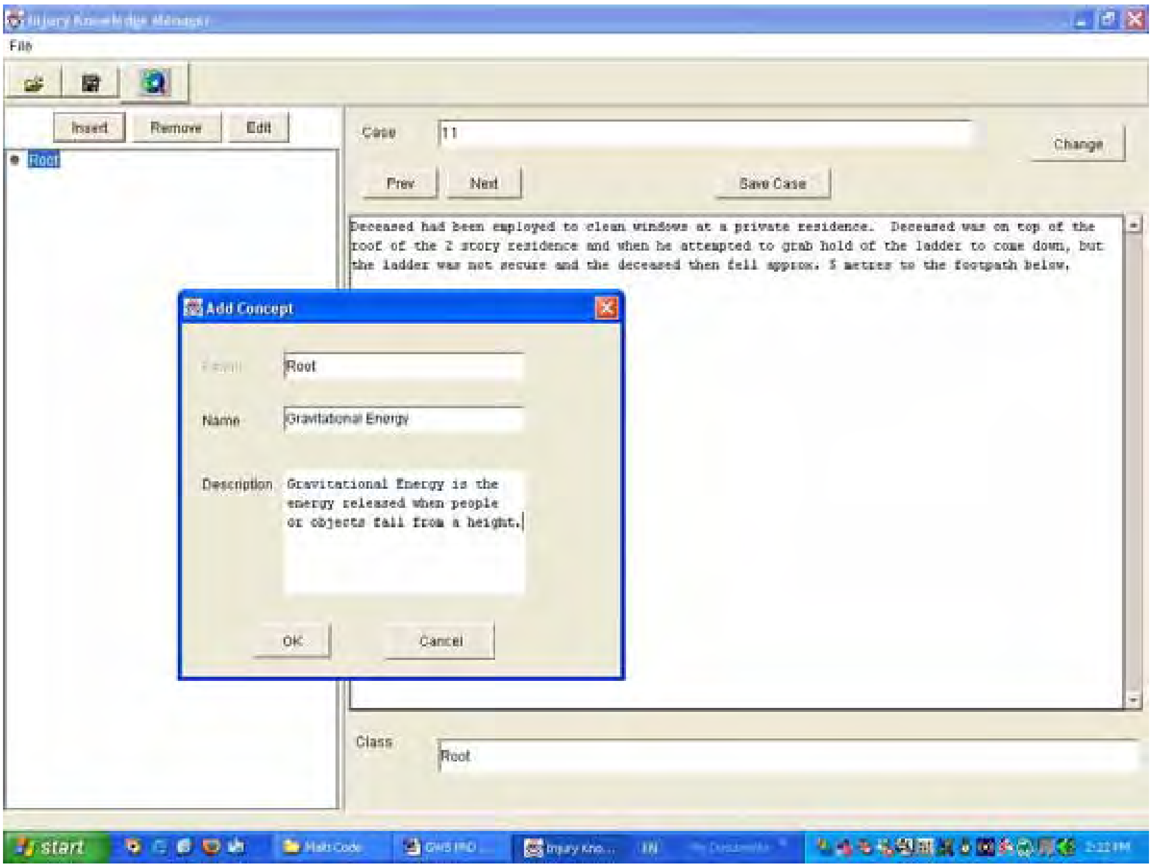


Figure 5.4: The *Add Concept* pop-up window for input of the desired injury classification system.

The new classification categories are displayed in a tree structure on the left side-panel. To add a sub-category, e.g. add *Falls of People* to *Gravitational Energy*, the user simply selects the new *Gravitational Energy* node and again clicks *Insert* (see **Figure 5.5** below). Similarly, categories can be edited by clicking on *Edit* or removed by clicking on *Remove*.

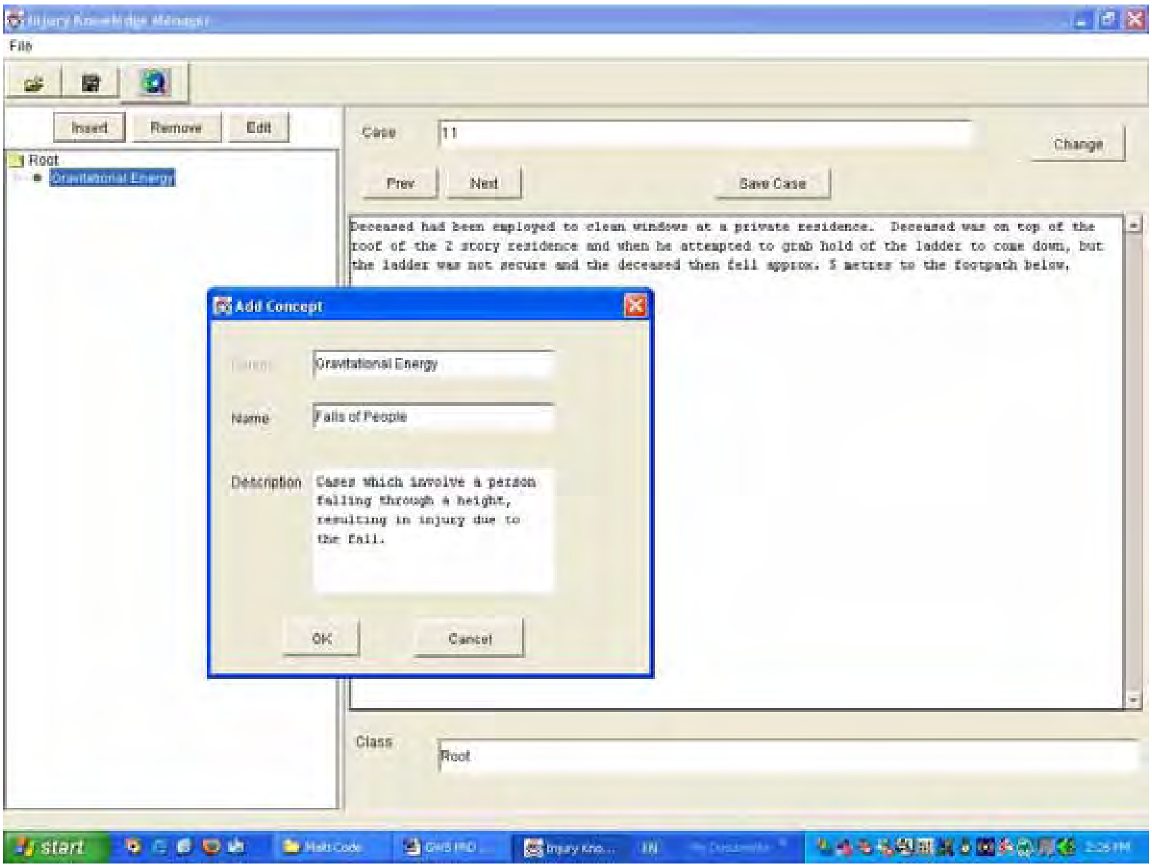


Figure 5.5: Adding the classification category Gravitational Energy – Falls of People to the domain.

In this fashion, the entire injury classification system can be entered and displayed in the left side-panel. The following screen dump (**Figure 5.6**) shows the complete domain for the present application; that is, the complete injury taxonomy by energy type (level I).

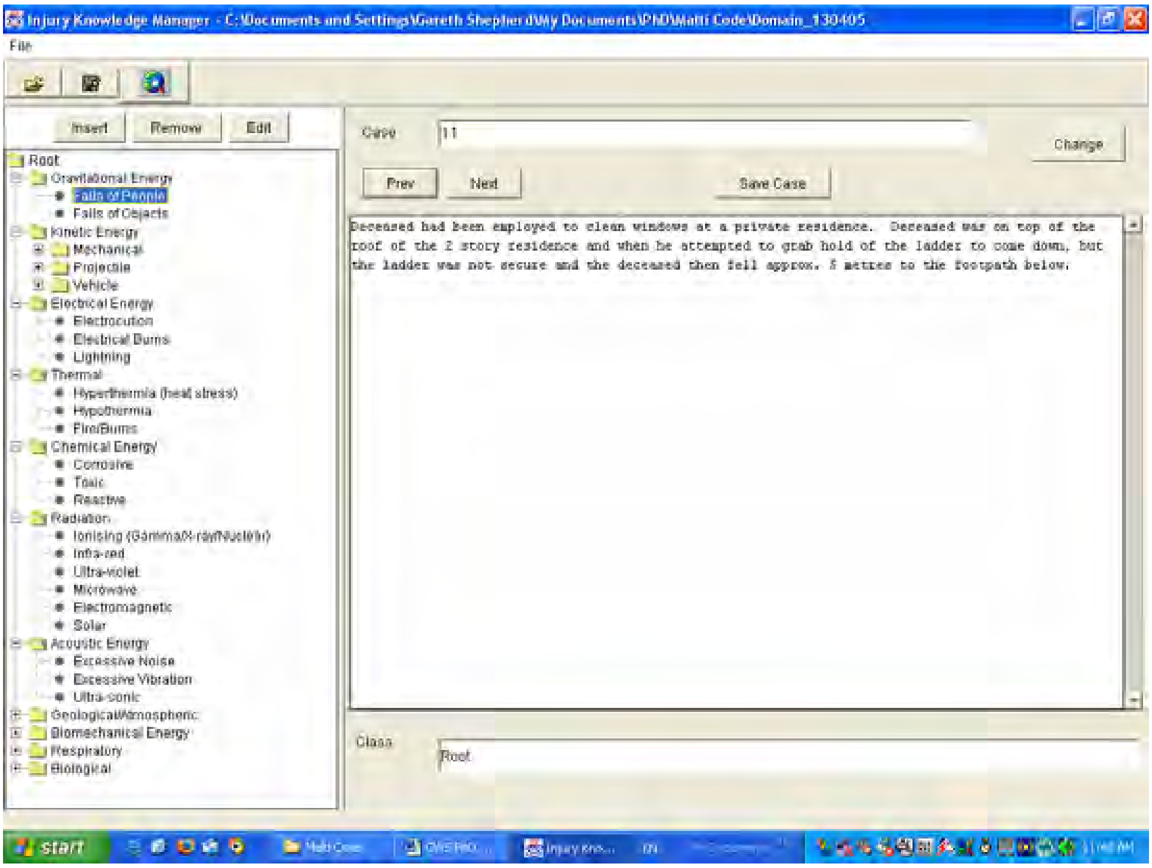


Figure 5.6: Display of the complete injury taxonomy (the chosen domain for the present application).

Finally, the *Open* and *Save* buttons at the top of the left panel allow the user to read and save classification categories. For example, if the expert wishes to apply a different classification system, a new file can be opened and the domain knowledge acquisition process repeated.

5.2.2.3 Acquiring Rule Based Knowledge

With the domain knowledge defined, the expert can commence processing individual cases sequentially such that Injury Knowledge Manager can acquire rule-based knowledge.

If no rules fire for the current case the default "Root" is returned and displayed in the *Class* box below the case. To propose a new classification the expert simply selects the correct classification category (left panel) and clicks on the *Change* button. This will trigger the

Make a new Rule window, which is used to select features in the case which define a new rule. For example, the screen dump provided as **Figure 5.7** depicts the process of making a new rule to couple the feature *electrocuted* with the category *Electrical Energy – Electrocution.*

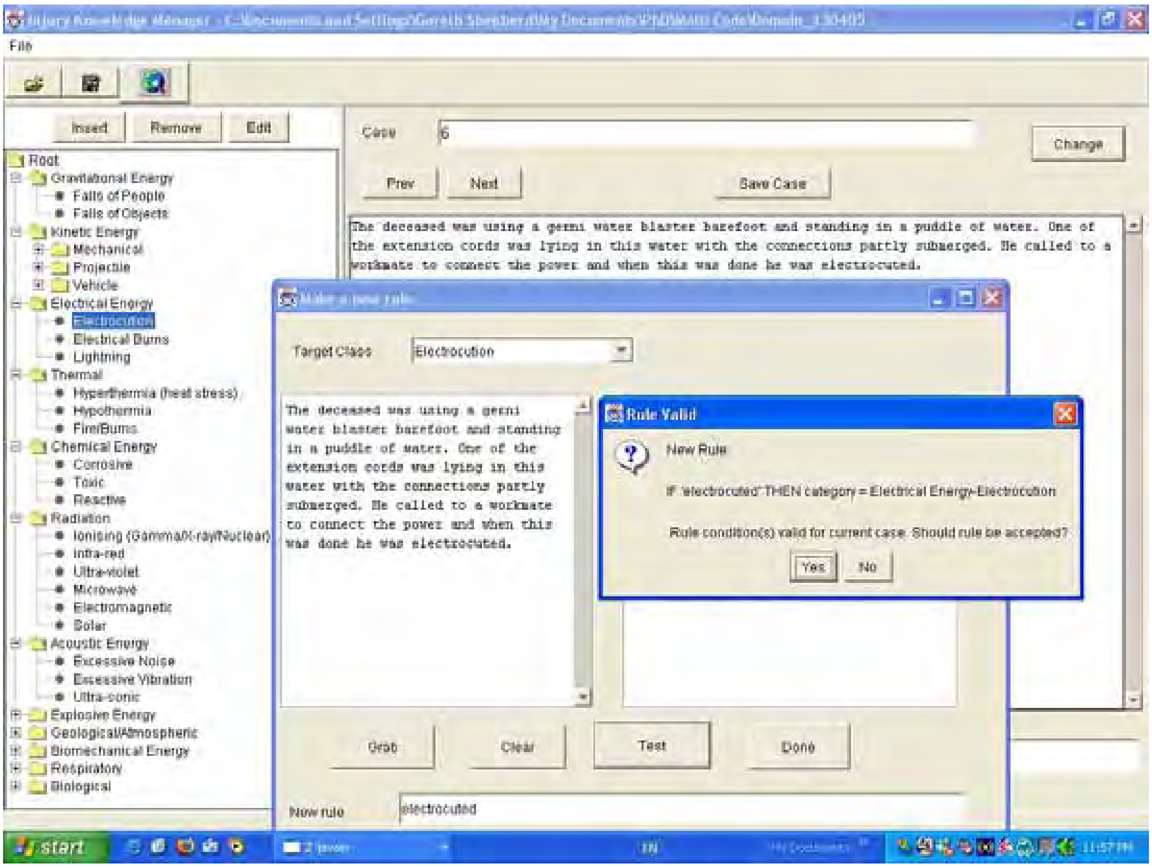


Figure 5.7: The *Make a new rule* pop-up window allows the expert to extract salient features of the case to generate a new rule. The *Rule Valid* box shows the expert that the rule is valid for the current case.

As such, the process of rule generation with Injury Knowledge Manager can be summarised as follows:

1. The expert identifies salient features in the case by reviewing the current case and decides which words or phrases (and/or the order thereof) lead to the correct classification.
2. The expert selects relevant text directly from the case and clicks on the *Grab* button to extract the feature for display in the *New rule* box. Alternatively, the expert can type in

words directly. The *Clear* button is available to remove the new rule conditions if an error is made.

3. A rule can contain any number and order of features connected by “AND” or “<” operators. For example, the rule “*cord, electric shock”* would denote that the two conditions *cord* and the phrase *electric shock* must be present. Alternatively, the rule “*cord<electric shock”* would denote that the word *cord* must appear before the phrase *electric shock*.
4. The *Test* button allows the expert to test validity of the rule by applying the rule to the current case as well as to any existing cornerstone case (if there is an original case to which the rule applies). The rule is not valid if it doesn’t apply to the current case or if it applies to both the current case as well as the cornerstone case. In such circumstances, the *New Rule* box is cleared and the expert is prompted to input new rule features(s) which apply to the current case but differentiate it from the cornerstone case.
5. The *Done* button allows the user to accept the validated new rule conditions so that the KA system can create a new rule. The pop-up window disappears and the new classification for this case will appear in the *Class* box at the bottom of the display case window.

If an existing rule fires on the current case, the KA system automatically proposes a classification category. The expert can accept the classification by clicking *Next* to move to the next case. If the classification is incorrect the expert can click *Change* (as above). In such circumstances the *Make a new rule* interface also displays the cornerstone case in the right-side panel (titled *Original Case*). In addition, the last 10 rules which have fired are displayed in the *Original Rule* panel at the bottom of the window. This information provides context to help the expert identify unique features which distinguish the current case from the original case.

For example, the screen dump provided as **Figure 5.8** shows a case which has been incorrectly classified by the KA system as *Gravitational Energy* due to the firing of the following existing rule:

Original Rule: IF *fall* THEN *Gravitational Energy*

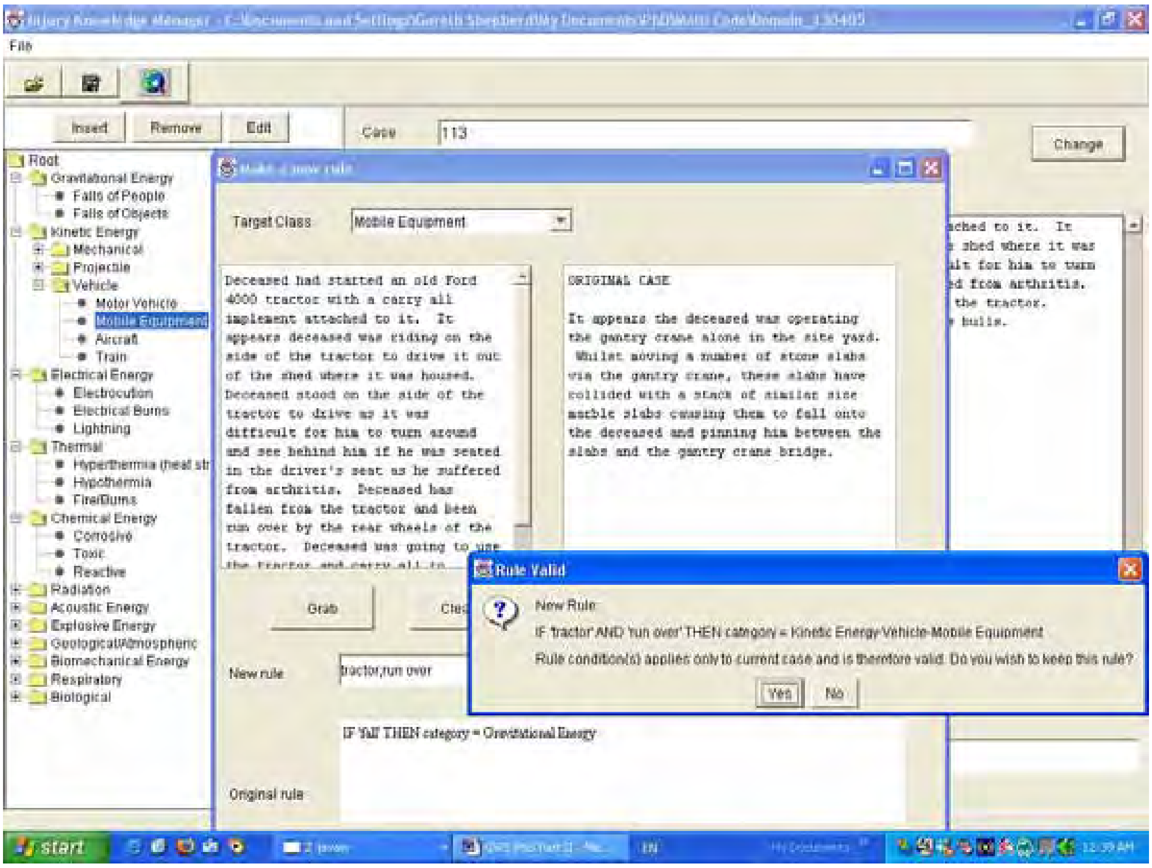


Figure 5.8: Example of expert input to resolve a misclassified case. The expert proposes a refinement rule and that new rule is checked for validity against the current case as well as the original case.

In this example, the expert has identified the correct classification of the case as *Kinetic Energy - Vehicle - Mobile Equipment* and selects the features *tractor, run over* to distinguish the case from the original case which fired the incorrect classification. Thus a new rule is proposed by the system:

New Rule: IF *tractor* AND *run over* THEN *Kinetic Energy - Vehicle - Mobile Equipment*

As before, the KA system checks the proposed new rule for validity against the present case and also ensures that it does not also fire on the original case. If the rule passes these tests the RDR method attaches a refinement to the original rule to correct the errant conclusion. Hence, when processing subsequent cases, if an original rule ‘fires’ (i.e. for a cornerstone case), the system checks for refinement rules.

In this fashion, rule-based knowledge is incrementally acquired from the expert, thereby increasing the accuracy of coding of subsequent cases by the KA system.

5.3 Testing of KA Software Tool

The following sub-sections of this dissertation describe the methodology adopted in testing the software tool (**Section 5.3.1**), followed by presentation of the test results (**Section 5.3.2**) and discussion (**Section 5.3.3**).

5.3.1 Test Method

The KA software tool was subjected to initial prototype testing and detailed experimental testing in order to evaluate its ability to accurately and efficiently code large numbers of injury cases, as follows.

5.3.1.1 Initial Testing of Prototype

The prototype software tool was initially tested and refined by applying the same test dataset utilised in **Section 4** for the testing of the injury taxonomy; that is, 400 randomly sampled occupational fatality cases supplied by the National Occupational Health and Safety Commission (NOHSC).

Initial ‘proof of concept’ trials were conducted in order to gauge the ability of the KA system to deduce rule-based knowledge from the human expert.

Following these trials, a series of experiments were performed to quantify the coding accuracy and efficiency of the KA system. The purpose was to gain insight into the number of cases which need to be manually classified by the expert (thus generating rules), before the KA system can accurately classify new cases without expert input.

The experiments involved classifying the 400 cases in ten successive batches of 40 cases (i.e. cases 0-39, 40-79, …, 360- 399), and assessing the efficiency and accuracy of the KA system when applied to the subsequent batch of cases (i.e. the next 40 cases which have not yet been classified).

The experiments proceeded as follows. Individual narratives in each batch of 40 cases were reviewed by the author and classified at the first level (by energy type) using the KA system (thus incrementally generating an RDR rule-base). The next 40 cases were then subject to KA system classification and reviewed by the same expert. The number of misclassifications were recorded to obtain an 'error rate' for each rule-base.

This process was repeated until the last batch of cases was classified (i.e. cases 360-399), after which the KA system was applied to the entire dataset with the classification error rate once again recorded.

The number of rules generated and the case processing time was also recorded for each batch of 40 cases, in order to gain insight into the efficiency of knowledge transfer.

5.3.1.2 Experiments Involving Coroners' Data

Following initial testing using NOHSC data, ethics approval was granted to enable authorised access to the complete National Coroners' Information System (NCIS).

The NCIS is a national internet-based data storage and retrieval system for Coronial cases in Australia, established in the year 2000. The database stores records pertaining to the approximately 18,000 deaths reported to Australian State and Territory Coroners' each year. Of these, approximately 11,000 cases are reported as 'due to natural causes' and 7,000 are reported as due to 'external causes' (such as accidents, homicides, and suicides). All jurisdictions have been reporting data to the NCIS since 1 January, 2001.

The NCIS database contains both coded and non-coded (textual) data. Coded data include date, location of incident, intent, and demographic details pertaining to the deceased. The coding system is described in detail by the NCIS Data Dictionary produced by the Monash University National Centre for Coronial Information (MUNCCI, 2001).

Full text reports regarding the incident are also available to authorised users once the case is 'closed', including: police summary of circumstances, toxicology and autopsy reports, and coronial finding. These reports are provided in Microsoft Word format. The police report is generally the most descriptive of the incident and is present in nearly all work-related injury cases (Driscoll, 2003).

A study population of NCIS work-related injury cases was collated by applying the following database screens (all other fields were left open):

1. Case Type (at completion) – Death due to External Cause(s).
2. Intent (at completion) – Unintentional.
3. Work-relatedness – Work Related (including travelling for work and commuting).
4. Date – 1st January, 2001 to 31st December, 2004 (4 year period).

A de-identified NCIS case record (main screen) is provided as **Figure 5.9** below.

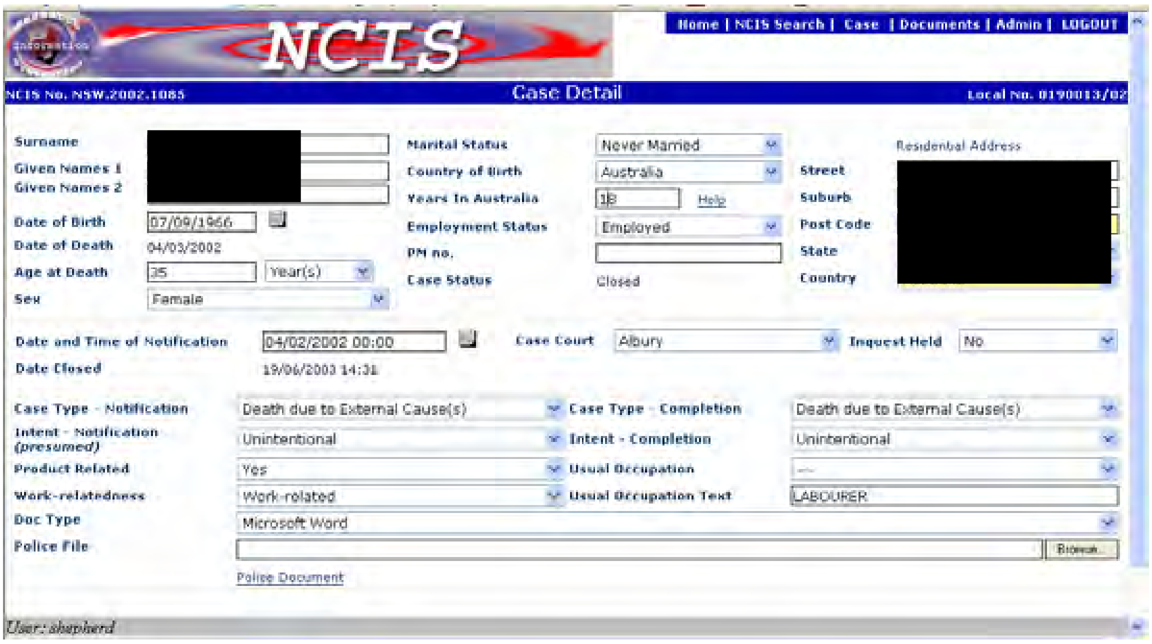


Figure 5.9: National Coroners Information System (NCIS) case detail. Note that identifying information about this case has been removed due to privacy and security.

Outcomes from the above screening process were supplemented by key-word searches of text documents within the specified dates, to identify additional cases involving work-related deaths which may not have been correctly coded as 'work-related'. This addition step was conducted as NCIS data have been found to underestimate the actual number of work-related deaths, despite offering a better estimate than the traditional use of ABS deaths data based on hospital records (Driscoll, Henley and Harrison, 2003). The ability to search and review the text documents is a key advantage of the NCIS relative to traditional 'pre-coded' datasets.

The following keywords were searched for: 'work'; 'working'; 'worker'; 'workplace'; 'occupation'; 'industry'; 'business'; 'employee'; 'employed'; 'staff'; 'labourer'; 'employer'; 'supervisor'; 'contractor'; 'self-employed'; 'sole-trader'; 'bystander'; 'commuting', and; 'assistant'.

Figure 5.10 below depicts the NCIS 'Document Search' screen, where the key-words were entered by way of a Boolean string (using the symbol '|' for the operator 'or'). The 'Score' value refers to how closely the document matches the search criteria; the minimum score of '20' was selected to maximise the number of returned documents. The 'Distance' field relates to searching for variations of a phrase where the nominated distance is the number of words between any of the key words; as such it is not relevant for the current purposes, and was set at '5' as a default.

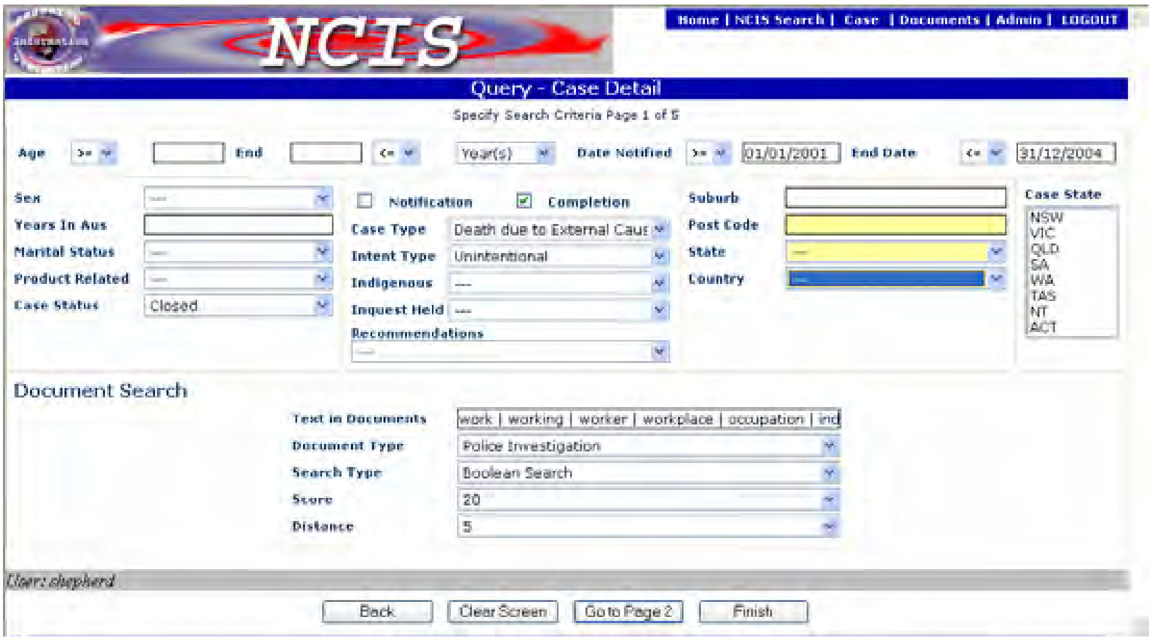


Figure 5.10: National Coroners Information System (NCIS) document search detail. The lower half of the screen shows keywords entered in a Boolean string (with the symbol '|' denoting the 'or' operator).

The documents which were returned from the key-word searches were cross-checked against those returned from the screening process and all cases were reviewed to verify 'work-relatedness'.

As a result of the above collation process, an overall study population of 1056 work-related death cases were identified, all of which were 'closed' cases and contained a detailed police investigation report. A representative case description extracted from the police report is provided as follows (once again de-identified by the author):

> *About 9.20am 25/07/01 the deceased was working as a painter at [redacted]. A witness (owner of the home) [redacted] was assisting him with the painting. The deceased was setting up the scaffolding which was*

> *approximately three metres high. The witness turned away from the deceased and was painting when he heard the deceased fall to the ground. The deceased was located unconscious with blood coming from the nose. CDA were contacted at 9.25am 25/7/01 and attended at 9.38am. He was transported to Royal North Shore Hospital suffering from head injuries. The deceased underwent an operation between the hours of 12.30pm and 4pm 25/7/01 in an attempt to release pressure from the brain. At the completion of the operation the deceased was stable. Overnight the deceased health declined and further checks AM 26/07/01 revealed zero brain activity, (brain death). This was confirmed by two independent Neurosurgeons and the attending physician Doctor [redacted]. Life was pronounced extinct at 11am 26/7/01 on the basis of the zero brain function.*
>
> *The deceased remained on the life support machine, having a heart beat but unable to breath independently*
>
> *Police also contacted Work Cover as to whether they wished to become involved. No one has been spoken to due to WorkCover closing prior to contact. Physical Evidence is also to be contacted re possible photos of the scene. The witness was spoken to by phone and particulars obtained. At this time there are no suspicious circumstances involved.*
>
> *On the 27/7/01 Police attended [redacted] where a number of photographs were taken. Particulars were obtained from the witnesses to the fall and after to the injuries the deceased sustained.*

As can be observed from the sample above, the NCIS police reports contain significant detail regarding the incident, and are generally written in a factual and 'chronological' style, in contrast to the less detailed 'summation' style of the NOHSC test dataset (for comparison refer to the representative NOHSC case narrative provided in **Section 4.2.1**).

The previously described series of tests (conducted with the NOHSC dataset) were repeated with the new dataset of 1,056 cases in order to quantify the coding accuracy of the KA software for the new dataset.

5.3.2 Test Results

As described above, a series of tests were performed involving splitting the 400 NOHSC injury cases into ten batches of 40 cases. Each batch was manually classified by energy type (first level) using the KA software, thus generating ripple-down rules. Following the classification of each successive batch, the KA system was applied to the next batch of unclassified cases to assess the efficiency and accuracy of knowledge acquisition. These experiments were repeated with dataset of 1,056 cases (police reports) from the NCIS database.

Data from these tests are tabulated below. The results are examined in detail in the subsequent Discussion section of this report.

5.3.2.1 Results from NOHSC dataset (n=400 cases)

Outcomes of tests using the NOHSC dataset are recorded in **Table 5.1** below.

	Ten batches of 40 NOHSC cases (total n=400)									
	1 0-39	2 40-79	3 80-119	4 120-159	5 160-199	6 200-239	7 240-279	8 280-319	9 320-359	10 360-399
Total time taken to manually classify cases (cumulative - hrs)	4.1	5.9	7.7	9.5	11.3	13.1	14.9	16.7	18.5	20.3
Total no. of rules in rule-base (cumulative)	37	66	88	104	115	123	129	134	138	140
Total no. of misclassified cases when rule-base is applied to next batch of 40 cases	29	22	16	11	8	6	5	4	4	n/a
Percentage error rate (for KA system classification)	**93%**	**73%**	**55%**	**40%**	**28%**	**20%**	**15%**	**13%**	**12%**	**3.3%***

Table 5.1: Test data arising from application of the KA system to classify the NOHSC dataset of 400 injury cases (in ten successive batches of 40 cases)

* Once all the cases (n=400) were classified, the knowledge base (consisting of 140 rules) was applied to the entire dataset to identify the extent of rule validation errors. This result reflects the overall error rate was 3.3% (or 13 mis-classified cases) when the complete knowledge base was applied to the entire dataset.

The initial findings from this pilot study were presented at the *6th World Conference on Injury Prevention and Control* (Shepherd, Cross, Compton et al, 2002).

5.3.2.2 Results from NCIS dataset (n=1,056 cases)

Outcomes of the series of experiments using the NCIS dataset are recorded below:

	Ten batches of 105 NCIS cases (total n=1,056)									
	1 0-105	2 106- 210	3 211- 315	4 316- 420	5 421- 525	6 526- 630	7 631- 735	8 736- 840	9 841- 945	10 946- 1055
Total time taken to manually classify cases (cumulative - hrs)	5.6	12.19	18.57	23.3	26.33	30.91	34.85	38.45	42.05	44.00
Total no. of rules in rule-base (cumulative)	182	214	239	259	276	293	307	319	329	337
Total no. of misclassified cases when rule-base is applied to next batch of 105 cases	23	18	13	11	9	7	6	5	4	n/a
Percentage error rate (for KA system classification)	**22%**	**17%**	**12.5%**	**10%**	**8.5%**	**7%**	**6%**	**5%**	**3.8%**	**3.1%***

Table 5.2: Test data arising from application of the KA system to classify the NCIS dataset of 1,056 injury cases (in ten successive batches of 105 cases)

* As before, once all the cases (n=1,056) were classified, the knowledge base was applied to the entire dataset to identify the extent of rule validation errors. This result reflects the error rate was 3.1% (or 33 mis-classified cases) when the complete knowledge base was applied to the entire dataset.

Following these experiments, the complete rule base was reviewed in order to identify any knowledge repetition (i.e. RDRs which are appear more than once through the tree structure). It was found that 31 rules were independently repeated (or 9.2% of the overall knowledge base of 337 rules).

5.3.3 Discussion of Test Results

This section discusses outcomes of the testing of Injury Knowledge Manager in terms of classification efficiency and reliability. Results are compared with the outcomes of manual classification which were outlined previously.

5.3.3.1 Outcomes from initial tests (NOHSC data, n=400)

The initial user trials and test results support the viability of applying knowledge acquisition technology to elicit rule-based knowledge from a human expert, thus automating the classification injury data.

Importantly, it was found that injury cases could be easily processed with the Injury Knowledge Manager software, enabling the expert to integrate the rule generation task as a minor extension to the standard (manual) classification process. As discussed earlier, the knowledge base develops without the user being aware of the structure of the knowledge or the knowledge representation.

From the user's viewpoint, the process is simply one of:

1. Process a case using Injury Knowledge Manager;
2. Review the systems' conclusion;
3. If agree – go to next case, or;
4. If do not agree - state which conclusion is correct and nominate distinguishing features.

This is what experts do naturally and it allows the RDR knowledge base to expand incrementally as more cases are processed by the expert.

Figure 5.11 shows the growth of the knowledge base for the initial dataset of 400 injury cases (based on data presented in **Table 5.1** in the Results section).

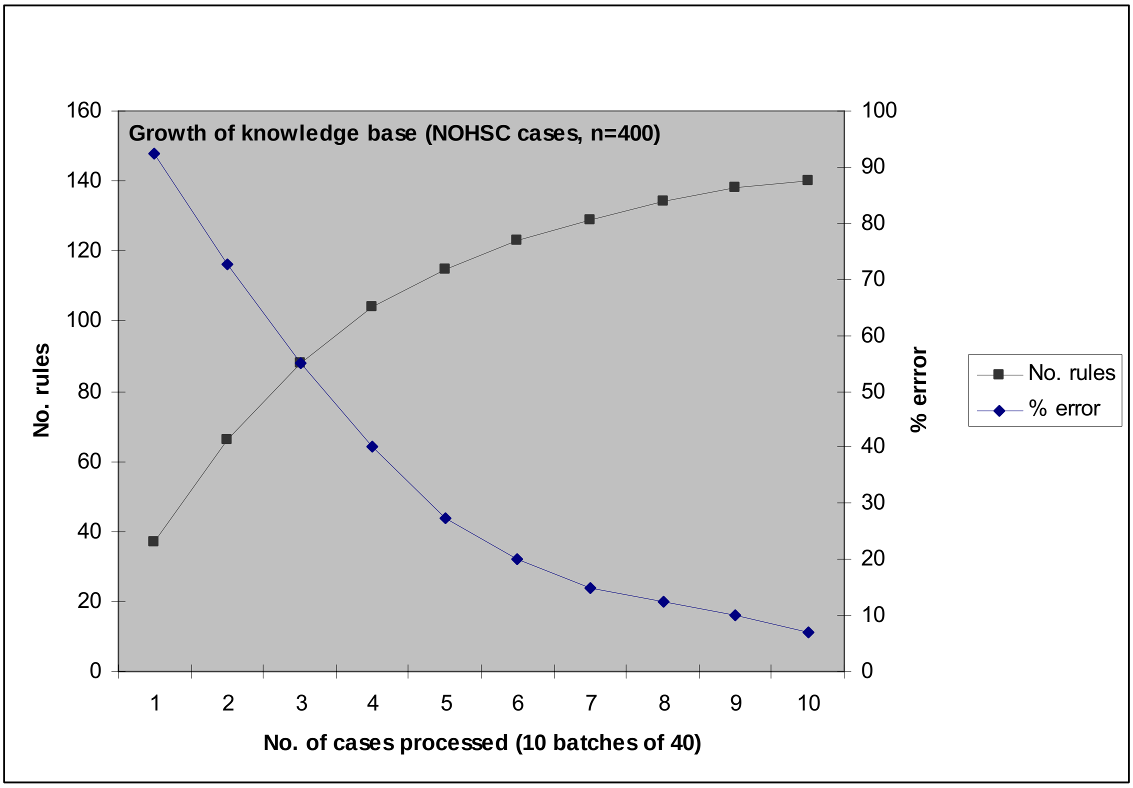


Figure 5.11: Growth of knowledge base as cases are processed (NOHSC dataset, n=400). The x-axis represents the number of cases processed while the y-axis tracks the increase in the number of rules and corresponding reduction in the percent error rate.

Figure 5.11 illustrates that, for this particular dataset and domain combination, the KA system is in a 'learning phase' for at least for the first 8 batches (320 cases) processed. This is evidenced by the steep learning curve where an average of 1 rule was generated for every 3 cases.

As such, the KA system error rate is initially very high. For example, with 40 cases manually classified (10% of the dataset) the error rate is 93%. The error rate then reduces markedly as more cases are classified. For example, with 320 cases classified (80% of the dataset), the error rate drops to 12%. This suggests that the error rate is a function of the number of rules in the knowledge base.

Figure 5.11 also reveals that the error rate following classification of all 400 injury cases is very low (3.3%, or 13 mis-classified cases). In all cases it was found that the systems' misclassification was due to poor quality case descriptions which could not be accurately classified by the expert, as was experienced in the previous manual classification of the same dataset. Disregarding these thirteen cases, the rule-base can be applied to the classified dataset with 100% accuracy. At first glance, this is not surprising as the system is simply classifying the same dataset from which the rules were generated. However, this result also provides evidence that the in-built mechanism for rule-validation at the time of KA is effective in generating a valid rule base.

In summary, a key goal of any classification system is to avoid misclassification. These results present much promise in this regard.

5.3.3.2 Outcomes from experiments (NCIS data, n=1,056)

As described in the Results section, further experiments involved applying the KA system (with the existing rule base) to the new NCIS dataset of 1,056 cases. The following **Figure 5.12** summarises performance of the knowledge base (based on data presented in **Table 5.2** in the Results section).

Figure 5.12 reveals that the initial classification error rate for the first batch of 105 cases (10% of the dataset) is around 22%. This compares favourably to the 93% error rate of the first batch for the initial NOHSC dataset and demonstrates that the existing rule base applies to the new dataset with reasonable accuracy, despite being generated from a different dataset.

This result also indicates that the rule-base is not just specific to one particular text-based dataset. This is a positive and intuitive result as the KA system, like the expert, should be applicable to different datasets as long as the knowledge remains relevant.

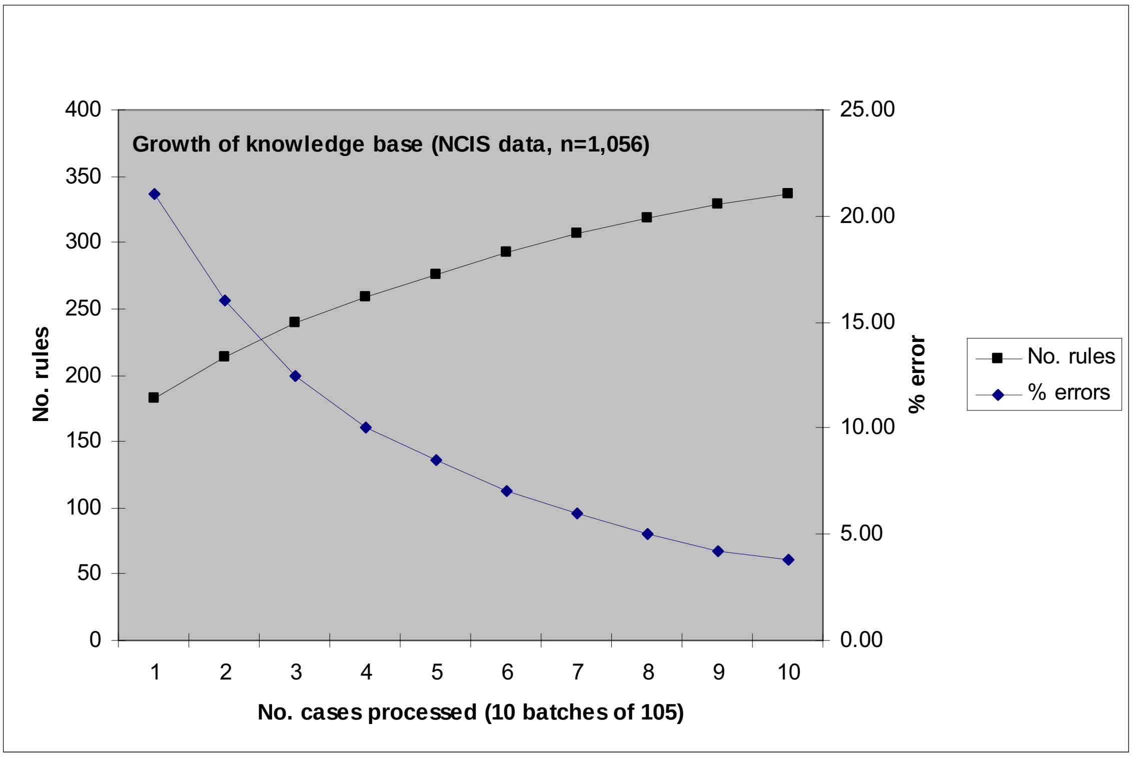


Figure 5.12: Growth of knowledge base as cases are processed (NCIS dataset, n=1,056). The x-axis represents the number of cases processed while the y-axis tracks the increase in the number of rules and corresponding reduction in the percent error rate. Note that the system starts with 140 rules from the existing rule base (derived from the initial dataset of 400 NOHSC cases).

However, it is also evident from the increase in the error rate from the fully classified NOHSC dataset (3.3%) to the first batch of NCIS data (22%) that application of the rule-base across the two datasets is not a 'perfect fit'. In reviewing the misclassified NCIS cases, it was found that the increased detail of text narratives presented by the NCIS police reports resulted in some mis-firing of rules. For example, an NCIS case involving the deceased falling off a crane included in the description that "the witness ran over to the crane to assist". This extraneous information about the witness resulted in the mis-firing of a rule involving 'run over - crane' rather than the correct classification of 'fell from – crane'. Thus, some of the existing rules required further refinement before they could be accurately applied to the NCIS data.

As such, when applying the KA system to a new dataset it will likely be necessary for an expert to process additional cases to customise the rule-base to the new data. This entails an injury researcher processing injury cases from the new dataset using the KA software system, such that new dataset-specific rules can be acquired by the system.

As before, **Figure 5.12** shows that processing new NCIS cases results in new rule generation, and a corresponding reduction in the error rate. For example, it can be seen that the error rate falls below 10% after 420 NCIS cases are processed (with a total of 259 rules generated). Once 319 rules are generated, the Injury Knowledge Manager becomes greater than 95% correct in its classifications, and thereafter appears to be in a 'maintenance phase' where rules are added only infrequently (an average of only 1 rule generated for every 13 cases).

The overall error rate of 3.1% is similar to the 3.3% error rate for the NOHSC dataset, and both compare favourably with the 5-7.5% random human error observed in the previous reliability studies for manually classifying injury data.

Figure 5.12 also indicates that if coding accuracy significantly greater than 95% is required, a large number of additional cases need processing (to generate new rules). For example, to increase the coding accuracy by just 1%, from 95% to 96%, required the review of a further 105 cases, generating 12 new rules (adding around 3% to the rule base). In other words, there appears to be a point of diminishing returns, in that the knowledge base will continue to evolve as more cases are processed but, theoretically, will never be entirely complete. As such, if maximum classification accuracy is demanded, some expert input may be required to validate new rules (albeit on an ever reducing percentage of new cases).

This finding is consistent with earlier results from RDR applications to medical expert systems, where about 230 rules were required for 95% accuracy but the system had to double in size to 550 rules before reaching approximately 99% accuracy (Compton and Jansen, 1990).

Importantly, the time taken to process cases is significantly reduced by applying the KA process. For example, it was found that the classification of the 1,056 NCIS cases using the KA software required a total of 44 hours of manual review/verification (average 2.5 minutes/case). This represents close to a 47% reduction in the time required to manually classify injury cases (average 4.75 minutes/case, as outlined in **Section 4**). Of course, the time-saving and reliability benefits of the KA approach are significantly enhanced as more and more cases are processed and further rules are acquired. For example, the final batch of 105 NCIS cases was processed in an average time of 1.10 minutes, with minimal human input.

In sum, the test results support the hypothesis that rule-based knowledge can be acquired from a human expert, leading to improved efficiency and accuracy in classification tasks.

5.3.3.3 Strengths and Weaknesses of the KA Approach

The demonstrated benefits of the KA tool in terms of classification efficiency and accuracy suggest that it can offer a valuable and scalable solution to injury researchers who require classification of large numbers of text based injury data against a chosen taxonomy.

The strengths of the ripple-down rule (RDR) method in acquiring rule-based knowledge include the incremental, user-driven and context-based nature of rule generation. As before, acquisition of knowledge can be efficiently incorporated into the human expert's normal classification process. The impact on workload and workflow is negligible. As such, the knowledge base can be built gradually over time while it is already in routine use.

Another strength of the RDR technique is that the expert is not required to have or provide some sort of integrated view of all the rule-based knowledge. Nor does the expert need to know how each new piece of knowledge is incorporated into the knowledge base. Rather, RDR achieves this via a refinement structure which automatically positions rules in the knowledge base in such a way that they will only be used in the same context in which they were provided.

A key advantage is that there is a separation between the human problem solving activity (i.e. conceptual classification and validation) and the KA system codification activity (i.e. rule generation). Problem solving is what experts do well, while codifying rules is mundane and prone to human error (i.e. is well suited for automation).

Moreover, the Injury Knowledge Manager interface is such that the expert requires no particular programming or computer skills beyond word-processing in a Windows based environment. In fact, the expert building the knowledge base can work without any consultation with the programmer/knowledge engineer. The only technical assistance that may be required is to import a new dataset or to alter any in-built functions.

This means that rule-based knowledge can be passed between injury researchers and customised by way of rule generation to suit any particular local variations. The tool can also act as an educational resource to transfer domain and rule-based expertise onto another novice user (e.g. to assist them become a domain expert).

Further, Injury Knowledge Manager could be used as an active surveillance tool where injury cases are automatically classified as they are recorded, allowing for identification of any significant changes in the frequency or severity of injury outbreaks for rapid intervention (as is currently achieved for disease surveillance). This goes well beyond the traditional use of injury data for passive surveillance, where injury research and pattern analysis is conducted post-hoc, often a number of years after the injuries occurred.

Of course, all of the above benefits imply the initial availability of a domain expert to test the knowledge base on new data and detect classification errors made by the system before being put into use. As before, for any new classification system (i.e. domain with an empty knowledge base) a large volume of cases must be dealt with by an expert to generate a sufficient rule-base for accurate automated classification of new cases. Nevertheless, this task should not be overly onerous as the previous empirical evaluation has shown that an expert can build a rule-base of 300-400 rules (enabling a coding accuracy > 95% for future cases) in around ten working days (for one person), while integrating the KA process into their normal classification routine.

The high degree of participation, ownership and control afforded by the KA tool, together with the simplicity of the RDR approach, should encourage user satisfaction and utilisation of the system.

One weakness with ripple down rules is the potential for repetitious knowledge acquisition. This is a result of the binary RDR structure wherein exception rules apply only to cases which fired the previous rule. Thus, rules are not globally applicable and the same rules can appear in different parts of the tree structure. However, for the present application it was found that rule repetition was not a significant issue. A review of the rule base revealed that 6.2% of the knowledge was repeated (i.e. rules that appear more than once in the structure). The efficiency of rule generation via the user interface easily offsets this mild level of rule repetition.

Another limitation to efficient and accurate classification is the quality of textual injury data. Generally, at least three to four lines of descriptive text is required to provide sufficient detail for accurate classification (by the human expert and/or by the KA system). This limitation is common to all classification methods; however, the KA system, unlike a human expert, is unable to recognise that a particular case lacks sufficient information to be accurately classified. In other words, the machine doesn't know what it doesn't know and will attempt, in error, to code an ambiguous case.

For example, it was found that thirty-three cases from the NCIS dataset could not be classified due to insufficient or unclear information. However, when the KA system was applied, rules fired for all of the ambiguous cases, resulting in the system assigning incorrect classifications (i.e. error rate of 3.1%). These errant classifications were identified by the human expert during the validation process and over-ruled as 'not classifiable'. This residual error inherent in the KA system is difficult to overcome, except by ensuring that poor quality data is removed from the dataset or 'washed' to ensure its validity, prior to the classification process.

5.4 Validation of the KA Software Tool in Practice

Following experimental testing and refinement, the KA software tool was applied in practice to classify descriptive injury data against the proposed taxonomy. The purpose was twofold:

1. To assess the outcomes of practical application of the KA tool, and compare the resulting taxonomy with existing tabulated data based on International Classification of Diseases (ICD) cause codes;
2. To trial the adaptability of the KA tool to different injury databases in practice.

Two discrete projects were conducted, based on application of the KA tool to the following injury datasets: Australian Work-related Fatalities 2001-2005 (based on the 1,056 NCIS cases described earlier), and; Australian Mining (drill and blast) Incidents (based on 456 incident reports collected by State Government mining departments).

The resulting practical outcomes are outlined herein, along with discussion of the findings and potential avenues for future development of the KA system.

5.4.1 Australian Work-related Fatalities (NCIS cases, n=1,056)

As described earlier, the KA system was used to classify the NCIS dataset of 1,056 Australian work-related fatalities by energy type. Test results in terms of coding efficiency and reliability were discussed in **Section 5.3.3**. The practical output of the classification, in terms of the overall taxonomy developed, is depicted by **Figure 5.13** below:

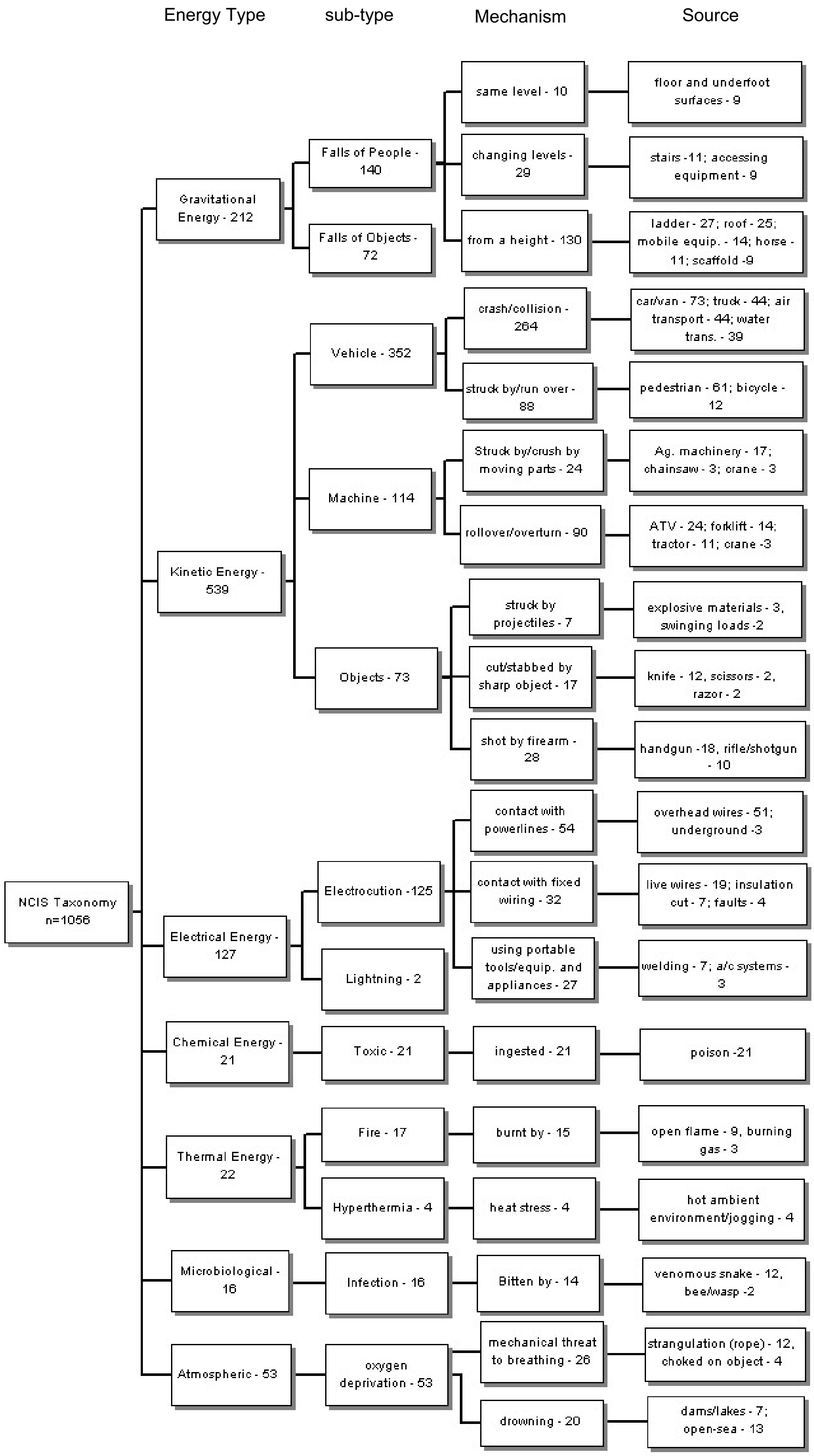


Figure 5.13: Breakdown of the NCIS work-related fatality taxonomy (n=1,056).

By way of comparison, it is instructive to evaluate the overall utility of the KA tool derived taxonomy above against traditional tabulated data (coded according to ICD cause codes). For such purposes, the following **Table 5.3** provides data relating to Australian work-related deaths (excluding Queensland) for the year July 2000 – June 2001, based on ICD-10 External Cause Codes (Australian Bureau of Statistics, 2003).

General circumstance (based on ICD Cause Code)	Number	Per Cent
Pedestrian	9	8.3
Car/Van	10	9.3
Heavy transport vehicle	5	4.6
Animal rider	1	0.9
Industrial vehicle	2	1.9
Agricultural vehicle	6	5.6
All-terrain vehicle	2	1.9
Unspecified vehicle incident	1	0.9
Water transport	5	4.6
Air transport	1	0.9
Falls	11	10.2
Struck by / strike against / caught between	19	17.6
Lifting devices	1	0.9
Hand tools	1	0.9
Agricultural machinery	2	1.9
Other machinery	2	1.9
Other inanimate mechanical forces	3	2.8
Threat to breathing	4	3.7
Contact with electricity	10	9.3
Fire and hot substances	2	1.9
Venomous plants, animals	1	0.9
Accidental poisoning	2	1.9
Assault	8	7.4
Total	**108**	**100.0**

Table 5.3 General circumstances, based on ICD-10 External Cause Code, for ABS work-related deaths; Australia (excluding Queensland), July 2000- June 2001, number and per cent (ABS, 2003).

It should be noted that while Australian Bureau of Statistics (ABS) data is the most accessible and widely used form of coded fatality data in Australia, it is also known to considerably underestimate the true number of work-related deaths (Driscoll et al, 2003). As can be seen above, the ABS data identifies 108 work-related deaths (including working and commuting) for July 2000 – June 2001, which is well less than the 1,056 NCIS identified cases over four years or average 264/year (even when the addition of Queensland data is accounted for).

As such, direct comparisons between the taxonomic classification (based on NCIS narratives) and the ICD-10 tabulated data (sourced from ABS) are not appropriate. Nevertheless, a comparative assessment can be made vis-à-vis the usefulness of the respective outputs for injury prevention and control purposes, as follows.

In relation to the energy-based classification of NCIS cases, it is evident that strong patterns emerge. In particular, the taxonomy reveals that the following five categories account for around 74% of the NCIS work-related fatalities:

- 33.3%: Kinetic Energy - Vehicle (transportation) – Crash/collision or struck by/run over (particularly involving cars, vans and trucks);
- 13.3%: Gravitational Energy (Falls of People) - From a height (particularly from roofs and ladders), changing levels (particularly stairs and accessing equipment), or from the same level (i.e. slips and falls on floor surfaces);
- 12.0%: Electrical Energy (particularly contact with overhead powerlines or live fixed wiring);
- 8.5%: Kinetic Energy – Machine (mobile machinery) – Rollover/overturn (particularly involving ATVs, forklifts and tractors);
- 6.8%: Gravitational Energy – Falls of Objects (particularly involving suspended loads, and objects falling from roofs and scaffolds on construction sites).

The emergence of clear patterns is consistent with outcomes of the three work-related injury case studies discussed in **Section 4** of this report (i.e. fatalities relating to cranes, electricity, and ladders). As before, this allows target areas for intervention to be identified for further analysis. For example, the high number of roll-over events involving ATVs, forklifts and tractors (i.e. in the Machine - Rollover/overturn category), raises questions as to whether there are common environmental, equipment design and/or behavioural issues relevant to the three machine types (e.g. design instability, absence of roll-over protective structures, seat-belts not available or not used).

In regards to the ICD coded data, patterns also emerge, though they are less well-defined. By way of comparison, the top five categories in **Table 5.3** account for around 60% of the ABS work-related fatalities:

- 17.6%: Struck by / strike against / caught between
- 13.9%: Transportation – Car/Van and Heavy vehicle
- 10.2%: Falls
- 9.3%: Contact with Electricity
- 8.3%: Pedestrian

As discussed previously, the lack of a clear conceptual basis limits the practical usefulness of ICD coded data in terms of providing insight into aetiology and identifying effective prevention and control strategies. For example, knowing that 17.6% of ABS cases are coded as '*Struck by / strike against / caught between'* does not provide sufficient insight to direct further research or conceptualise control measures. The use of additional ICD codes (such as 'Type of injury', 'Activity' or 'Occupation') may assist; however, by classifying a single event into multiple unrelated uni-dimensional codes, it no longer becomes possible to maintain critical associations between the components of data. As was outlined earlier, the original identity of the occurrence is lost.

Further, while categories such as *'Contact with electricity'* are inherently sound, others such as '*Other inanimate mechanical forces'* and *'Struck by / strike against / caught between'* cover a wide variety of unrelated circumstances; for example the latter includes events such as: person struck by a falling load from overhead; person struck by a wind-blown object; person caught between moving parts of a crane (e.g. slew-gear), and; person crushed against a wall by a forklift after the park-brake failed. It is far from ideal to code such diverse sequences into one category, particularly one so broadly defined (many fatal events, if not most, will involve a mechanism related to the victim being struck by, striking against, or being caught between).

Such ambiguity in coding categories is compounded by the lack of cohesion between categories. In particular, the ICD cause code categories in **Table 5.3** embody a range of concepts, including: injury mechanism (e.g. 'Falls'); source (e.g. 'Hand tools'); context of person injured (e.g. 'Pedestrian'), intent (e.g. 'Assault'), and; activity (e.g. 'Animal rider'). As before, this leads to conceptual difficulties as injury sequences can easily involve any number of such concepts and categories; for example, a 'Pedestrian' (context) may be 'Struck by' (mechanism) an 'Animal rider' (activity) resulting in a heavy 'Fall' (injury mechanism).

In contrast, the taxonomic classification, based on the three-tier 'Energy Type – Mechanism – Source' structure, provides a consistent means to conceptualise the injury events, and ensures the maintenance aetiological associations between the data. By way of comparison, whereas the ICD combines a number of diverse injury sequences as '*Struck by / strike against / caught between'*, the injury taxonomy separates unrelated cases; for example, struck by a falling load is classified as '*Gravitational Energy – Falls of Objects – Suspended load'*, and crushed by moving crane parts is classified into a separate category as '*Kinetic Energy (Machinery) – Struck/Crushed by moving parts – Crane slew-gear*'.

The advantage is that the fundamental aetiological agent (i.e. the type of energy causing damage) is clearly identified along with the common antecedents. This provides a cohesive and objective underlying basis for the classification, as well as a means to conceptualise control measures (e.g. by applying Haddon's ten energy-management strategies, as outlined earlier). This is particularly useful for specific injury problems (e.g. the previous crane, ladder and electrical fatality studies), where detailed insight can be gained into the major causative sequences.

As a result, the taxonomic output is such that individual cases are classified alongside other 'like' cases. In this fashion, the taxonomy helps to organise a large amount of information into causal pathways, where the number of cases in each taxon suggest how the most common events occurred. To provide a further example, an identifiable category in **Figure 5.13** is 'Microbiological Energy – Bitten by – Venomous snake' (n=12), which clearly defines the fatal event. In contrast, such detail is not provided by tabulated ICD coded data, where such events are reported as simply '*Venomous plants/animals'* (as per **Table 5.3**).

In sum, this work has supported earlier applications of the injury taxonomy, and demonstrates that the taxonomic output can provide a logical basis for understanding injury aetiology. Moreover, it was found that the KA derived injury taxonomy offers conceptual and practical advantages in comparison to the traditional use of tabulated ICD cause code (i.e. E-code) data. As such, the KA tool offers a practical means to identify effective injury control measures and/or serves as a useful foundation for subsequent causal analysis.

5.4.2 Australian Mining (drill and blast) Incidents (n=456)

The second practical application of the KA tool involved classification of 456 Australian mining incidents relating to drill and blast activities. The purpose was to test the adaptability of the KA tool to a new dataset in practice, and assess the quality of outcomes.

In terms of providing classification outputs, this component of the work was commissioned by Rio Tinto subsidiary Hammersley Iron, in order to assist management focus their preventive strategies for this high risk area. Prior to this study there was little information available regarding the patterns and determinants of injury relating to drill and blast activities (which involve exploration, drilling, charge laying and detonation). The only data available was internal company incident records that pertained to so-called 'near-miss' incidents, rather than actual injury events.

The underlying hypothesis explored was whether the pattern of drill and blast injuries matches the pattern of reported incidents. As such, outcomes may have relevance outside this specific domain.

In order to obtain quality descriptive injury and incident data, an approach was made to key State government agencies within Australia to supply all available case records relating to drill and blast incidents, with the following data being supplied:

- 214 lost-time injury reports from 1983-1998 (involving lost time of one shift or more), supplied by the *Queensland Department of Minerals and Energy* (now Dept. Natural Resources and Mines);
- 128 lost-time injury reports from 1994-1998, supplied by the *Western Australian Department of Minerals and Energy* (now Dept. Industry and Resources);
- 114 reported dangerous occurrences from 1989-1998 (i.e. reported near-miss incidents), supplied by the *New South Wales Department of Mineral Resources*.

As above, the QLD and WA data pertained to 'lost-time injury reports' (defined as involving one shift or more lost time), whereas the NSW data pertained only to 'reported dangerous occurrences' (i.e. reported incidents based on perception of high risk).

The KA tool was applied to determine and compare the patterns in injurious energy type associated with two distinct study populations, namely: actual injury cases (combined QLD and WA data, n=342), and; reported dangerous occurrences (NSW data, n=114). It was assumed that industry conditions and exposures are comparable between jurisdictions.

It was found that the drill and blast injury and incident data could be readily processed by the KA software tool, with the human expert assuming a 'review' role to assign new rules for misclassified cases. The two populations of 342 injury cases and 114 reported 'dangerous occurrences' were processed in 8.5 hours (average 2.12 minutes per case) with an overall error rate of 3.4%.

These results are broadly consistent with the previous application of the KA tool to NCIS cases (n=1,056), where the average processing time was 2.5 minutes per case and overall error rate was 3.1% (see **Section 5.3.3**). The similarity of these results supports the hypothesis that the KA tool is adaptable in practice to these new text-based injury datasets. The increase in the error rate was found to be due to a larger number of poor quality text descriptions, while the reduction in processing time was due to the reduced detail provided by the drill and blast injury and incident narratives (relative to the NCIS data).

In short, the key metrics of processing time and error rates do not appear to be significantly affected by the application of the new study populations to the KA system. As before, both metrics compare favourably with the traditional manual classification process (i.e. average 4.75 minutes/case and error rate of 5% to 7.5%, as per **Section 4.3.1**).

Practical safety outcomes of the study are outlined in **Appendix VII**, based on a published paper (Shepherd et al, 2004), which compares the pattern of injury cases (n=342) with the pattern of 'dangerous occurrence' reports (n=114).

For reference, **Figure 5.14** below shows the distinct patterns which emerged from the coding of the drill and blast injury cases (QLD and WA data, n=342). As can be observed, a majority of drill and blast injuries (i.e. 73%) related to just three energy types, namely: Gravitational Energy - Falls of People; Biomechanical (Human) Energy (e.g. lifting and carrying), and; Kinetic Energy - Machines (e.g. caught in/struck by). This enabled specific recommendations regarding preventative measures to be made, focussed on these key areas, as outlined in **Appendix VII**.

By way of comparison, **Figure 5.15** which follows, shows the distinct patterns which emerged from the coding of the drill and blast reports of 'dangerous occurrences' (NSW data, n=114). As can be seen, most of the reported 'dangerous occurrences' (i.e. 84%) pertained to either Thermal Energy (Fires) or Vehicle Energy (Collisions).

As such, it is clear that the pattern of drill and blast injury occurrences and the pattern of reported incidents diverge significantly.

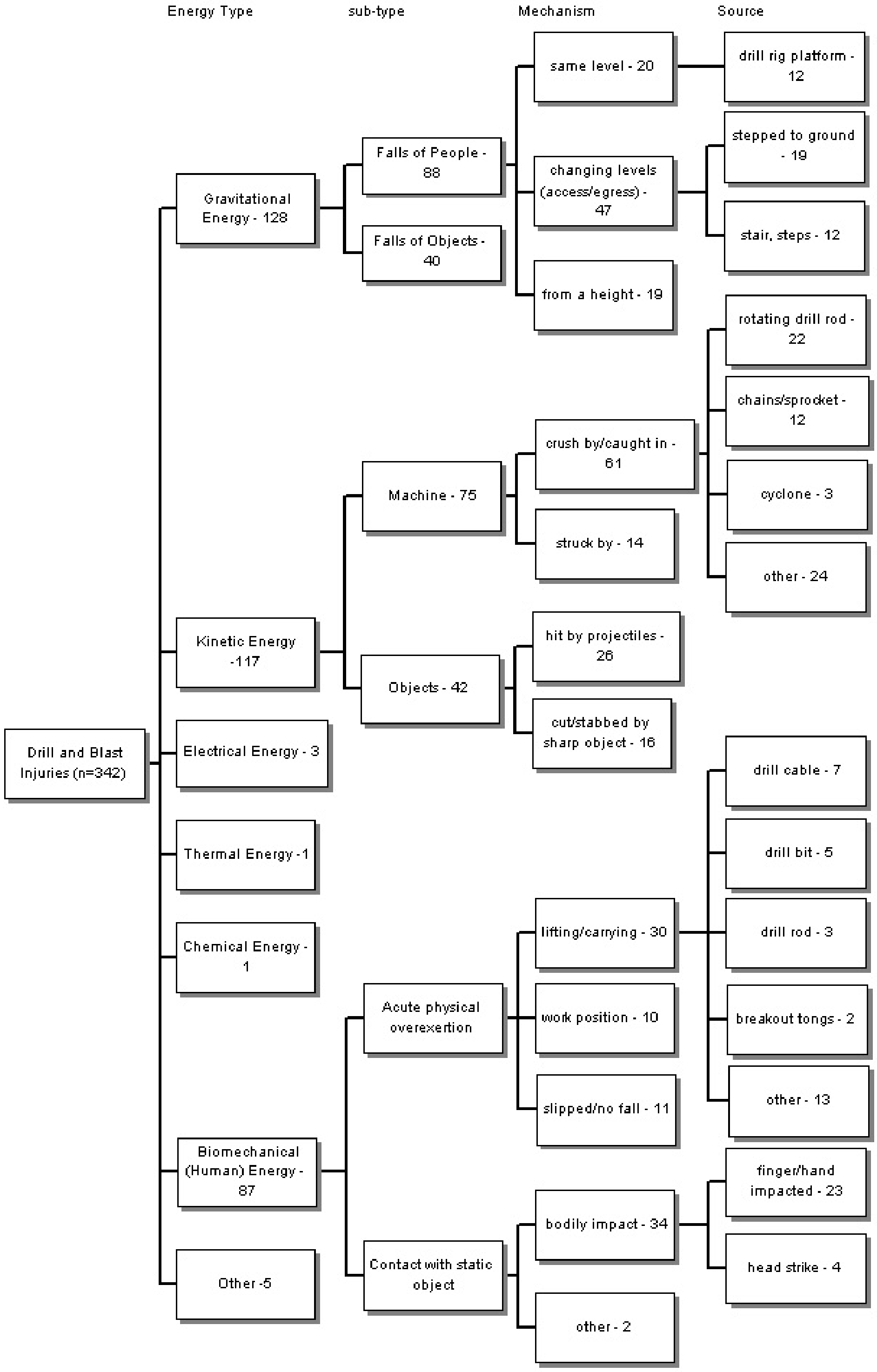


Figure 5.14 Partial taxonomic breakdown of drill and blast *injury* cases (n=342).

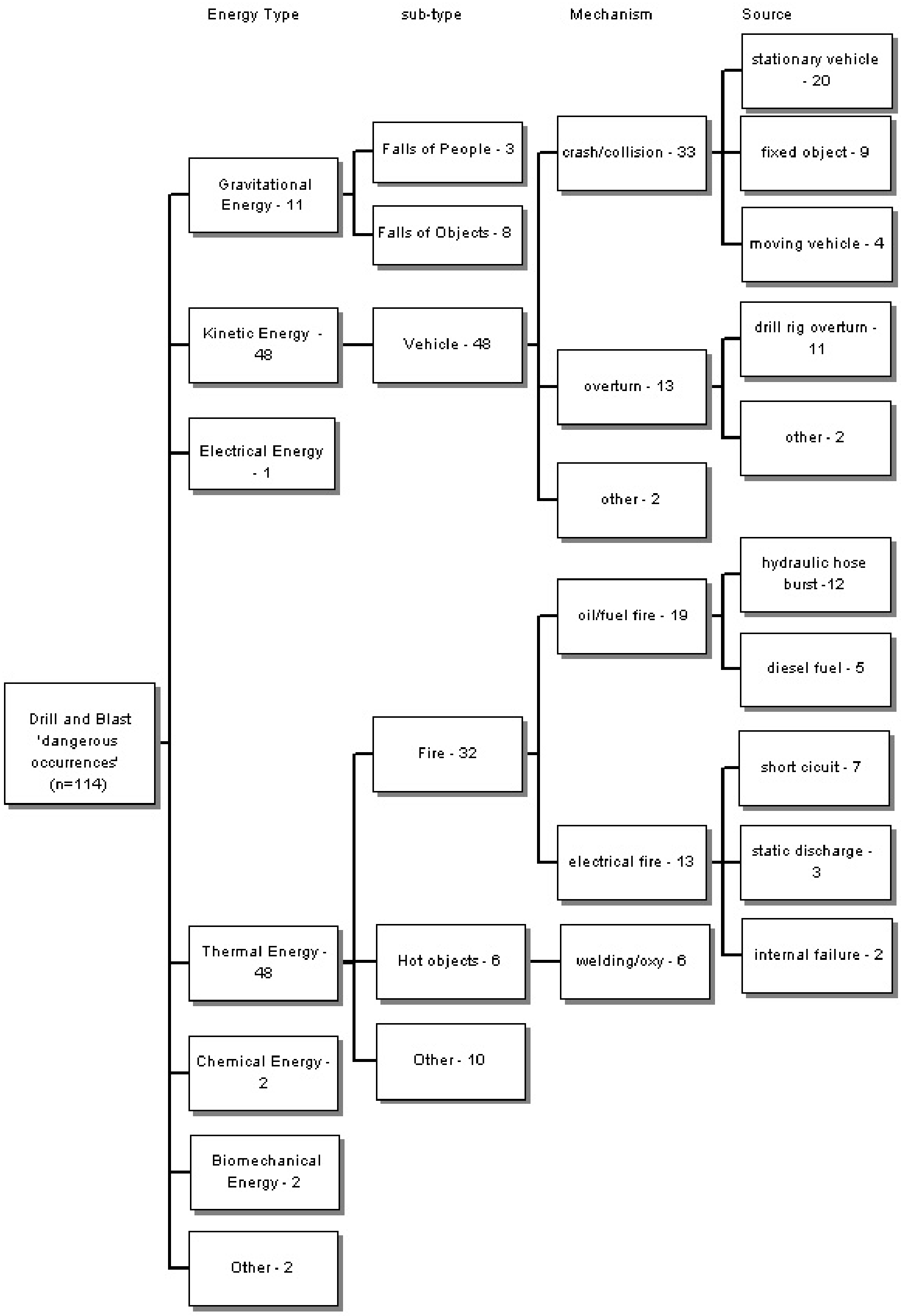


Figure 5.15 Partial taxonomic breakdown of reported *'dangerous occurrences'* (n=114).

The following **Figure 5.16** graphically illustrates the gross differences in energy types represented by injury cases versus reported dangerous occurrences.

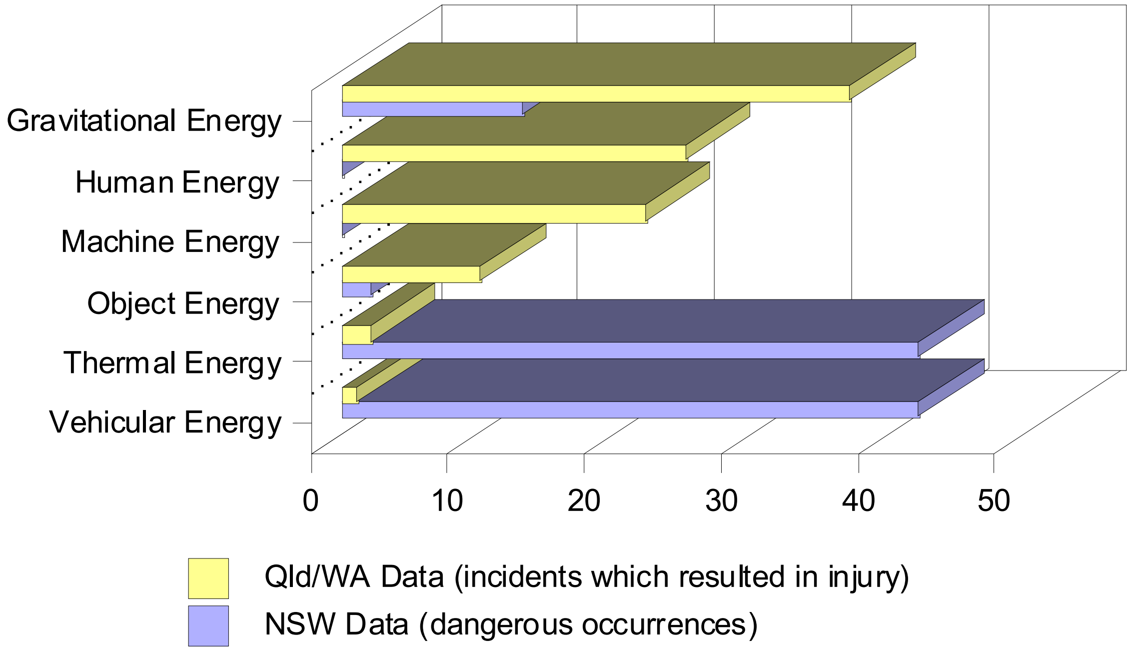


Figure 5.16 Percentage Involvement of Damaging Energies (Australian drill and blast cases, n=456).

Based on the gross differences in patterns, it was concluded that perceptions of risk in the drill and blast industry (as reflected by reports of 'dangerous occurrences') do not match the reality of how people are injured. For instance, most of the reported dangerous occurrences pertained to either minor collisions (e.g. reversing into a stationary drill rig), or cases of localised ignition of oil or fuel on part of the drill-rig. Neither set of events are represented in the injury data (where falls and manual handling dominate).

It is postulated that the differences relate to misperception of risk amongst those reporting 'dangerous occurrences'. In particular, it appears that risk perception may be skewed towards energy sources such as *Thermal Energy – Fire* and *Vehicle Energy – Collision*, rather than the more common injurious mechanisms such as *Gravitational Energy - Falls of people* and *Biomechanical (Human) Energy - manual handling*. There are a range of possible explanations. One is that the former energy sources tend to result in equipment damage and thus may be more likely to be reported (compared to near-falls and heavy manual handling which, at the time, may result in no perceived equipment or personal damage). A second possible reason is that they may be a lack of risk perception for familiar ‘mundane’ situations like falls and manual handling, relative to potentially high-impact events such as fires and collisions.

This is an important finding as it raises questions about the practice of using the pattern of non-injurious ‘incident’ reports to predict future high risk exposures. This practice is commonplace amongst many government agencies and large companies, where both injuries and ‘near-miss’ incidents are recorded. The implicit assumption is that the pattern of reported incidents matches, and will predict, the pattern of injury. The present application of the KA tool reveals that this assumption may be in error, at least as it relates to the Australian drill and blast industry.

Nevertheless, this finding should not be seen as discouraging the reporting of ‘near-miss’ incidents for prevention purposes (as certain types of individual incidents can predictably result in severe outcomes, e.g. rollover events); the point here is that the overall pattern of reported incidents may not be a valid predictor of the overall pattern of actual injuries, thus there is little relevance in attempting to targeting areas for intervention based simply on the number of near-miss incident reports.

In summary, this work has demonstrated that the KA tool is adaptable to new text-based datasets, and can assist in the efficient and reliable analysis of both injury and non-injury data to challenge existing assumptions, and help identify focus areas for prevention and control. A key advantage of the computer-based approach is that large numbers of cases can be efficiently processed to test hypotheses and assumptions.

5.5 Future Work

It has been shown that the current version of the KA tool (Injury Knowledge Manager) can be applied in practice to classify injury cases against the first level of the proposed injury taxonomy; that is, based on the ‘energy’ type which caused injury (outlined in **Section 4**).

Further, it was found that the tool can be applied with high coding accuracy (at least in relation to NOHSC and NCIS data), and has the flexibility to adapt to new datasets (such as Australian Mining Department narratives). If additional rule-generation is required to customise the rule-base to a new dataset, ripple-down rules can simply be added to the knowledge base by the expert (i.e. injury researcher); no further knowledge engineering is required.

Further development work could assist in enhancing the present KA system accuracy, such that it can be efficiently applied to additional levels of the injury taxonomy and/or alternative or more complex domains. Such future development should consider the addition of a formal logic-based system to better capture the contextual semantics and apply natural language processing (NLP) techniques to capture more features from the narrative texts, in addition to key words/phrases and their order. For example, algorithms could be applied to account for semantic variations such as the words scalds and blister.

Another desirable refinement would be to add a 'stemming' function. Stemming is a process which accommodates variations in key word morphology and transforms various other keywords with the same meaning into the keyword. For example, the words burning, burns, burnt could be stemmed to the word burn. Such refinements would likely enhance the efficiency of knowledge acquisition, as fewer RDRs would need to be acquired.

Further, given that the rate of knowledge transfer can increase if multiple experts are involved, it would be desirable to implement a system to allow multiple users to dynamically update the knowledge base. In addition, a workflow or approval process would be worthwhile to ensure a limited subset of privileged users can be nominated to approve updates to the rule base. While this is not essential to maintain integrity of the rule-base, such an approval process may be desirable for user acceptance and to help domain experts train other experts.

Finally, inductive modelling techniques could be combined with the existing RDR elicitation by developing an algorithm for the induction of ripple-down rules. This could allow for combined expertise transfer and machine learning; for example, automatic induction could be used to suggest rules to the expert, thus speeding up the classification process.

5.6 Summary

In summary, this work has demonstrated the viability of applying the developed KA tool (Injury Knowledge Manager) to overcome current methodological problems associated with manually classifying large numbers of injury cases. The computer offers the advantages of efficient and accurate classification of large datasets, as well as the flexibility to use different data sources and apply alternative classification systems.

6.0 SUMMARY AND CONCLUSIONS

Over the past half a century, there has been an increasing recognition of injury as a leading public health problem and priority. Indeed, unintentional injury now surpasses disease as the dominant global cause of death and disability before age 60, claiming over 5.8 millions lives each year.

The field of research known as ‘injury prevention and control’ has emerged with the aim of applying scientific methods to the injury problem, in emulation of the success achieved within the public health arena in reducing the burden of disease. This approach begins with observation, description and classification of injury data. Currently, injury data is sourced in text (narrative) or tabulated (coded) format from a range of databases world-wide. This data is traditionally coded using descriptors such as ‘age of person’, ‘activity’, ‘part of body injured’, and ‘time of day’. Such classifications have proved invaluable in terms of elucidating the distribution of injury and identifying priority areas (i.e. descriptive epidemiology). However, describing ‘who’, ‘what’, ‘where’ and ‘when’ does not provide meaningful insight into ‘how’ and ‘why’ the injury event occurred.

The underlying hypothesis of this dissertation is that future progress lies in understanding and classifying injury occurrences aetiologically, thereby enabling the identification of effective prevention and control measures (i.e. analytical epidemiology).

The advancement of a practical means of classifying injury aetiology has so far been inhibited by two related limitations: 1. Structural limitation: The absence of a cohesive and validated aetiological taxonomy for injury, and; 2. Methodological limitation: The need to manually classify large numbers of injury cases to determine aetiological patterns (a time-consuming and error-prone task, which must be repeated if a new data-source or different classification system is selected).

The work presented herein was directed at overcoming these impediments to injury research.

Section 3 summarised evolution of the scientific approach to understanding and classifying injury. A critical landmark was the conceptualisation of injury as the outcome of an energy exchange which goes beyond tolerable limits of the susceptible structure (i.e. an excess of thermal energy may result in burns, while a lack of thermal energy may result in frost bite). This led to energy being recognised as the fundamental aetiological 'agent' of injury, in close analogy to disease phenomena. It was recognised that for both injury and disease, the interaction of agent, host and environment (physical and socio-cultural) are necessary. These insights yield immense conceptual and practical value, particularly in terms of the opportunity to classify injury according to its fundamental causative agent (energy) as well as the ability to identify measures aimed at preventing or controlling the energy exchange (and thus injury). The hypothesis is that pursuing this epidemiologic avenue will complement existing approaches and classification systems.

Section 4 outlined the advancement of an aetiological taxonomy for injury, based on the energy-damage concept. A three-tier hierarchical structure was designed in accordance with epidemiologic principles, to capture: the energy type which was released (e.g. chemical energy); the key mechanism by which energy was released/transmitted (e.g. absorbed through skin), and; the source which conveyed the energy (e.g. insecticide). Clear conventions were defined such that each injury case has only one correct and unambiguous location within the 'energy type – mechanism – source' structure.

Validation testing was conducted to quantify coding accuracy and reliability by applying the taxonomy to a test dataset of 400 injury cases (derived from Coroners' reports). It was found that the taxonomy could be independently applied by coders with a high degree of accuracy (coder/expert agreement was 92.5-95.0%), and with high reliability (as measured by kappa) in terms of both inter-coder reliability (93.0-96.3%) and intra-coder reliability (93.5-96.3%). Overall coding errors were in the range 5.0% to 7.5%, which compared favourably with other published studies. Further, errors were found to be overwhelmingly random in nature (i.e. due to human/coder error), as opposed to being systemic (i.e. inherent to the taxonomy). It was also found that that the manual classification process was time intensive, and required four working days to code the 400 cases (average processing time of 4.75 minutes per case).

Following this experimental testing, the taxonomy was applied to three practical case studies in order to qualitatively assess the classification outcomes and to trial its adaptability to different datasets in practice. The case studies related to crane fatalities (n=525), electrical fatalities (n=243) and ladder fatalities (n=277). Detailed findings from these three case studies are outlined in corresponding journal papers (annexed to this thesis).

In summary, it was found that the proposed injury taxonomy can be applied as a reliable way to classify injury cases and provide insight into aetiology. However, it was also revealed that the manual classification process suffers from substantial limitations in terms of inefficient coding time and human (coder) error.

Section 5 outlined the development of a knowledge acquisition (KA) software application aimed at automating the classification process to overcome existing methodological limits.

A KA algorithm was developed based on an expert-systems technique called ripple down rules (RDR), which enables the incremental transfer and refinement of rule-based knowledge. Unlike most knowledge acquisition methods, RDR does not rely on the expert to specify what they know. Instead, tacit knowledge becomes codified by the RDR system while the domain expert demonstrates their expertise. As such, the software tool was designed with a user interface to allow an injury researcher to input their chosen classification system (i.e. to define the 'domain'), with the computer then acquiring rules as the researcher classifies an initial sample of injury cases against the domain.

The software tool was subjected to pilot trials, followed by experimental testing and application using a sample of 1,056 fatality narratives compiled from the National Coroners' Information System (NCIS). Injury cases were processed by the expert in ten successive batches, using the KA system, while measuring the case processing time, number of rules generated, and the coding error rate.

As expected, the coding error rate was found to drop rapidly as more cases were processed (i.e. as more rules were acquired by the system). A distinct KA 'learning curve' was observable, which began to plateau after around 259 rules were acquired (at which point the coding error rate fell below 10% for all new cases). Ultimately, the coding error rate dropped to 3.1% once all 1,056 cases were processed, which, along with a 2.50 minute processing time, compared favourably with results from manual classification (i.e. 5.0%-7.5% error rate and 4.75 minutes/case, respectively).

The KA system was also applied to a case study of 456 Mining (drill and blast) incidents to assess its use in practice and trial its adaptability to a new dataset. It was found that the mining industry data could be readily processed by the KA system, with the human expert largely assuming a 'review' role to assign new rules to any misclassified cases. The overall error rate of 3.4% and the average processing time of 2.12 minutes per case, were once again favourable relative to manual classification results.

Overall, these results support the hypothesis that knowledge acquisition technology can offer injury researchers a viable alternative to the traditional manual classification process. In particular, the KA software tool was found to provide a relatively efficient and reliable means to classify large numbers of injury cases, along with the flexibility to apply different data sources and/or alternate classification systems.

This offers a significant practical advantage to researchers in the academic, corporate and government domain who have a need to deduce useful patterns from injury data and test hypotheses regarding causation and prevention. As such, a pluralistic approach is supported whereby the KA generated injury taxonomy can be available alongside existing classification systems (such as ICD E-codes and HFACS/human error approaches).

The main limitation of the KA approach is that if data quality is poor or ambiguous, higher coding error rates may occur and a human coder may need to adopt a 'review' role to correct any mis-classified cases. Future work is proposed which will assist in developing the tool further to overcome these limitations.

In conclusion, this work represents a significant step towards providing an automated aetiological classification tool for injury epidemiologists. It is aimed at contributing to the long-term vision of injury research, as described by the National Health and Medical Research Council in their discussion paper *Injury: from Problem to Solution* (1999):

> *"In the long term, injury research should become a cohesive and vibrant discipline, making a significant contribution to the health of Australians and to the global knowledge of injury, its prevention, treatment and rehabilitation. New research and statistical models will emerge and methods dealing with the development of effective systems of intervention for complex problems and physical injury patterns will emerge.*
>
> *The need for sound development has been recognised at the most authoritative levels. The major vision is to stem the epidemic of injury in both the developed and developing world."*

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APPENDIX I:

Taxonomic classification of Injury Occurrences

based on the Energy Involved

CLASSIFICATION OF INJURY OCCURRENCES BASED ON THE ENERGY INVOLVED.

In terms of aetiology, physical injuries are characterised by an exchange of energy which goes beyond tolerable limits of the susceptible structure (i.e. human tissue).

Injury can occur as a result of an excess of energy (e.g. excess of thermal energy – burns; excess of electrical energy – shock), or as a result of an insufficiency of energy (e.g. lack of thermal energy – hypothermia; lack of atmospheric pressure – hypoxia/altitude sickness).

More specifically, injury aetiology can be seen in terms of transfer of a distinct energy *type* by way of a specific *mechanism* from an energy *sourc*e. For example, burns result from a transfer of thermal energy (energy type) by way of contact with hot liquid (mechanism), originating from boiling tap water (source). This conceptual approach is analogous to the classic epidemiological model for infectious disease, whereby disease occurs as a result of transmission of an agent (e.g. influenza virus) by way of a mechanism of transmission (e.g. sneezing/airborne droplet spread), originating from the source/carrier (e.g. infected person).

The following matrix outlines the proposed three-tiered taxonomic structure for classifying injury occurrences:

Energy Type	Mechanism	Source
Definition: The type of energy of which control was lost, resulting in the energy being released or transferred, precipitating the injury sequence. **Coding convention:** Where multiple energy types and/or multiple injuries are involved, classify according to the underlying energy type which leads to the principal (most dominant) injury. **Example:** If a person falls off a ladder from a height causing severe injury, the energy type is classified as ‘gravitational energy’, as this is the energy released by the fall from the ladder, before being transformed into kinetic energy during the fall.	**Definition:** The means by which (i.e. how) the energy was released, transmitted or transferred. **Coding convention:** Code according to the underlying mechanism (which initiated the dominant injury sequence). If it is not possible to distinguish between mechanisms, code as ‘unspecified mechanism’. **Example:** If person trips over an appliance cord and then hits their head on a counter, the tripping over the cord is the underlying mechanism (the action that starts the injury event).	**Definition:** The energy source is the object (e.g., a car, heater, knife) or substance (e.g., hot water, flames) which conveys the mechanism of injury. **Coding convention:** As before, the convention is to code the underlying source (present at the initiation of the injury sequence) involved in the most dominant injury. Code as ‘unspecified source’ where the source is unidentifiable. **Example:** If a person is electrocuted while holding a crane-suspended load due to crane contact with overhead power-lines, the underlying source of electricity is the power-lines (not the crane or load).

Energy Type		Mechanism	Source
Type	**sub-type**		
Gravitational Energy	▪ **Falls of People**	**Same Level: Falling, stumbling, jumping, pushed** Includes: Falling/stumbling by slipping on same level Falling/stumbling by tripping on same level spraining ankle when walking and not falling falling from bumping against an object falling due to surface moving underfoot or stepping into a void striking or hitting an object when jumping or diving falling from a pedal cycle Excludes: crushed or pushed by a crowd or stampede **Changing Level: Falling, stumbling, jumping, pushed on stairs/steps or while accessing equipment** Includes: ascending or descending stairway stepping to/from ground stepping to/from top platform Excludes: free fall from stairway (over edge) if known to be 1 metre or more **From a Height: Falling, stumbling, jumping, pushed (from height of 1 metre or more)** Includes: striking or hitting an object when jumping or diving falling while being carried by a normal-sized adult falling from a horse falling from ladder, building, roof or elevated structure (e.g. person overbalanced, slipped, mis-stepped, struck by or thrown/knocked from, cardiovascular accident, electric shock precipitated fall) falling with ladder, building, roof or elevated structure (e.g. outward sliding of support, destabilization, structural collapse) **Falling, stumbling, jumping, pushed from an unspecified height** **Other unspecified falling, stumbling, jumping, pushed** including body collapse due to musculoskeletal failure, medical condition, effect of drugs etc.	**Floor surface** platform, balcony or deck walkway or pathway other floor or related fitting/feature **Other Underfoot surfaces (wet/dry)** bathtub, shower uneven surface sliding mat, rug **Personal walking-aid device** wheelchair or commode chair cane, walker, walking stick, walking frame prosthesis or other personal aid **Recreational Equipment** wheeled, un-powered riding toy or go-cart skate, roller-blade, skateboard scooter, moped snow ski, snow board sled, toboggan, sleigh, snow disc/tube **Stairs, steps** steps anywhere (eg. leading to beach) access to mobile equipment stair or step covered with ice **Moving ramp, escalator (incl. travelator)** **Baby products** baby pram, buggy, pusher, stroller, walker baby exerciser, jumper, or portable swing high chair, booster seat cot, crib, baby bed, carrier baby baths or bathinettes changing table/change platform **Sporting Equipment** trampoline gymnastic equipment diving board, platform exercise, fitness equipment **Ground surface** cliff slope, ramp trench, ditch, pit, channel sewer and drainage grate, open drain **Playground equipment** tree house, play house flying fox slide, sliding board swing, swing set, monkey bars seesaw, teeter totter powered amusement rides (e.g. roller coaster) **Land mammal** Horse, pony, donkey, mule, ass Elephant Other land mammal **Climbing and Elevated Surfaces** ladder, movable step scaffolding, formwork lift, elevator elevating equipment (EWP, crane) roof other building component or fitting

Energy Type		Mechanism	Source
Gravitational Energy (continued)	▪ **Falls of Objects**	**Struck by thrown or falling object from same level** Includes: objects on the same level (e.g. table) destabilising, overbalancing, toppling and falling onto a person objects collapsing on the same level Excludes: objects rolling/sliding (not free falling) **Struck by thrown or falling object from overhead** Includes: free falling rock, stone, or tree cave-in suspended loads parts of overhead structures (e.g. crane booms and other crane parts) collapse of a building or part thereof being struck by a thrown ball Excludes: being shot by a firearm/weapon continuous movement against skin	**Building/Construction components** roofing structure and materials hoisted and suspended loads containers, bins, tanks other building components/fragments **Hoisted/Suspended loads** loads hoisted by cranes and other lifting equipment loads suspended by chains, ropes, wire loads or objects being handled manually (and dropped) working under suspended vehicle **Natural materials** snow, ice rock, stone tree branch, wood – timber, board, gravel, soil, sand bales of hay, straw grain in bulk including silo other natural materials **Other elevated objects**
Kinetic Energy (moving equipment and objects)	▪ **Vehicle (transportation)**	**Crash/Collision event** Includes: crashes and other injurious events occurring in the course of transportation Injury resulting from events involving a device being used primarily for conveying persons or goods from one place to another multi-vehicle and single-vehicle collisions situations where the vehicle occupant is ejected during a rollover/overturn event Excludes: collision events where the injured person is a pedestrian, bystander, cyclist or motorcyclist (see below) collision events where the vehicle occupant was injured due to being struck by an object **Occupant struck by** Includes: cases where the vehicle occupant was struck by a fixed object from outside the vehicle (e.g. barrier penetrates the windshield) **Person struck by/run over** Includes: cases where a person (pedestrian, bystander, observer etc) was injured due to being struck or run over by a moving vehicle **Pedal cyclist struck by/run over** Includes: cases where a pedal cyclist was injured due to being struck or run over by a moving vehicle **Motorcyclist/ motorcycle rider struck by/run over**	**Land vehicle or means of land transport** pedal cycle motorcycle, moped, scooter, vespa three-wheeled vehicle or scooter passenger car (Including station wagon, minivan/bus carrying up to 10 people) light truck, Sports Utility Vehicle (SUV), utility van, 4x4 vehicle, jeep, minibus (11 to 19 seats) special all-terrain vehicle/off-road vehicle cable car, ski chair lift, ski lift with gondola motorised wheelchair bus, coach (more than 20 seats) heavy truck trailer or horse-float **Rail or track mounted vehicle** streetcar, tram, electric car, car trolley train monorail, or other similar rail vehicle **Watercraft or means of water transport** merchant ship, cargo ship, oil tanker passenger ship, ferry, ocean liner fishing boat, trawler motorized yacht, motorboat, powered boat, personal powered watercraft hovercraft, airboat submarine or related craft sailboat, unpowered yacht canoe, kayak, row boat, wave board, surfboard, paddle ski windsurfer part/component of watercraft (e.g. propeller) **Aircraft or means of air transport** helicopter airship, blimp, balloon ultralight powered aircraft fixed-wing powered aircraft spacecraft parachute hang-glider, glider part/component of aircraft (e.g. propeller)

Energy Type		Mechanism	Source
Kinetic Energy (continued)	▪ **Machine (fixed/ mobile machinery)**	**Run over by mobile machinery** run over by mobile cranes, tractors, harvesters and other industrial machines **Roll-over/Overturn of mobile machinery** situations where the occupant is ejected during a rollover/overturn event **Struck by/crushed by or caught between moving parts of machinery** contact with a chain hoist, drive belt, pulley, transmission belt, winch, etc. contact with a powered lawnmower, chainsaw, hedge-trimmer contact with a blender, powered knife, sewing machine, spin drier, washing machine contact with an animal-powered farm machine, harvester, reaper, thresher contact with recreational machinery, machinery Excludes: exposure to electric current **Cut by moving parts of machinery** Excludes: abrasion caused by contact with machinery **Exposure to vibration/jarring** Includes: rough ride from mobile equipment vibrating jackhammer	**Mobile machinery** ride-on lawnmower tractor harvesting machine auger, post-hole digger equipment towed or powered by tractors (slasher, cultivator, fertilizer spreader) forklift or lift truck mobile crane battery-powered airport passenger vehicle tram, truck, or tub in mine or quarry scraper, roller, grader **Machinery or fixed plant** cutting/slicing machinery or plant crushing/pressing machinery/plant lifting and hoist machinery crane machinery or fixed plant elevated work platform conveyors, etc. shearing plant dairy/milking plant press, cutter garbage compactor, threshing machine **Powered hand tool/equipment** drill chainsaw other power saw (e.g. jigsaw) welder, welding equipment nail gun, stud driver grinder, buffer, polisher, sander powered garden tool (e.g. shredder, hedge trimmer) powered push lawnmower industrial vacuum cleaner jackhammer
	▪ **Object (projectile)**	**Struck by moving objects or projectiles** Includes: hit or struck by sports equipment (eg., hockey stick) or a blunt weapon (eg., cudgel) person moving in front of a moving object (eg., someone being hit by a ball as they moved to try and catch it) objects rolling/sliding (not free falling) foreign body on cornea or under eyelid wind blown object Excludes: being shot with a firearm or arrow **Pinching, crushing between objects** crushed beneath an object caught or jammed between moving and stationary objects (eg., hand caught in a car door) Excludes: injury caused by being struck by a thrown or falling object transport injuries **Cut by, stabbed or body part severed by sharp object** cases where the skin was cut and where there was deep penetration of underlying tissue	**Industrial objects and materials** Moving or swinging suspended loads Explosive powertool (nail, stud) Dust/foreign body in eye Construction materials/fragments Hoisted and Suspended loads Containers, Bins, Tanks **Sporting/Recreational equipment** Ball (including inflatable beach ball, soft ball, puck/hard ball, golf ball, cricket ball, baseball. Spear, javelin Bow, arrow (bow and arrow), crossbow Other specified sports projectile Bat, hockey stick, racquet Other hand-held sports equipment **Flying or projectile toys** slingshot, bow and arrow designed as toy toy cap, cap toy, cap gun, other toy gun knife designed as toy kite or kite string Frisbee boomerang **Cutting implements** Cutting tool (chisel, handsaw etc Knife Scissors, pin, needle Razor, razor blade cooking or food processing utensil (e.g. bottle opener)

Energy Type		Mechanism	Source
		stabbed with a knife, sword or other sharp-edged instrument severing a body part with an axe, panga, machete, or cutlass being cut (eg., cutting one's finger with a knife, broken glass or the edge of paper) **Shot by firearm** Includes: struck by a bullet or other projectile from a gun using a powder or charge Excludes: struck by a projectile from a BB or pellet gun non-shooting injury by a firearm (eg., struck by gun) **Shot by other weapon** Includes: arrow from bow and bolt/arrow from crossbow slug from a spring-actuated weapon	Excludes: hypodermic needle **Unpowered hand tool/equipment** push lawnmower (unpowered) hammer, mallet chopping tool cutting tool (chisel, handsaw) digging or tilling tool (spade) lifting tool nail, screw, tack fishhook rat/mouse trap **Stationery items** pen, pencil stapler, hole puncher, letter opener **Firearm or related item** Hand gun Rifle, shotgun Airgun Other specified firearm or related item
Electrical	▪ **Shock/burns** ▪ **Lightning**	**Exposure to electric current** Includes: burning from electric current, electric shock, electrocution direct human contact with powerlines (e.g. working from power pole, tower, ladder or EWP) indirect contact with powerlines (e.g. via mobile equipment such as crane, load, agricultural equipment, truck, drill rig, conductive ladder or scaffold) contact with exposed live conductors and live wires faulty equipment faulty or damaged electrical cords insulation penetrated on wires repairing/servicing equipment using portable tools/equipment electric shock from static discharge arcing explosion Excludes: lightning **Exposure to lightning strike** Includes: direct lightning strike on person indirect shock via ground potential (due to proximal strike)	**Overhead powerlines** elevated transmission and distribution lines induced power (transmission lines) Excludes: powerlines in or around buildings **Fixed Wiring** Electrical wires and circuits in and around buildings (e.g. ceiling space) Electrical fixtures including outlets, sockets, general purpose outlet, switches **Tools/equipment and appliances** refrigeration equipment oven and stoves (e.g. microwave) air conditioning systems dishwashing machine audio-visual equipment (TV, video) drill chainsaw other power saw (e.g. jigsaw) welder, welding equipment nail gun, stud driver grinder, buffer, polisher, sander powered garden tool (e.g. shredder, hedge trimmer) powered push lawnmower industrial vacuum cleaner other portable power tools **Flexible electrical cord and fittings** cords of household appliances extension cords electrical pins and sockets **Switchboards/Distribution boards** temporary and fixed distribution boards **Underground Power** any voltage underground powerlines **Natural source** electrical storm

Energy Type		Mechanism	Source
Thermal	▪ **Fire**	**Burnt by contact with fire or flames** Includes: forest fire, campfire, fire in a fireplace or stove, fire in a burning building ignition of highly flammable material (eg., gasoline, kerosene, petrol) ignition or melting of clothing (eg., nightwear) fire caused by lightning fire caused by/following explosion inhalation of smoke from fire	**Fire, flame** Burning oil Lighter, match Candle, candlestick Cigarette, cigar, pipe Open-fire stove, oven, BBQ Other burning liquid Burning gas Controlled fire, flame (Includes: fire in fireplace, campfire, open fire) Uncontrolled fire, flame (Includes: burning building, burning fittings, furniture, forest fire etc). Other specified fire or flame Excludes: molten metal molten glass smoke from burning oil **Unspecified as to whether fire, flame, or smoke caused the injury** Includes: cases where it is obvious that fire or flame resulted in fatal injury (eg. burns), however, the underlying cause is not clear (e.g. inhalation).
	▪ **Burns**	**Burnt by contact with hot liquid, steam, or other hot gas** Includes: hot water in a bath, bucket, or tub hot water running out of a hose or tap water/liquids heated on a stove inhalation of hot air and gases contact with molten metal Excludes: smoke inhalation burning liquid **Burnt by contact with hot object or solid substance** Includes: contact with a hot household appliance (eg., cooker, kettle, stove, iron, etc.) contact with a hot heating appliance (eg., radiator, heater, etc.) contact with a hot engine, tool, or machinery contact with an object that is not normally hot, but is made hot (eg., by a house fire, by prolonged sun exposure) Excludes: burning object or solid substance (i.e., an object on fire)	**Hot liquid** Hot tap water (Includes hot water in bath, bucket, tub, showerhead) Boiling water (other than tap water) Hot drink (includes coffee, tea) Hot cooking oil or fat Excludes: burning oil **Hot gas** Hot air or gas Steam, hot vapour Other specified hot air or gas Unspecified hot air or gas **Hot objects/solid substances** electric kettle Stove, oven, cooktop, grill Electric frying pan, deep fryer Electric bread making machine Electric toaster, toaster oven Microwave oven Other electric cooking or food processing appliance Iron Foodstuffs Electric or gas radiator, heater Hot engine parts heating/cooking machinery/plant refrigeration machinery/ plant Other hot object/substance
	▪ **Hyperthermia (heat stress)**	**Excessive Heating: whole body:** Includes: Natural mechanism: heat stroke, sunstroke, marathon running Artificial mechanism: being confined in room, (over)heated by other artificial means	**Hot environment** exposure to body overheating due to hot weather conditions and exertion (i.e. exposure to high ambient temperature environment)
	▪ **Hypothermia (effect of cold)**	**Excessive Cooling: whole body** Includes: Natural mechanism: frostbite, hypothermia due to natural cold Artificial mechanism: contact with or inhalation of dry ice, liquid air, nitrogen, or hydrogen Artificial mechanism: prolonged exposure to deep freeze unit	**Cold environment** exposure to excessive body cooling due to cold weather conditions (i.e. exposure to low ambient temperature environment)

Energy Type		Mechanism	Source
Chemical	▪ **Toxic** ▪ **Allergenic** ▪ **Corrosive** ▪ **Highly flammable** ▪ **Highly reactive**	**Inhaling chemical or other substance (breathed)** Includes: inhaled motor vehicle exhaust gases inhaled chemical dust molecules inhaled aerosol **Ingesting chemical or other substance (swallowed)** Includes: ingestion of tablets, pills, etc. substances dissolved in water or alcohol and ingested substances injected intravenously or subcutaneously Excludes: substances dissolved in water or alcohol and ingested **Absorption of chemical or other substance (contact skin)** Includes: tissue damage due to chemical effects of a strong acid, alkali, etc non-corroding irritation (eg., paint in the eyes) Excludes: rubbing, chafing, abrading damage due to the temperature of a substance **Unspecified effect of exposure to chemical or other substance** Includes: exposure to solid, liquid or gaseous substances	**Gaseous/Airborne chemicals** Includes: known gases (methane etc) potroom fumes dust and aerosols smoke ddeodorants motor vehicle exhaust gas **Liquid chemicals and chemical substances** Includes: poison battery acid Cosmetics (perfume, cologne) Glue or adhesive Fuel or solvent Gas, petrol, diesel, gasoline Lubricating oils, motor oil Methylated spirits Kerosene/paraffin, turpentine Alcohol Paint, coating or stripping agent Pet (veterinary) product, pesticide, herbicide Mouse, rat poison Moth repellent Insecticide or pesticide Fungicide or herbicide Cleaning agent (bleach, chlorine, detergent, disinfectant) Plant food or fertiliser, plant hormones Fabric dye Photographic products **Solid chemical** Pharmaceutical substance for human use, i.e. drug, medicine Includes: Analgesic, antipyretic, antirheumatic Antimicrobial, anti-infective agent Cold and cough preparation Asthma therapy Antihistamine Antidepressant Sedative, hypnotic, antipsychotic Anticonvulsant Cardiovascular drug Diuretic Anticoagulant Gastrointestinal preparation Anaesthetic (Nitrous oxide) Narcotic antagonist Eye/ear/nose/throat preparation Topical preparation Vitamin or dietary supplement Electrolyte or mineral Serum, toxoid, vaccine Hormone, hormone antagonist, contraceptive "Street"/recreational drug Other specified pharmaceutical substance or complementary healthcare substance for human use Heavy metal Includes: mercury, lead, barium, cadmium, copper, selenium, thallium arsenic

Energy Type		Mechanism	Source
Radiation	▪ **Electromagnetic (incl. solar)** ▪ **Non-ionising (UV, IR)** ▪ **Ionising (X-ray, Gamma, Nuclear)**	**Exposure to natural radiation**: Includes: sunburn Excludes: sunstroke (see thermal energy/heat stress) **Exposure to artificial radiation** Includes: infrared, laser, radio frequency radiation radioactive isotopes, x-rays Exposure to welding/UV light Exposure to other visible and Excludes: exposure to natural radiation **Exposure to other or unspecified radiation** inhaled radio nuclides	**Sun** Includes: solar radiation **Devices with electromagnetic fields** Includes: mobile telephones radio transmitters transmission towers high-voltage transmission lines **Devices which emit UV light** Includes: laser pointer welders and oxy-acetylene torches **Radiological devices** x-ray machines irradiating devices **Radioactive materials** uranium (e.g. nuclear power-plant) plutonium (e.g. lab-based isotopes) cesium
Acoustic Energy (noise)		**Acute exposure to sound (high dose)** Includes: loud noise sonic boom **Sustained exposure to sound (low dose)** Includes: low-level background noise auditory shock (low dB) ultrasonic	**Explosion/Blast** **Loud operating equipment** Includes: percussion devices (e.g. jackhammer) sonic boom (e.g. aircraft) **Music** Includes: concert environment audiovisual equipment/headphone **Work environment** call centre construction site other work-site
Geological/ Oceanographic		**Exposure to (effect of) precipitation** exposure to rain action / flooding flood from remote or direct storm melting snow of cataclysmic nature flood caused by collapse of a dam **Exposure to (effect of) wind action** tidal wave caused by a storm **Exposure to (effect of) earth or ocean movement** Includes: exposure to tidal wave surge exposure to mudslide exposure to avalanche **Exposure to earthquake** tidal wave caused by an underwater earthquake (tsunami) other exposure to earthquakes **Exposure to (effect of) eruption** exposure to volcanic eruptions fire/flame caused by lava exposure to other effect of eruption **Exposure to other weather event, natural disaster, or force of nature**	**Weather sources** storm, hurricane tornado windstorm dust storm blizzard **Oceanographic sources** Includes: tidal wave surge Excludes: tidal wave following an underwater earthquake **Geological sources** underwater earthquake land-based earthquake volcanoes mudslides, avalanche (mountain)

Energy Type		Mechanism	Source
Biomechanical Energy (Muscular Energy of humans and animals)	▪ **Human**	**Acute physical/muscular over-exertion or over-extension** Includes: manual handling (lifting, carrying, pushing and pulling) other manual work (shovelling, hammering, reaching, throwing, kneeling/squatting) walking/running (sudden movement, struck against, twisted, foot stuck) jumping/stepping to ground slip/trip or stumble with no fall **Gradual onset physical over-exertion** Includes: conditions of gradual and/or delayed onset (e.g. postural stress, repetitive motion, prolonged twisting, bending, stooping, grasping) conditions due to cumulative effects of multiple episodes of activity **Other physical over-exertion** **Struck or kicked by a person** Includes: application of bodily force hit (with fist), struck, kicked, shaken, butted with head, or twisted by another person – whether intentional or not (eg., during horse play, inadvertent hitting thumb with hammer) force applied by self (eg. hitting one's own head with one's fist) Excludes: being scratched by a person being struck by objects being hit by a falling person being kicked by an animal **Sexual assault by bodily force** Includes: rape, attempted rape sodomy, attempted sodomy **Other contact with a person** Includes: crushed by a crowd or stampede Excludes: fall due to collision of a pedestrian with another pedestrian **Contact with static object** Includes: walking into a wall Excludes: walking into a wall and being injured by falling down	**Person, body parts** Includes: cases where person's own body weight is largely responsible for injury (e.g. hands, fists, foot/boot) Crowd of people Other persons **Equipment and tools** Includes: portable (hand-held) equipment, components, etc. construction equipment (e.g. ladders, scaffolds) audiovisual equipment (e.g. TV's, hi-fi systems) other (e.g. gas cylinders, trolleys) **Appliances** Includes: Cleaning or laundering appliances or tool (e.g. Washing machine, dryer) Other appliances **Furniture/furnishing** Chair, sofa, couch, lounge, divan Stool Table, stand, cupboard, shelf or partition Rack, bookshelf Cabinet, cupboard, side board, chest of drawers, tall boy, dresser Dining room/kitchen table, kitchen bench **Decoration, decorating item** Rug, mat, loose carpet Draperies, curtains Roller/venetian blind or indoor shutter Mirror or mirror glass Portrait, picture, picture frame, or other wall hanging or similar decoration Ornament, bric-à-brac, knick-knack, statue, vase, urn Christmas tree **Door, window, or related fitting/feature** Door, door sill Security door or gate, fly gate (Burglar) bars on windows Window Exterior window shutters Other specified door or window related fitting/feature **Other objects or materials**

Energy Type		Mechanism	Source
Biomechanical Energy (Muscular Energy of humans and animals (continued)	▪ **Animal**	**Contact with animal: non-piercing or non-penetrating** Includes: person struck or kicked by animal Excludes: being stung or scratched/clawed by an animal **Bitten or scratched/clawed by an animal** Includes: person being bitten (suffering crush and/or puncture type injuries) person being scratched/clawed Excludes: being stung or scratched/clawed by an animal **Thrown from an animal** Includes: thrown from an animal being ridden (e.g. horse) **Other contact with object or animal**	**Land mammal** Dog Cat Rat, guinea pig, mouse Pig, wild boar Sheep, goat Cow, bull, bovine animals Horse, pony, donkey, mule, ass Baboon, monkey, chimpanzee, gorilla Marsupials (kangaroo, wallaby) Deer, moose, antelope, zebra, wildebeest Hippopotamus Lion, puma, panther, cougar, tiger Bear, grizzly bear, polar bear Elephant Buffalo, bison, African buffalo Other land mammal **Marine animal** Shark Other fishes Sea snake other marine animal **Bird** Ostrich, emu Raven, crow, magpie Other specified bird **Reptile or amphibian** Non-venomous snake Crocodile, alligator Other specified reptile or amphibian
Atmospheric Pressure	▪ **Explosive Blast** ▪ **Implosion/ Suction**	**Exposure to explosion or blast** Includes: explosive material air pressure caused by a blast compression/tension (e.g. recoil of a spring, release of objects under tension i.e. chain, cable, hose) pressure (e.g. tyre/rim separation, high pressure water hose, leaks, ruptures) objects/debris projected by a blast Excludes: flames following a blast or volcanic eruption **Exposure to implosion** Includes: underwater vessel crushed by water pressure **Exposure to suction (air pressure)** Includes: being sucked into the skimmer box of a swimming pool filtration system, having hair sucked into the suction points of a spa	**Explosive material or flammable object/substance** Fireworks Explosive (Includes: dynamite, blasting caps, homemade bombs, incendiary device) explosive material in dump, factory, grain store, munitions explosive gas other explosive material or flammable object/substance **Pressure-based equipment** Gas or air cylinder Pressurised hose, pipe Fire extinguisher High-pressure jet water from a fire hydrant/hose fluid from a pressure-washer Mains – gas, water, sewerage, steam, hot water, electricity fittings/pipes for gas, water, steam, etc. swimming pool/spa filtration system other pressure-based equipment **Water pressure** swimming pool/spa filtration system underwater environment

Energy Type		Mechanism	Source
Atmospheric Pressure (continued)	▪ **Oxygen Deprivation (hypoxia)** ▪ **Excess Oxygen (hyperoxia)**	**Mechanical threat to breathing** Hanging Strangling External compression of airway, chest effect of cave-in **Obstruction of airway by inhaled object/substance** Includes: choking on food, a toy, etc. Excludes: carbon monoxide poisoning **Obstruction of airway by object covering mouth and nose** Includes: suffocation by putting a plastic bag over one's head suffocation by a pillow being put over one's face **Drowning/near drowning** Drowning/near drowning following fall into water Includes: fall into a bucket, bath tub, swimming pool, or natural body of water fall off a watercraft or part thereof fall off a dock, pier, jetty Drowning/near drowning while in a body of water Includes: being in a bucket, bath tub, swimming pool, or natural body of water Drowning/near drowning due to collision with a watercraft or part thereof while in body of water Other drowning/near drowning cases where it was unknown whether the injured person fell into a body of water or was already in a body of water **Confinement in oxygen-deficient place** Excludes: gassing with exhaust fumes taking place in a motor vehicle/confined space confinement in a plastic bag smoke inhalation **Altitude sickness** **Oxygen toxicity** breathing gas (e.g. diving disorder/bends) mechanical ventilation (e.g. intensive care patient)	**Toy – art, craft, or kit** Includes: building set, building blocks, Lego blocks chemistry/science kit model kit, rocket kite, or fuel-powered model needle craft kit plasticine, modelling clay Board game or accessory/piece Doll, doll accessory or part, stuffed toy Balloon (toy) Other inflatable toy Marble, bead Pacifier, dummy Baby bottle or nipple Diaper, nappy Diaper fastener Other baby or child article Clothes, foot wear, or related products **Other material or substance** rope, string, wire cords of household appliances food stuffs **Body of water** Man-made well, dug well for underground water Above-ground swimming pool, external spa, or hot tub Water reservoir Puddle Dam, lake River, stream Swamp, marsh Beach, seashore Open sea Other body of water Mine inundation **Oxygen depleted (hypoxic) environment** high altitude aircraft cabin depressurisation **Excess oxygen (hyperoxic) environment** breathing gas scuba diving medical ventilators
Microbiological Energy	▪ **Infection** ▪ **Pathogen** ▪ **Mutagen** ▪ **Parasite**	**Bitten or infected by person** Includes: being bitten by person or oneself (e.g., biting one's own tongue) cases where the bite does not break the skin Excludes: being bitten by an animal or insect	**Infected Human** Includes: Bitten by infected person Punctured by infected medical/surgical device (e.g. Hypodermic needle/syringe) **Infected bird** Parrot, parakeet, cockatoo

Energy Type		Mechanism	Source
Microbiological Energy (continued)		 **Bitten/stung by infected animal** Includes: being bitten by a horse, dog, shark, etc. being bitten by a venomous snake Excludes: human bite a bite that has become infected – not an injury **Bitten/stung by insect or other invertebrate** Includes: being stung by a mosquito being stung by a bee, wasp, or scorpion being bitten by a spider being stung by a jellyfish anaphylactic shock following a bee sting, etc. Other specified biting, stinging, invenomating **Unspecified biting, stinging, invenomating** Includes: biting/stinging where unknown whether or not animal/insect was poisonous or not **Contact with/by venomous or toxic plant**	Raven, crow, magpie Other specified bird Unspecified bird **Infected/ venomous insect, invertebrate** Bee Wasp Hornet Ant Spider Scorpion Tick Centipede, millipede Snake Other specified insect, invertebrate **Infected land mammal** Dog Cat Rat, guinea pig, mouse Pig, wild boar Sheep, goat Cow, bull, bovine animals Horse, pony, donkey, mule, ass Baboon, monkey, chimpanzee, gorilla Marsupials (kangaroo, wallaby) Deer, moose, antelope, zebra, wildebeest Hippopotamus Lion, puma, panther, cougar, tiger Bear, grizzly bear, polar bear Elephant Buffalo, bison, African buffalo Other land mammal **Infected/venomous marine animal** Shark Other fishes Sea snake other marine animal **Venomous plant** Tree, plant Leaves, flowers Mushroom, toadstool, fungus Plant seed Fruit from plant Plant thorn Branch or stick (as separate from tree, plant) other venomous or toxic plant

APPENDIX II:

Case Study: Crane Fatalities in the Construction Industry, 1985-1995 (n=525)

PERGAMON

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Crane fatalities — a taxonomic analysis

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Abstract

> It should not be necessary for each generation to rediscover principles of safety which the generation before already discovered. We must learn from the experience of others rather than learn the hard way. We must pass onto the next generation a record of what we have learnt. Jessie C. Ducommun

Cranes are remarkable and invaluable tools for hoisting and carrying. Like all other tools they have significantly increased humans' capacity to work; they marshal far more energy than can human or animal muscle. However, the large quantities of energy involved and the human–crane–environment interactions required result in there being a high potential for damage to occur to people and equipment. The current situation is that similar serious crane occurrences continue to repeatedly recur, albeit separated in terms of time and space. As a result, crane fatalities can be considered as endemic, at least; many would suggest epidemic. To gain sufficient insight into the aetiology of crane-related damage, and establish key focus areas for future control, there is a need to establish the pattern of crane-related damaging occurrences. To achieve this for fatalities, an approach was made to the US Occupational Safety and Health Administration (OSHA), which provided over 500 crane fatality narratives for the years 1985–1995. This information was scientifically organised using the taxonomic process involving observation, description and classification of the data into groups. The pattern is presented along with discussion regarding the application and limitations of the information. The data are intended to add to the information base of crane designers, owners and users in order to challenge the status quo and generate effective change for the future.

Keywords: Crane; Fatality; Taxonomic analysis

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1. Introduction

When one examines industrial injury and fatality statistics in developed countries, those involving cranes are heavily represented. Most of these occur in the construction industry, although other industries such as manufacturing, transportation and public utilities are also involved.

Construction fatalities in the US represent approximately 16% of all workplace fatalities (BLS, 1996, 1997). For US construction labourers, the fatality incidence rate was 33 fatalities per 100,000 workers (in 1994), and was 39 fatalities per 100,000 workers (in 1995). Based on these conservative statistics, the following statement can be made:

> The risk of a US construction labourer being fatally injured at work in any one year is greater than 1:3000.

The proportion of fatalities and injuries that are crane related is difficult to accurately deduce. In the US, approximately 30–50 crane fatalities occur in the construction industry per year, with there being a total of approximately 70 crane fatalities across all industries per year (OSHA, 1996). As described in the OSHA document "Crane and Hoist Safety", over 1000 construction injuries were reported to involve cranes and hoisting equipment in 1987 (23 states reporting). The document goes on to make the following point:

> However, under reporting of crane related injuries and fatalities, due to misclassification and a host of other factors, masks the true magnitude of the problem.

MacCollum (1993) has made best estimates that crane hazards are the source of about 25–33% of casualties in construction and maintenance activities. With respect to fatalities only, the Construction Safety Association of Ontario (1969–1994) reports that an average of 10% of construction fatalities were related to cranes and rigging from 1979 to 1994. A taxonomy of 193 construction fatalities in the New South Wales construction industry (AFCC, 1987) indicates that approximately 12% of fatalities were crane related.

The size of the problem is such that crane and hoist safety is currently on OSHA's list of priority problems. Rationale for this assignment of priority is provided (OSHA, 1996):

> Crane and Hoist Safety meets several of the criteria for designation as an OSHA priority. The very serious nature of the hazard, the magnitude of the risk (high rate of fatalities and serious injuries relative to the number of workers exposed), the potential for catastrophic accidents, and the considerable knowledge about effective protective measures clearly demonstrate the need for action to address crane and hoist safety.

As one examines literature pertaining to crane-related damaging occurrences (injuries and fatalities), it becomes clear that there is a paucity of data regarding the size and nature of the problem.

A number of authors have provided some insight into the problem, such as Dickie (1975), Butler (1978), Hakkinen (1978), Jarasunas (1978) and Paques (1993). Based on data sources including incident statistics held by insurance and government agencies, these authors were able to elucidate the breakdown of fatalities and serious injuries involving cranes. These documents are invaluable in describing the problem at the first level.

However the pattern of crane-related personal damage has not yet been sufficiently established. The need for detailed analysis of quality historical data is eloquently addressed by MacCollum (1993):

> Serious injury or death that occurs repeatedly from similar circumstances should be considered epidemic. These occurrences should be examined to identify hazards so that appropriate hazard prevention measures can be initiated in the same diligent manner that the medical profession examines a disease or infection to develop a vaccine or antibiotic for its prevention or control.

2. Methodology

The study of any epidemic, by definition, warrants application of the discipline of epidemiology. Epidemiology concerns itself with the scientific study of the patterns and determinants of damage in human populations. It is equally applicable to 'injury' and 'illness/disease' phenomena, as discussed by Gordon (1949), Waller (1973) and Baker (1975).

The first step of the process is dependent on the availability of quality data which can generate understanding of the patterns of aetiology of crane fatalities. To gain insight into the aetiology of crane-related fatalities, it became clear that there is a need for information of a much higher quality than the traditional tabulated fatality data.

An approach was made to the US Occupational Safety and Health Administration (OSHA), which provided over 500 fatality narratives for the years 1985–1995. The narratives, or fatality reports, are based on fatality/catastrophe inspections conducted by State or Federal OSHA, which were reported as violations of the relevant sections of the Code of Federal Regulation: Labor 29, part 1926 (1995). The data are from the OSHA Integrated Management Information System (IMIS).

The data include construction industry crane fatalities related to mobile cranes, tower cranes, derrick cranes and elevating work platforms (aerial lifts). The population does not include crane fatalities that were not reported to, or investigated by, Federal OSHA.

For the information to be of value, there is a need to organise the data in a scientific and useful way. The method that was used for organising the data was the taxonomic process. Taxonomy can be described as observation, description and classification of data into hierarchical groups according to common patterns and individual differences. The aim is to paint a broad picture of what exists and to indicate the relative importance of different phenomena according to how frequently they occur.

The data can be classified in a variety of different ways, e.g. by age of deceased, year of occurrence, etc. These classifications were completed, although not presented here.

A most effective way to classify the crane fatality data is according to the forms of damaging energy involved. This is based on the concept that damage results from an energy exchange which goes beyond tolerable limits. In epidemiologic terms, the type of damaging energy is the agent involved in the damage to people, as developed by King (1949), Gibson (1961), Haddon (1970) and others. Insight into the energy which resulted in the damage allows control measures to be focussed on preventing or reducing the damaging energy exchange (McDonald, 1995). Essentially, the output is a descriptive taxonomy of the crane fatality problem, broken down at the first level by the damaging energy involved. Subsequent levels of the taxonomy were developed based on an assessment of 'usefulness' in terms of the classification for identifying prevention strategies.

3. Results

The complete taxonomy of crane fatalities in the US construction industry (1985–1995), including individual accident descriptions has been documented (Shepherd and Kahler, 1996). A second level breakdown of the taxonomy is depicted in Fig. 1. Crane type was specified in 67% of records; of these 65% pertain to mobile cranes, 20% to aerial lifts, and 6% relate to tower cranes. The next level of detail can be provided with reference to the taxon numbers.

For example, breaking down Taxon 1.1.1 Overhead Power Lines reveals that 190 fatalities were associated with crane/load contact with overhead power lines (mobile cranes), with direct human contact resulting in 24 fatalities (aerial lifts). A breakdown of the location of the person when the crane contacted energised lines can be provided (Fig. 2). The data also reveal that powerline contact occurs either by the crane boom (102 cases, 54%), by the loadline (72 cases, 38%), or by the hoisted load (16 cases, 8%).

Figs. 3–5 depict breakdowns of fatalities involving falls of objects, falls of people, and moving machinery, respectively. Similar breakdowns can be provided for each taxon; however, space restrictions prevent the display of these here.

4. Discussion

With reference to the taxonomy presented, it is evident that patterns emerge with respect to crane-related fatalities. This is consistent with the core concept in epidemiology that fatality (and injury) distributions are highly non-random (Haddon,

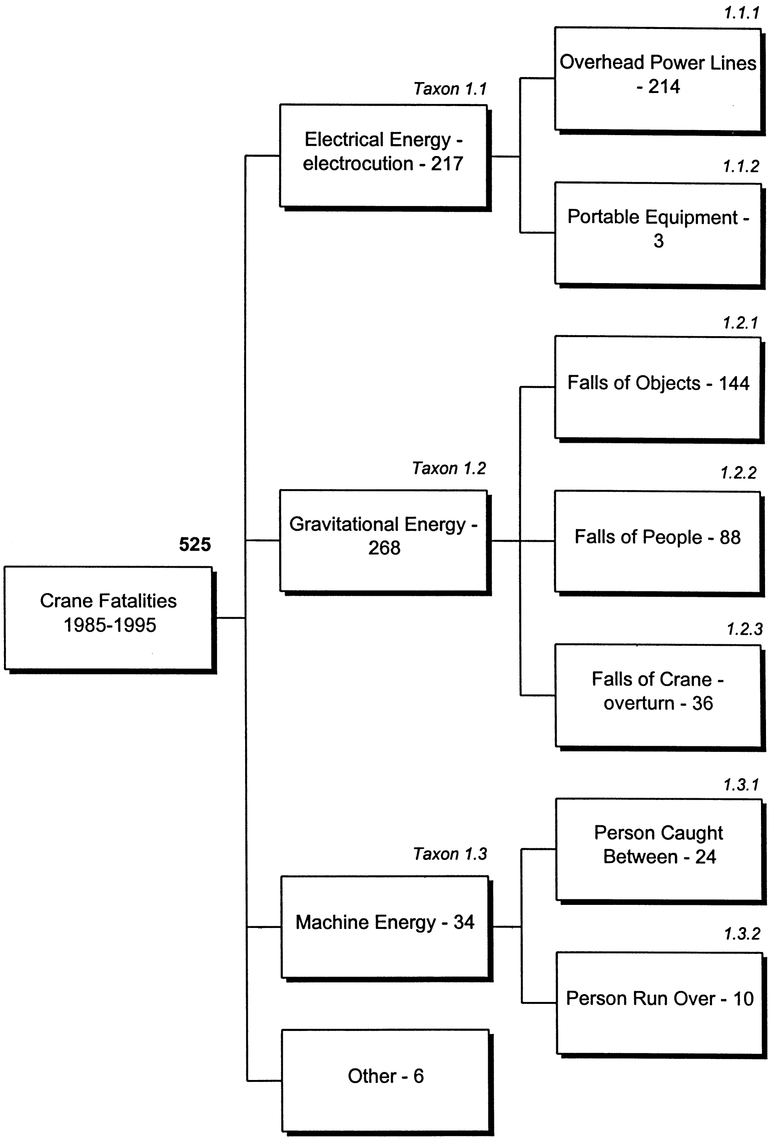

Fig. 1. Second level breakdown of 525 US crane fatalities.

1980). Gravitational energy and electrical energy are over-represented, similar to many other studies of fatalities.

The complete crane taxonomy indicates that approximately 79% of the crane fatality problem can be managed with focus on the following few taxon:

1. crane contact with overhead power lines — 190 (36% of the problem with 57% of these involving electrocution of the person handling the load);

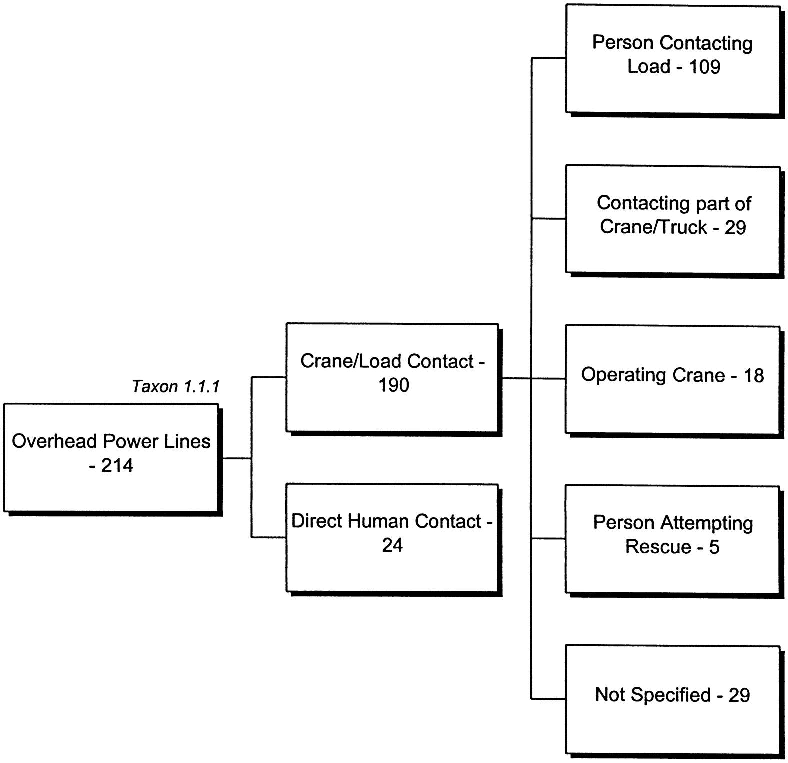

Fig. 2. Taxon 1.1.1 — contact with overhead power lines.

2. falls of people from a height — 88 (17%), the use of fall protection equipment would have prevented most of these;
3. falls of a suspended load onto a person under the load — 55 (10%);
4. crane overturns and falls onto people — 36 (7%);
5. falls of lattice boom during dismantling — 30 (6%); and
6. person caught between swinging counterweight and crane structure — 15 (3%).

However, some limitations of the taxonomy are stressed:

1. The proportion of crane-related fatalities that are investigated by OSHA is unknown; the pattern may alter if a significant number of fatalities are not investigated.
2. The taxonomy is for the US construction industry; the pattern may be different for other western countries (e.g. Australia).
3. Most importantly, the taxonomy is based on fatalities only. The number of fatalities in each taxon is only one indicator of where industry priorities should lie in terms of crane safety development. Previous studies of other large injury

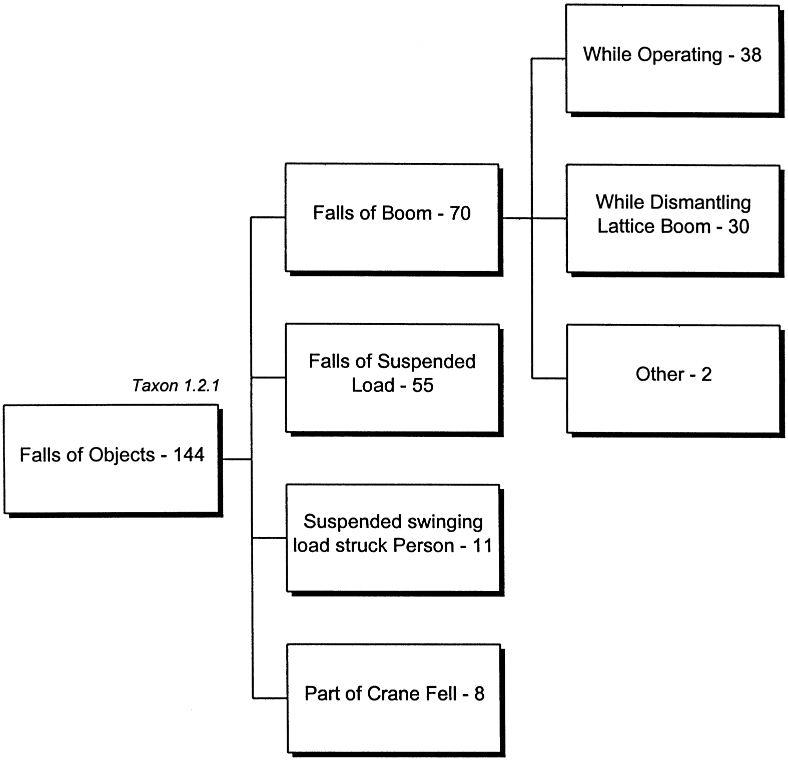

Fig. 3. Taxon 1.2.1 — falls of objects.

and fatality groups indicate the majority of personal damage arises from non-fatal permanent disability (McDonald, 1995; Kahler, 1996). Thus, in the short term, further consideration should be given to those taxa which would be strengthened by the inclusion of non-fatal permanent disability data (e.g. gravitational energy — falls of people — crane access, and human energy — lifting, pushing, pulling, etc.), and in the long term a taxonomy of non-fatal permanent disabling crane incidents be completed. Progress is dependent on an accurate description of the problem.

In the past, control measures for the hazards described have been focussed on training and education of employees, and procedures such as maintaining safe clearances from electrical lines.

These countermeasures are essential, but limited, as they do not effectively manage the damaging energies in force or the propensity for human error to be involved in the release of these energies. Continued emphasis on these controls alone will simply ensure the pattern of damage continues.

It is proposed that the next most significant gains with respect to reducing crane fatalities and serious injuries will be made by providing equipment which

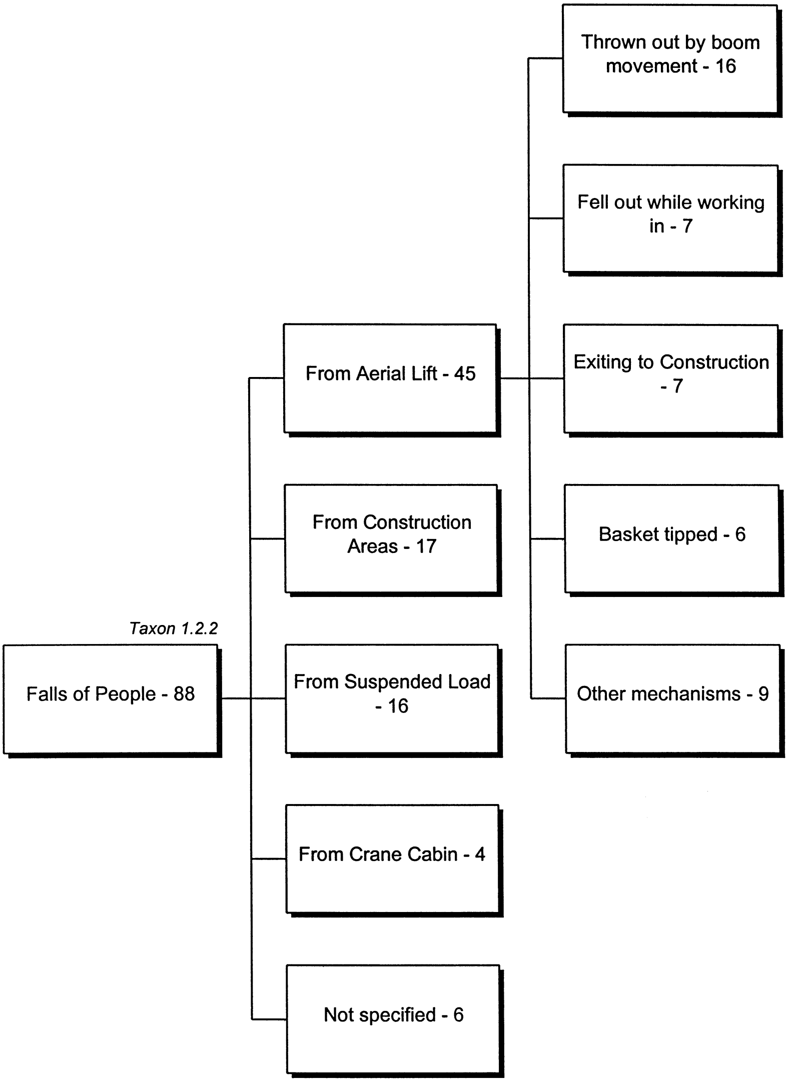

Fig. 4. Taxon 1.2.2 — falls of people.

accommodates predictable and undesirable human error and behaviour. Application of this principle in conjunction with historical data which is scientifically organised, can assist developing focus areas for future control. For example, the use of insulated links on crane cables has the potential to manage up to 57% of inadvertent powerline contact fatalities (about 20% of the crane fatality problem). Insulating links have been available for a long time (US Patent Office, 1958) and are often used on cranes in other industrial environments; e.g. in aluminium smelters. However, this technology may require further investment before it becomes commercially

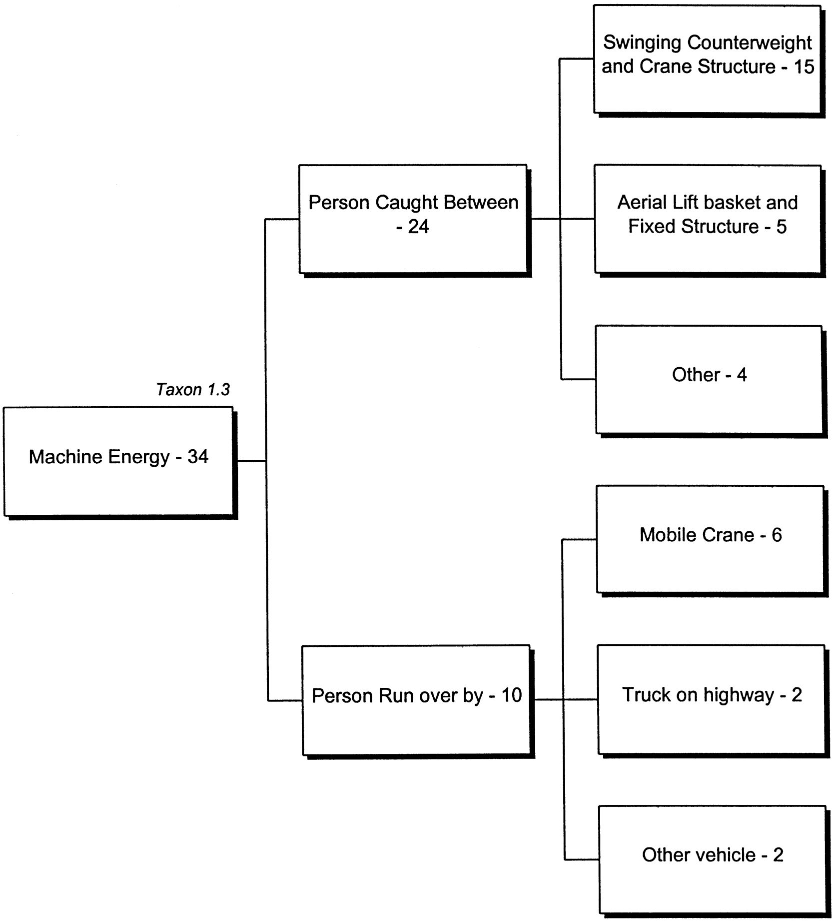

Fig. 5. Taxon 1.3 — machine energy.

viable for all mobile cranes. It would be recommended that development and usage of insulated links complement other energy management measures such as de-energisation of power lines prior to work, the use of insulating line sheaths and electrostatic warning devices.

5. Conclusion

In summary, a descriptive taxonomy of 525 US crane fatalities has been completed, some of the results of which are presented here.

The taxonomy is intended to yield insight into the extent, nature and patterns of crane-related fatalities. The disciplines of epidemiology and taxonomy are considered invaluable to observing, describing and classifying large quantities of fatality data. These disciplines are used to great success in fields such as medicine and biology, but are underused in occupational health and safety.

Patterns emerged with respect to crane fatalities with electrical energy — crane contacting overhead power lines and gravitational energy — falls of people and suspended loads accounting for most of the problem. The challenge is to conceive and implement effective solutions that have the capacity to manage these energy sources and people's interaction with the equipment and environment in the long term. Simplistic behavioural solutions are unlikely to achieve this.

In summary, crane fatalities are not 'freak occurrences'; they are both predictable and preventable — the massive loss of human life is unnecessary. Effective management of the energies marshalled and focus on the priority areas identified will avoid continuation of the pattern of crane-related damage. This requires action (change for the future) on behalf of crane designers, manufacturers, owners and users and other stake holders including government and industry.

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APPENDIX III:

Case Study: Australian Work-related Electrical Fatalities, 1989-1999 (n=243)

THE PATTERN OF ELECTRICAL FATALITIES

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KEYWORDS

ELECTRICAL
OCCUPATIONAL FATALITIES
TAXONOMY
CONSTRUCTION INDUSTRY
OVERHEAD POWERLINES

ABSTRACT

Electricity is a common source of fatal damaging energy in the workplace. However, the detailed pattern of electrical fatalities is not known. Descriptive data (fatality abstracts) of 243 electrical fatalities involving Australian workers were reviewed to establish the pattern. The data was sourced from records of electrocutions held by Australian State Electrical Regulators for the period 1989-1999.

The data indicates that, contrary to popular belief, electrical fatalities involving Australian workers are not reducing over time, and that 240 volts is by far the most common source.

The pattern of electrical fatalities is presented in taxonomic form. The taxonomy is intended to add to the information base of industry associations, unions, government, employers and workers and present challenges with respect to effective change for the future. Recommendations are made with respect to overhead powerlines, drilling into cavities, ceiling space work, and temporary power.

INTRODUCTION

Contact with electrical energy accounts for about 10% of all Australian workplace fatalities.[1] Industries such as construction are over-represented; 20% of Australian construction fatalities relate to contact with electricity[2].

Some insight into work related electrocutions is provided by the National Occupational Health and Safety Commissions "*Work-Related Fatalities Study 1989-1992*"[1]. According to the study, 122 workers died over the 4 year period, as a result of contact with electricity.

Figures 1 and 2 depict breakdowns with respect to industry and occupation.

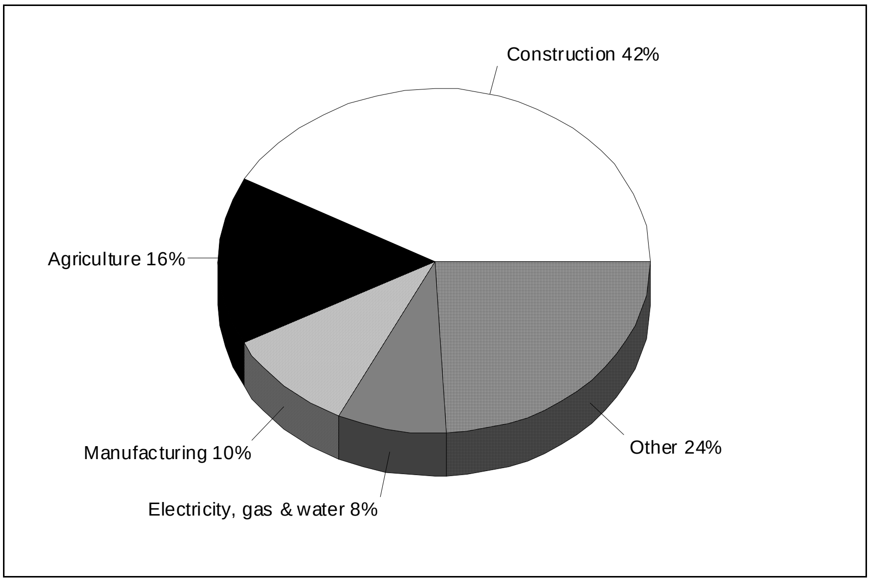

Figure 1 Australian work-related electrical fatalities by Industry, 1989-1992 (n=122)

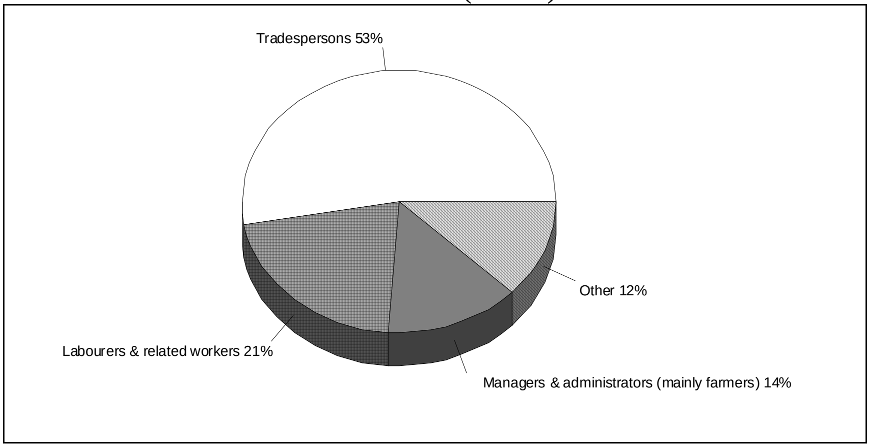

Figure 2 Australian work-related electrical fatalities by Occupation, 1989-1992 (n=122)

The study quotes the most common sources of electrical damage as:

- *"fixed wiring, including direct contact with wires, contact with wires while using hand tools (eg. arc welding equipment) and contact with switchboards and control panels (50 incidents);*
- *powerlines (usually direct contact by an object with low or high voltage overhead powerlines) (47 incidents); and*
- *extension cords and accessories."*

In summary, with respect to electrocution it is known that the major industry involved is construction (particularly occupations of tradespersons and labourers). Contact with powerlines and fixed wires account for a majority of the fatalities.

The above information is invaluable to establish the first level of the problem, and direct change. However, the detailed pattern of Australian electrical fatalities has not yet been established.

METHODOLOGY

"The employer who wants to prevent injuries in the future, to reduce loss and damage, and to increase efficiency, must look systematically at the total pattern of accidental happenings, whether or not they caused injury or damage, and must plan a comprehensive system of prevention rather than relying on the ad hoc patching up of deficiencies which injury or accidents have brought to light."

Robens Committee 1972

To gain insight into the pattern of electrical fatalities, there is a need for quality descriptive data regarding the occurrences. An approach was made to the Office of the Chief Electrical Inspector in Victoria who assimilated and provided descriptions of:

- X 451 fatalities recorded by all Australian State and Territory Electrical Regulators and/or Electrical Supply Companies for 1989-1999.

This study population is said to consist of all people who died as a result of electrocution (100% of electrical cause or suspected to be of electrical cause) for the time period.

Examples of the incident descriptions provided are given in **Table 1** below:

Table 1
Incident descriptions of people who died as a result of electrocution

State	**Date**	**Sex**	**Age**	**Area**	**Voltage**	**Description**
QLD	07/02/91	M	66	Caravan and Outside	240V	A night watchman received a fatal electric shock of 240 volts when he touched the energised doorway of a caravan. The van had become energised due to a fault in an extension lead which was used in association with another unearthed makeshift lead.
VIC	5/94	M	54	Non Electrical Worker	22kV	A 22kV overhead line was struck by a crane. The victim was walking and steadying a load, being transported by the mobile crane, with his hand. The load was fabricated steelwork, lifted by steel chain. The jib moved into contact with the 22kV conductors. The victim received the fault shock through hand to foot.

A broad definition was used to distinguish two samples:

- X Workers (n=243) - person engaged in some work related activity (for pay/profit) at the time of death;
- X General Public (n=208) - person not working (eg. at home, public place) at the time of death.

Figures 3, 4 and 5 illustrate general trends in the data relating to workers – by year, by age of deceased and by voltage contact.

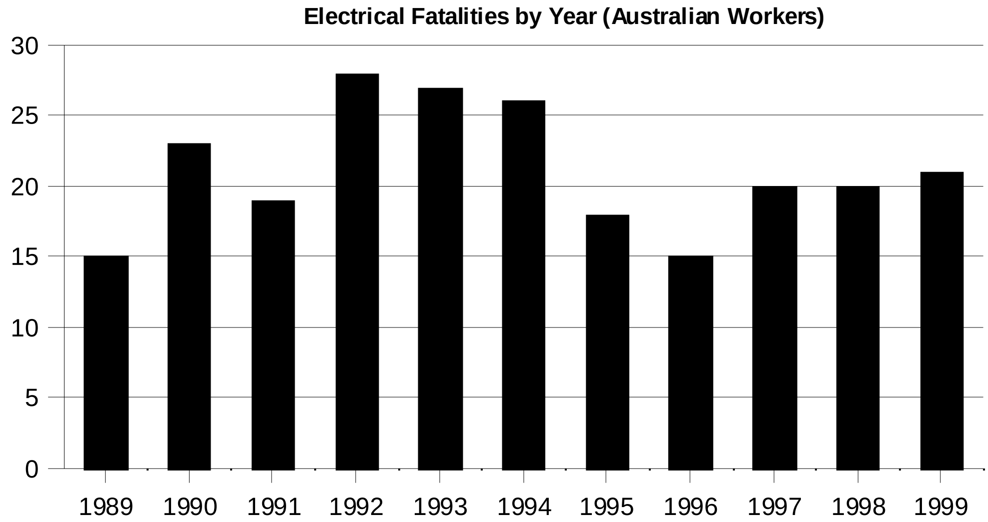

Figure 3

Figure 4

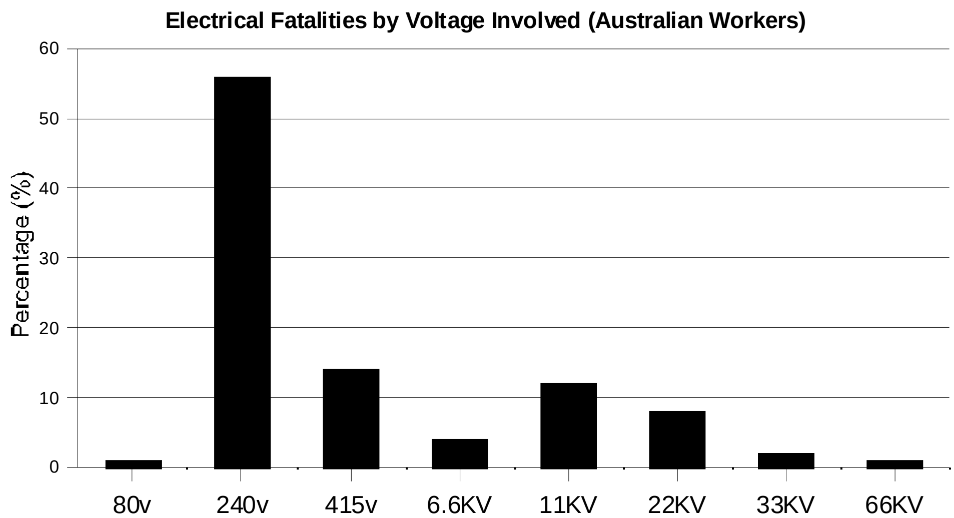

Figure 5

A second level breakdown of the taxonomy is depicted in **Figure 6**.

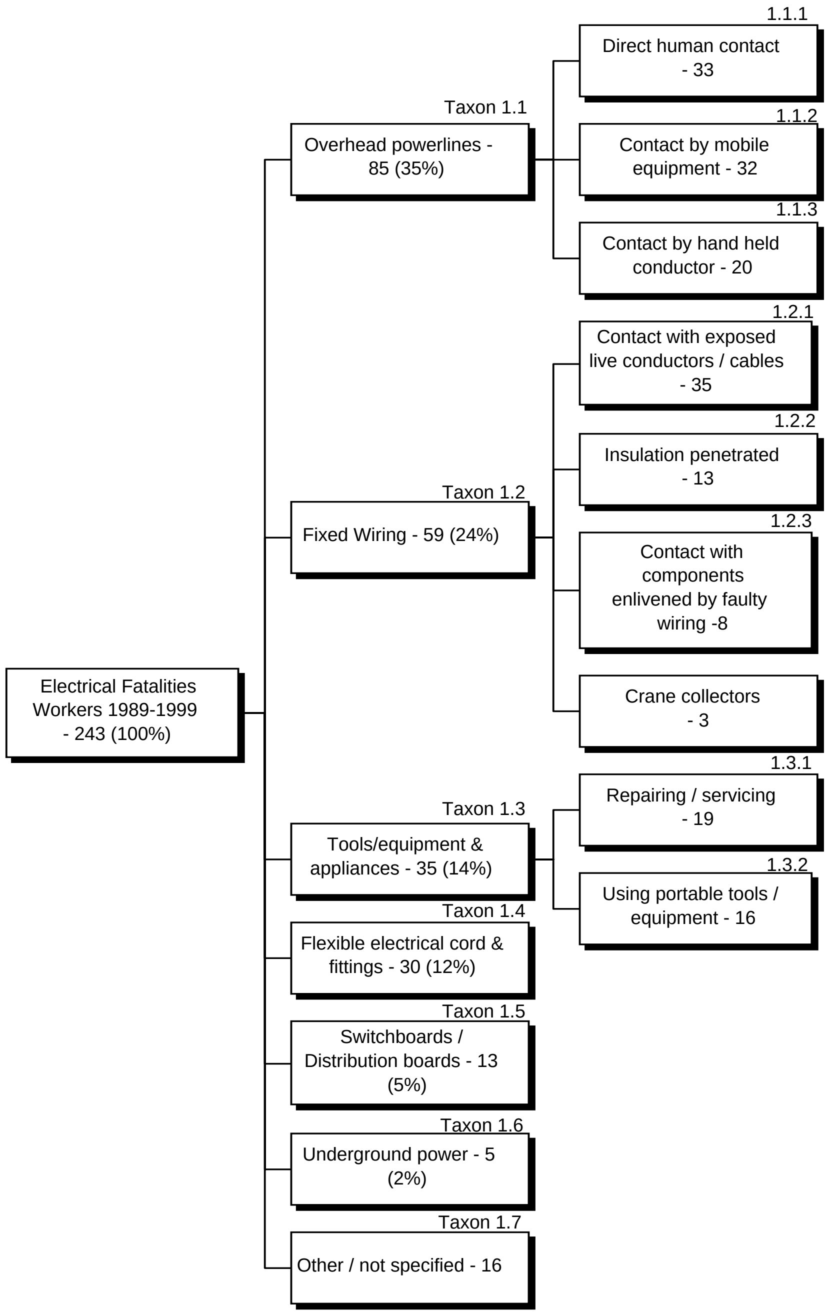

Figure 6

The next level of detail can be provided with reference to the taxon numbers.

For example, further breakdowns of Taxon 1.1.1 Direct Human Contact with Overhead Powerlines and Taxon 1.1.2 Contact Overhead Powerlines by Mobile Equipment are given in **Figures 7 and 8**.

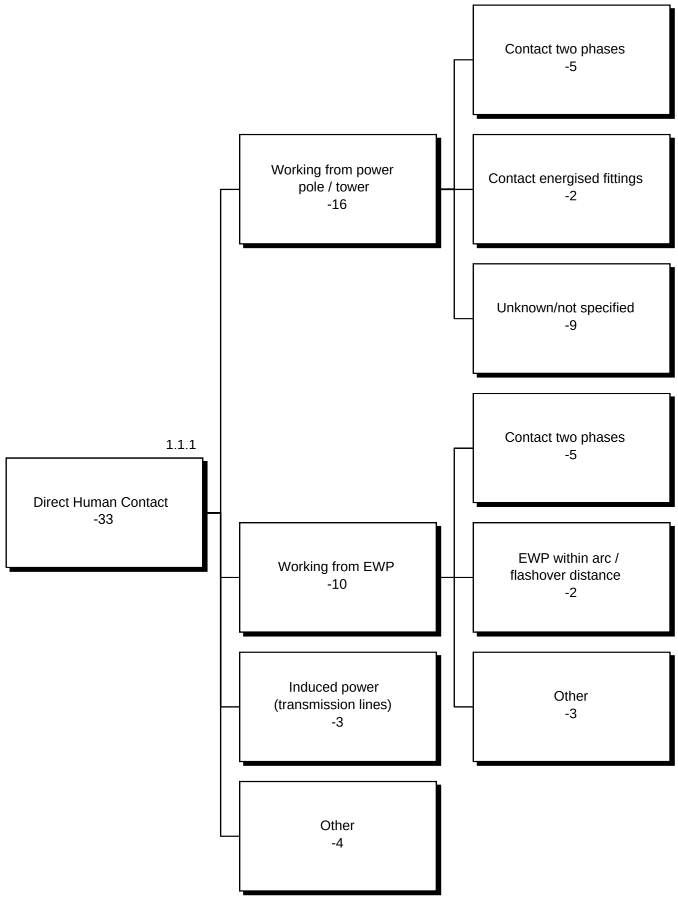

Figure 7

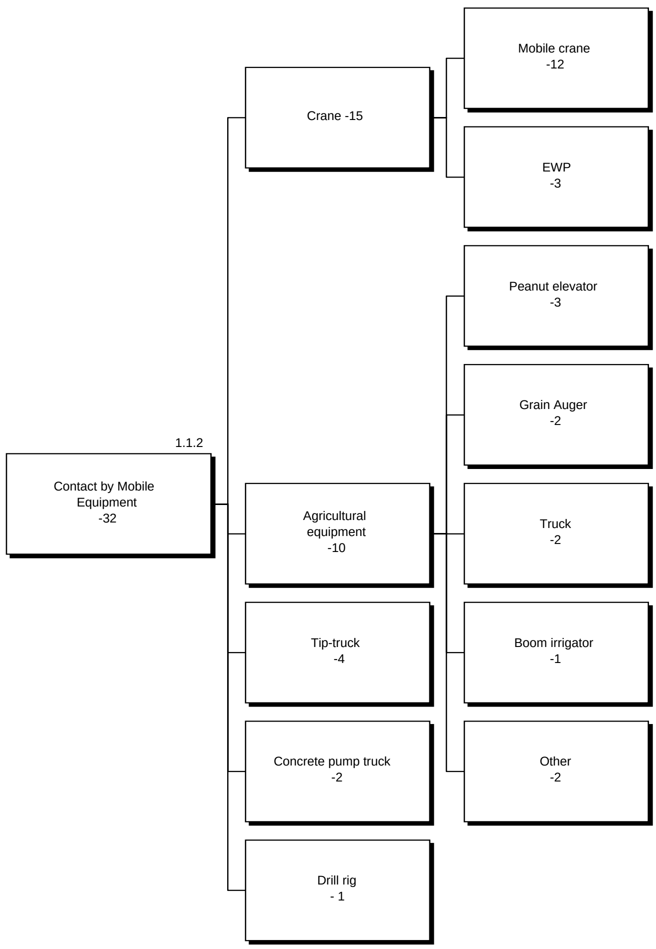

Figure 8

Figures 9, 10 and 11 depict breakdowns for fixed wiring, tools/equipment and appliances, and flexible electrical cord and fittings respectively.

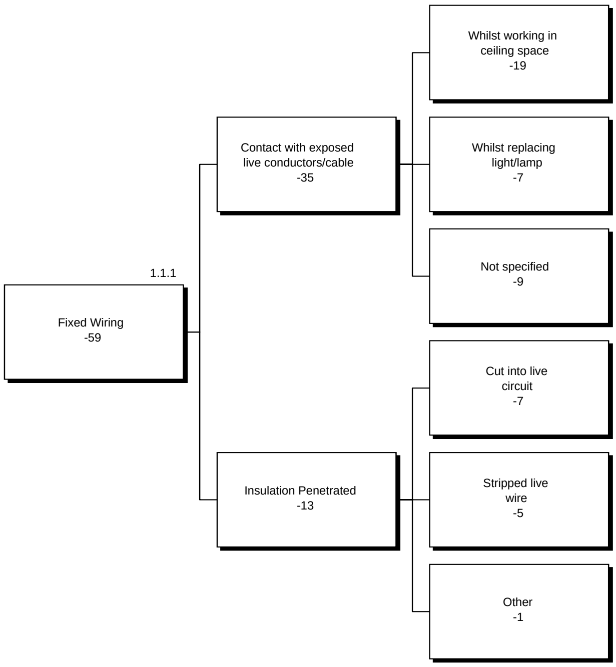

Figure 9

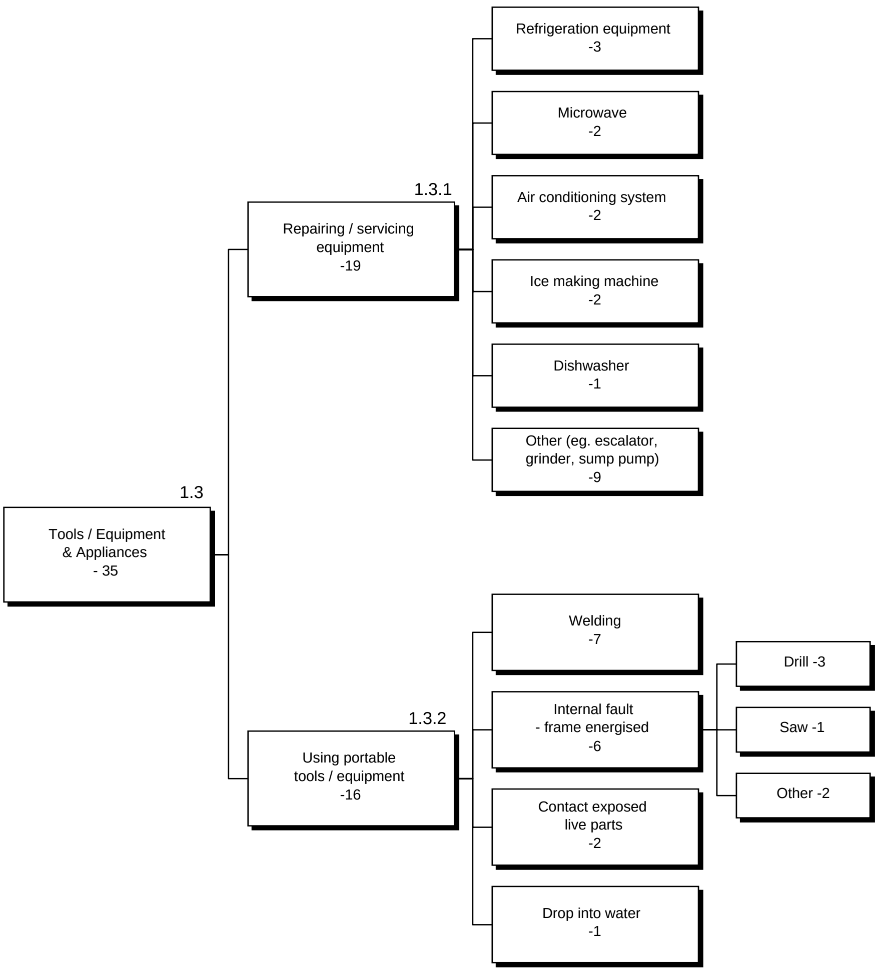

Figure 10

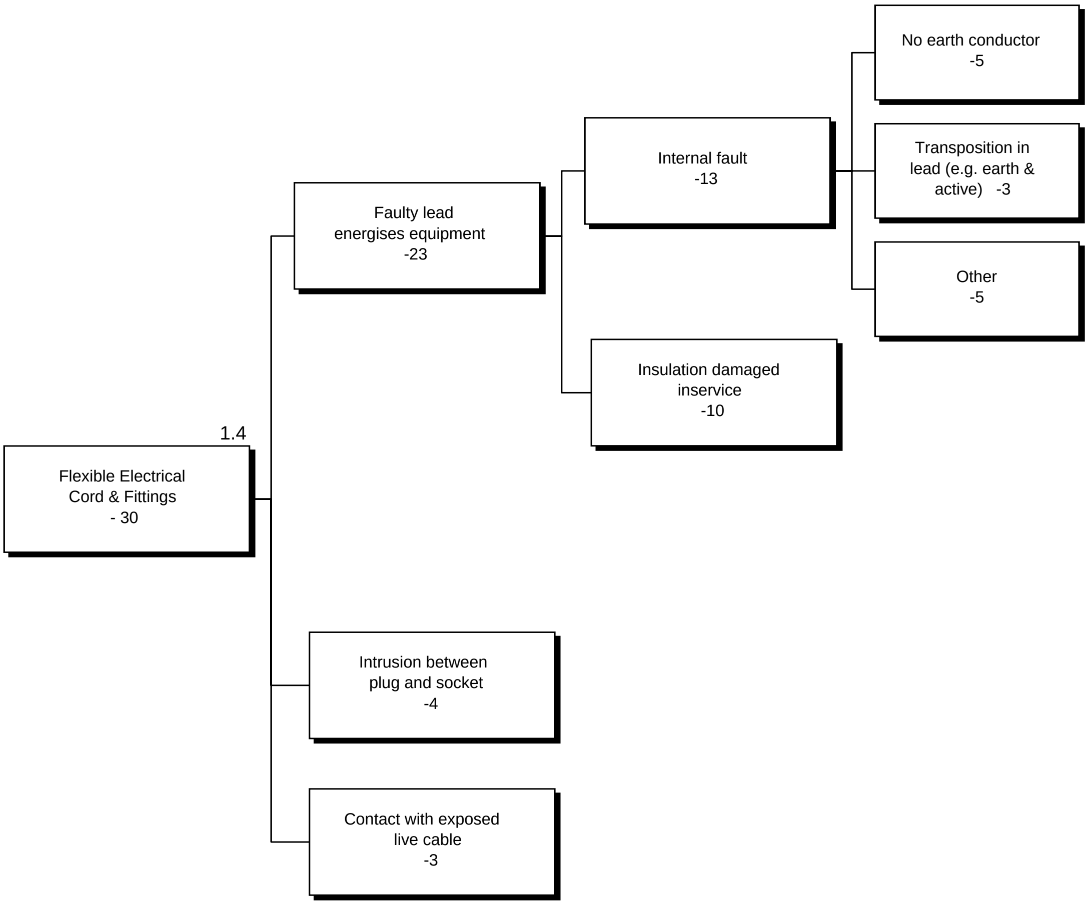

Figure 11

DISCUSSION

It is evident that patterns emerge with respect to electrical fatalities. This is consistent with the core concept in epidemiology that fatality (and injury) distributions are highly non-random.[4]

Like all taxonomies, it is possible to be lost in the maze of taxons and percentages, particularly when the number of incidents represented by a particular taxon become quite small. At this point in time in the management of electrical energy, it is necessary to focus on those few taxon that embrace a significant percentage of all fatalities without detracting from any of the current effort being applied by government, industry and the unions.

The complete electrical fatality taxonomy indicates that over 80% of the problem can be managed with focus on the following areas:

1. overhead powerlines - mobile equipment contact, direct human contact and contact via handheld conductor
2. fixed wiring - direct contact with exposed live conductors or cable
3. the use and repair of tools, equipment and appliances
4. the use of flexible electrical cord and fittings

These are discussed as follows:

1. Contacting overhead powerlines – 85 (35% of the problem, with the majority involving direct human contact or mobile equipment contact). See **Figures 7 and 8**.

   Common factors with respect to direct human contact with powerlines include:
   - Lines not de-energised
   - People working within minimum clearances
   - People contacting live components (eg. phase to phase, energised fittings)
   - Live components not insulate
   - PPE (including gloves) not worn

Common factors with regard to mobile equipment contact include:

- Overhead powerlines not de-energised
- Mobile equipment (particularly cranes) operating in proximity to powerlines
- Overhead powerlines not insulated (non-use of insulated line sheaths)
- Mobile equipment not insulated (eg. non-use of insulated links, boom guards)
- Minimum clearance are not maintained
- Inadvertent contact with powerline occurs.

2. Fixed wiring – 59 (24% of the problem, with the majority being associated with contacting exposed live conductors or cutting into/stripping live wires). See **Figure 9**.

   Common factors include::
   - Working on or near live fixed wiring circuits (eg. domestic/commercial)
   - Contact with exposed conductors (especially ceiling spaces)
   - Contacting undetected power (eg. drilling into a cavity, cutting into live circuits)
   - Absence of earth leakage or residual current devices (RCDs) on circuits.

3. The use and repair of tools, equipment and appliances – 35 (14% of the problem). See **Figure 10**.

   Common factors include::
   - Repairing equipment live
   - Not wearing PPE (gloves, mats)
   - Using welders
   - Absence of earth leakage devices on portable equipment

4. Flexible electrical cord and fittings – 30 (12% of the problem with a majority involving faulty leads). See **Figure 11**.

   Common factors include::
   - Faulty lead energising equipment (eg. internal fault – no earth conductor)
   - Earth leakage device (or RCD) not used on cord
   - Absence of a flange on the socket to prevent intrusion

Many existing controls for the abovementioned hazards are behavioural or procedural in nature. Basic training and procedures is an absolute minimum requirement for electrical safety, but these controls are limited as they do not manage the damaging of energy involved (in this case electricity), nor the propensity for human error and behaviour to be involved in the release of this energy. The consequence of electrical incidences is often fatality, thus it is necessary to identify and implement more reliable design and engineering controls where practicable.

For example, currently with regard to mobile equipment contacting overhead powerlines there is a strong focus on training personnel in the procedure of working outside exclusion zones (1-2 metres from powerlines); i.e. “look up and live”.

A previous study of 525 crane fatalities[5], found that 190 crane fatalities involved the crane contacting overhead powerlines, with the majority of fatalities involving the person contacting the load.

It is believed that training itself will be insufficient to manage these interactions. One underutilised commercially available technology is are insulated links which are fitted to crane hooks and are load rated up to 160 tonne and electrically related to 50kV.

With regard to fixed wiring, particularly drilling into cavities, the common procedure is to “visually” identify the presence of power and then to use electrical gloves and insulated mats prior to drilling. The reality of work is that it can be extremely difficult to visually identify power and personnel often simply “drill blind” into cavities, rarely using electrical gloves or mats. Whilst reinforcing the need for PPE, it would be highly desirable to provide personnel a means of detecting power prior to drilling – there are a number of electrical cable tracing devices new to the market which can fulfil this function. There are also electric drills available which cease operation when they “detect” contact with metal conductors.

RECOMMENDATIONS

Based on the analysis of 243 workplace electrical fatalities, and an understanding of the industry situation, a number of recommendations can be made which are focussed on controlling the major areas of risk identified previously.

1. Recommendations regarding work near overhead powerlines. These are intended to supplement other strategies aimed at preventing contact (training, spotters, exclusion zones, etc).
    - Refocus procedures to de-energise powerlines – much easier to do in the planning stage.
    - If overhead powerlines cannot be de-energised, insulated links and proximity warning devices should become standard practice on mobile cranes when working within 10 metres of energised overhead powerlines.

    With regard to direct human contact with powerlines:
    - Ensure the use of insulated EWPs
    - Assess and provide insulated working gloves which are practical for manipulative work yet have a sufficient insulating capacity.

2. Recommendations with regard to drilling into cavities.
    - Provide handheld electrical cable locating devices which can trace power prior to drilling
    - Consider use of drills which automatically shuts off if contact with metal conductors occurs
    - The use of double insulated power tools must be standard.

3. Recommendations with regard to ceiling space work.
    - Provision of a pocket tester for electrician to detect live cabling (eg volt stick, metal detectors).
    - Provide hands-free high intensity lighting (eg. miners lamps or cap lamps mounted to the headband, belt or pocket)
    - Clear establishment of a Work Permit System where if frayed or broke insulation or unauthorised wiring is observed in ceiling spaces, the work ceases and the house circuit is de-energised.

4. Recommendations with regard to flexible electrical cord and fittings (temporary power).
    - The use of portable residual current devices or earth leakage on all tools and appliances (preferably fixed to the cord)
    - A standard for extension cords which includes:

    a. an LED display for internal faults (earth faults, neutral active interposed)
    b. overlap on socket to shield pins and prevent intrusion.

Acknowledgments
The author of this paper would like to extend sincere thank you to Leighton Contractors Pty Ltd for funding the research, and the Office of the Chief Electrical Inspector (Victoria) for supplying fatality data.

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APPENDIX IV:

Case Study: United States Fatalities Involving Portable Ladders, 1984-1998 (n=277)

Ergonomics,
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Ergonomic design interventions – a case study involving portable ladders

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Portable ladders are one of the most ancient tools conceived by man. They remain ubiquitous and indispensable even today. It is interesting to note that there is little difference between the makeshift portable ladders used throughout history and some still used today. The design of portable ladders seems to have simply evolved, rather than been subject to formal design process, including ergonomic criteria. An analysis of 277 fatalities associated with ladders was conducted to describe the pattern of ladder fatalities and identify and assess ergonomic design controls. All ladder fatalities analysed were found to contain multiple human, equipment (ladder) and environmental causative factors. It is hypothesized that significant gains with regard to reducing future fatalities can be achieved by applying ergonomic design principles to ladders to accommodate predictable and undesirable human behaviour. Without effective future change, the only prediction that can be made is that the pattern of ladder fatalities will simply continue.

Keywords: Ladder; Taxonomy; Portable ladders

1. Introduction

1.1. *Background*

The fundamental purpose of access systems is to allow humans to move through a height. The design should optimize human safety, performance and comfort in achieving this goal.

Access systems can be divided into two broad categories. First, traditional access systems whereby the human provides energy involved in raising the body through a height and, second, mechanical access systems whereby mechanical equipment provides the energy to raise the body through height.

Traditional access systems, available since prehistoric times, are defined by Templer (1992) in relation to the angle of ascent (or slope) as: ramps (nominally 0–20°, preferably

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0–7°); steps and stairways (nominally 20–45°, preferably 20–35°); and ladders (nominally 60–90°, preferably 70–75°).

Templer (1992) also points out that there is little difference between the design of access systems used in early history and some still used today: 'Stairs, ladders and ramps entered the thesaurus of building components in prehistoric times. Yet even the earliest known and simplest demonstrations are still constructed today'.

Human beings adapt to these access systems, such that the gait pattern adopted, although complex biomechanically, becomes largely an 'overlearned' activity, which takes place almost without conscious control (Hammer and Schmalz 1992).

Ladders present a special case relative to walkways, ramps and stairs, in that:

a) The direction of travel is the same for ascent and descent (i.e. person faces the access system);
b) The centre of gravity of the person moves outside the foot support point;
c) The person marshals more gravitational energy (i.e. can fall from a greater height);
d) Feet and hands are used to maintain balance.

A number of authors have provided insight into the biomechanics and ergonomics of ladder-climbing activities (Dewar 1977, MacIntyre 1983, Bloswick and Chaffin 1987). Ladders can be defined as either portable or fixed, with portable ladders being far the more commonplace.

1.2. *Context – the size and nature of the problem*

Ladders have long been recognized as a potential source of damage to people. The International Labour Organisation's (ILO) Information Sheet on ladders (International Labour Organisation 1966) suggested that about 2% of all occupational incidents reported resulted from ladders.

The ILO information sheet goes on to say:

> Generally speaking, the portable ladder is a rather hazardous piece of equipment and should be employed only where the use of a more suitable means of access is precluded. Wherever possible, it should be replaced, depending on the circumstances, by either fixed stairway, solid scaffolding, stairs with handrails or some other suitable arrangement.

A number of authors have analysed injuries associated with ladders (Cohen and Lin 1991, Bjornstig and Johnsson 1992). Cohen and Lin (1991) studied 123 non-fatal ladder falls resulting in admission to a hospital emergency room. Major mechanisms of ladder falls were categorized as over-reaching (19%), slip on rungs (14%), mis-step on rungs (10%), failure of ladder structure (9%) and being struck by or attempting to catch/avoid falling objects (8%).

Bjornstig and Johnsson (1992) studied 114 ladder injuries based on hospital admissions data. They found the most common incident type involved was falling from straight tilting ladders (73%) followed by falls from stepladders (20%). The dominant mechanism was for tilting ladders to slide outwards on the ground (41%) and for stepladders to displace laterally (48%).

2. Methodology

To establish the pattern of serious ladder incidents (resulting in fatality), an approach was made to the United States Occupational Safety and Health Administration (OSHA) who provided detailed reports of 277 portable ladder fatalities. The reports are based on fatality/catastrophe inspections conducted nationwide by OSHA from 1984 to 1998, which were reported as violations of relevant sections of the Code of Federal Regulations, Labour 29, Part 1926 (US Department of Labour 1995).

The following is an example fatality report, drawn from the data.

****** Incident Data ******

> **6/25/98**
> **Description: Employee killed in fall from ladder after striking head.**
> **Abstract:**
> Employee one was climbing a 4m long ladder to access a landing that was 3m above an adjacent floor. He was carrying a heavy electrical saw. The ladder slid down the wall it was leaning against, causing the employee to fall striking his head on the ground, receiving fatal injuries. The ladder had slip resistant feet, however, it was being used on a dusty terrazzo floor, and was not secured. In addition, the ladder did not extend 3ft above the landing. The employer did not have a ladder safety training program for the employees. The employee was working at a job site where a house was being remodelled. A second storey building was being built on the north half and a garage was being added to the front.

In order to elucidate detailed patterns in the data, the 277 fatality reports were individually reviewed and manually classified by a single injury researcher (i.e. the expert). The classification was completed at the first level according to the types of damaging energy involved. This is based on the concept that injury results from an energy exchange, which goes outside tolerable limits. In epidemiological terms, the type of damaging energy is the agent involved in damage to people, as developed by King (1949), Gibson (1961) and Haddon (1970). Subsequent levels of the taxonomic classification were developed based on the mechanism that led to loss of control; that is, the means by which energy was released, transmitted or transferred (having regard to interactions of the human, energy type and the environment). Where multiple energy types or mechanisms were involved, classification was based on the underlying energy type or mechanism, which directly resulted in fatality (i.e. the most significant energy type or mechanism).

3. Results

Of the 277 US ladder fatalities, 247 involved straight/extension ladders (89%), 16 involved stepladders (6%), four involved fixed ladders (1%) and ten did not specify ladder type (4%).

Figure 1 provides a high-level breakdown of the taxonomy of US ladder fatalities (1984–1998) and reveals 181 ladder fatalities analysed pertaining to falls of people (65%) and 86 pertaining to electrocution (31%). Subsequent levels of detail are available with reference to the taxon numbers, as per figures 2–5.

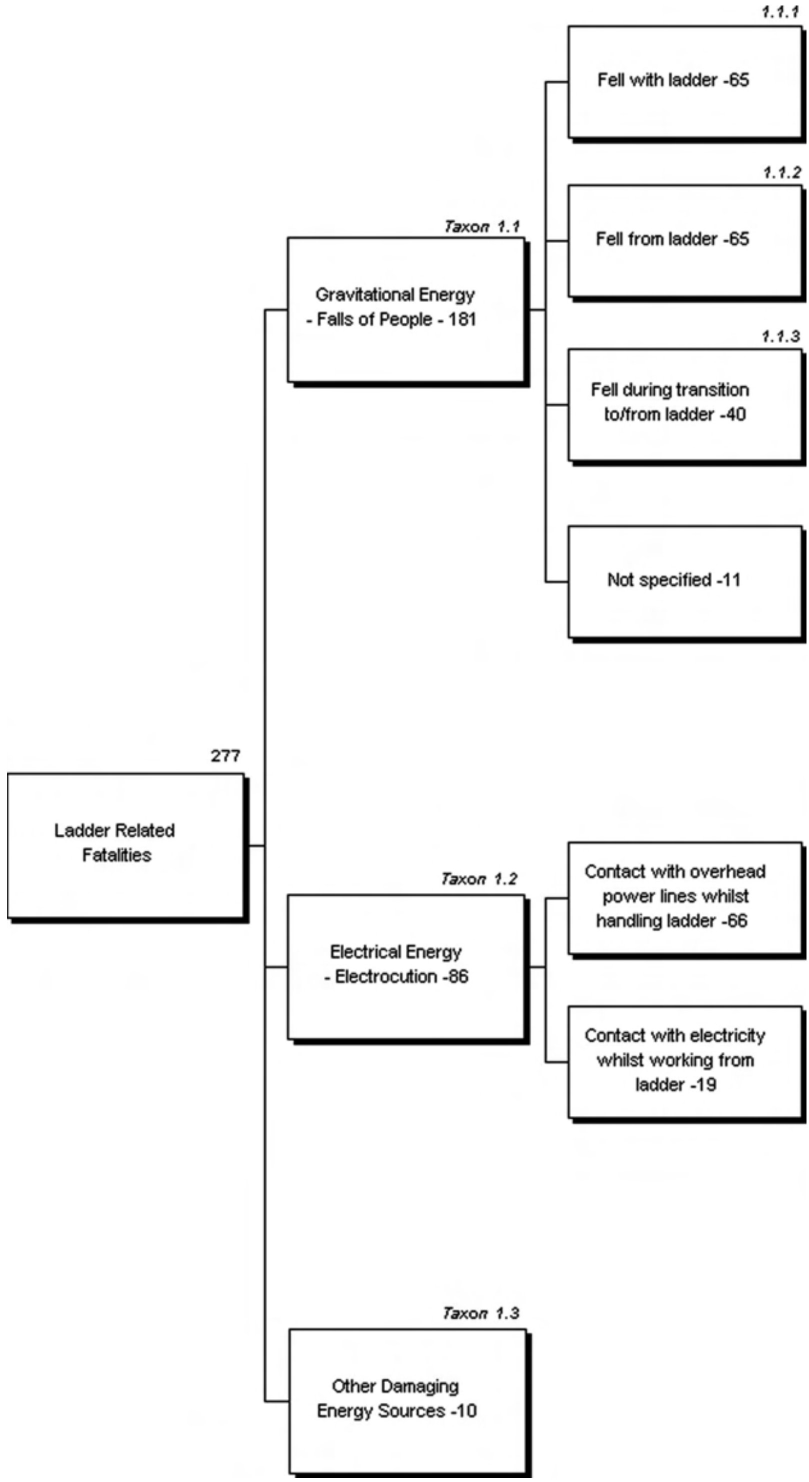

Figure 1. Second level breakdown of the taxonomy of 277 ladder fatalities (1984–1998).

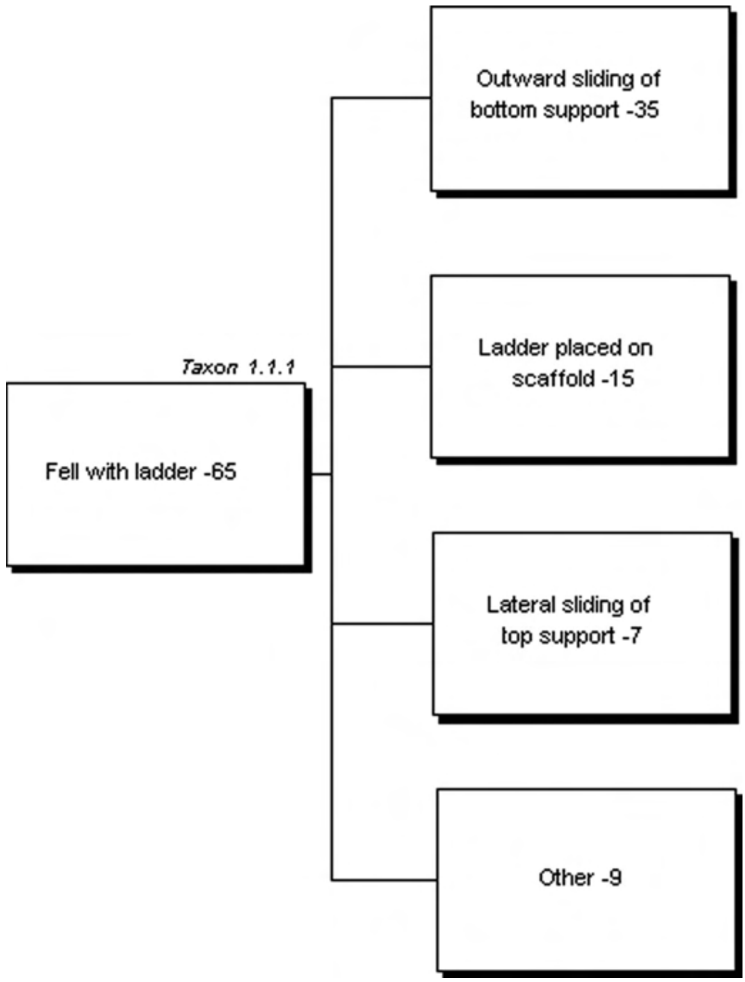

Figure 2. Taxon 1.1.1 fell with ladder.

Figure 2 reveals 65 ladder fatalities analysed pertaining to falls of people with the ladder (23%) with 35 (54% of these) involving outward sliding of the foot off the ladder.

Figure 3 reveals 65 ladder fatalities analysed pertaining to falls of people from the ladder (23%) with 34 (52% of these) involving the person overbalancing, slipping or otherwise mis-stepping whilst on the ladder. A further eight fatalities involved falls of people from the top step of a step ladder (representing 50% of all step ladder fatalities in the sample).

Figure 4 reveals 40 ladder fatalities analysed pertaining to falls of people, which occurred during transition onto or off the ladder (14%) with a range of mechanisms being involved.

Figure 5 reveals 86 ladder fatalities that occurred as a result of electrocution (36%), with the majority (66 fatalities or 77% of electrocutions) involving the ladder contacting overhead power lines during handling.

4. Discussion

Strong patterns emerge with regard to the ladder-related fatalities analysed, which can provide a focus of ergonomic design activity towards major areas of risk. In particular,

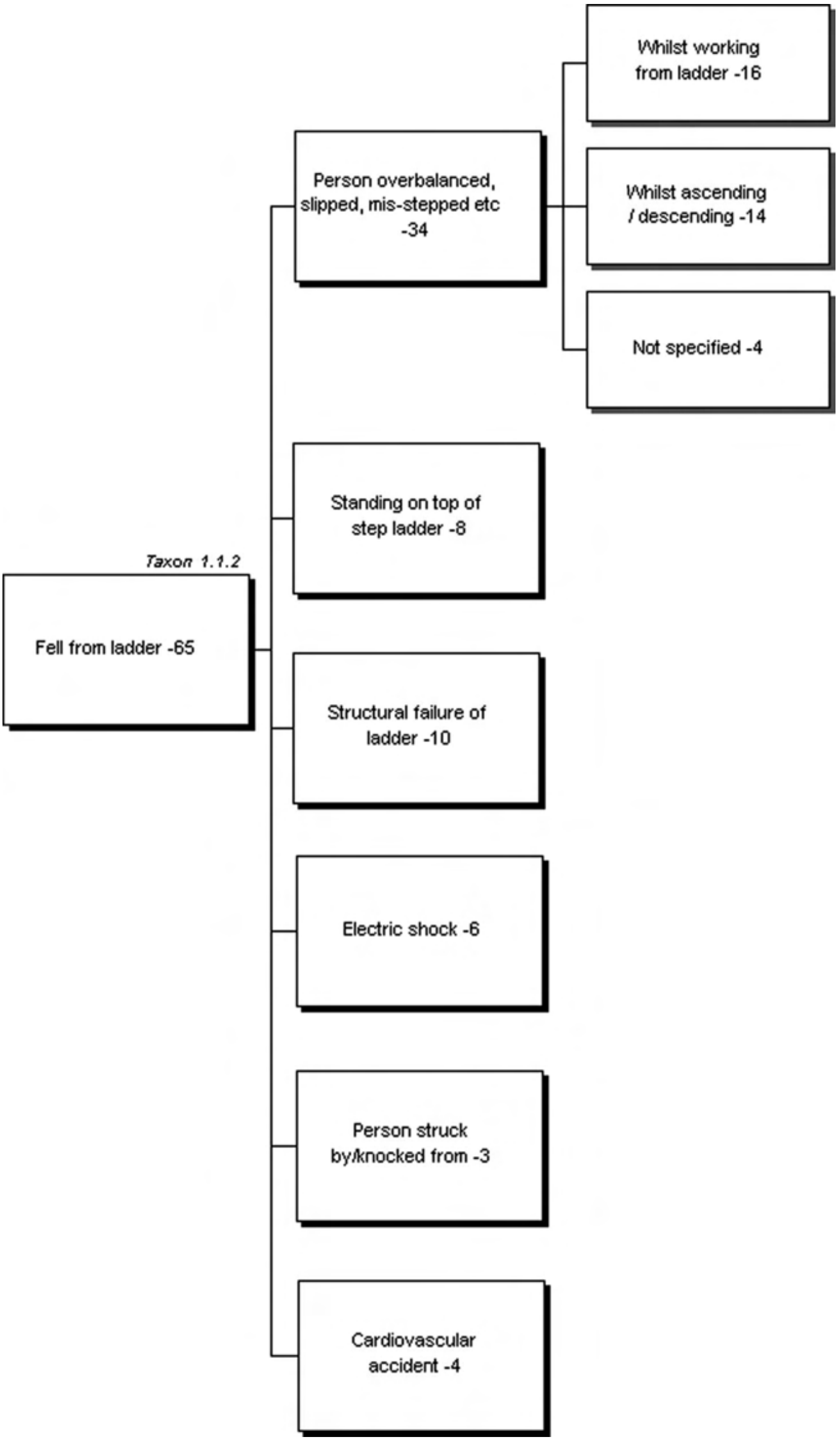

Figure 3. Taxon 1.1.2 fell from ladder.

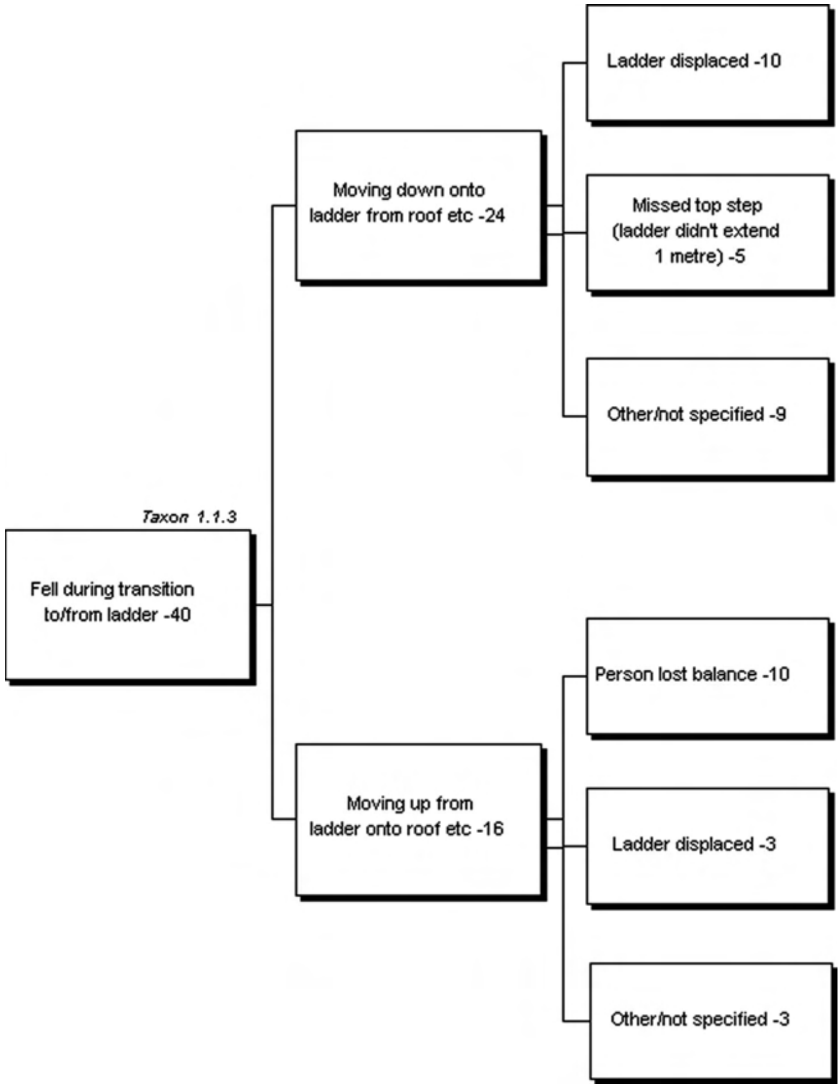

Figure 4. Taxon 1.1.3 fell during transition to/from ladder.

the complete ladder taxonomy indicates that approximately 210 of the 277 ladder fatalities (76% of the ladder fatality problem) can be managed with focus on the following key areas:

1. Electrocution of person whilst handling or working from ladder –86 (31% of the problem, with the majority involving a conductive ladder contacting overhead power lines during handling).
   Common causative factors were found to include:
   (a) People handling ladders (e.g. carrying, erecting and lifting into position);
   (b) Overhead power lines were in close vicinity to work;
   (c) Ladder was 6–12 m long;
   (d) Ladder contacts overhead power lines;

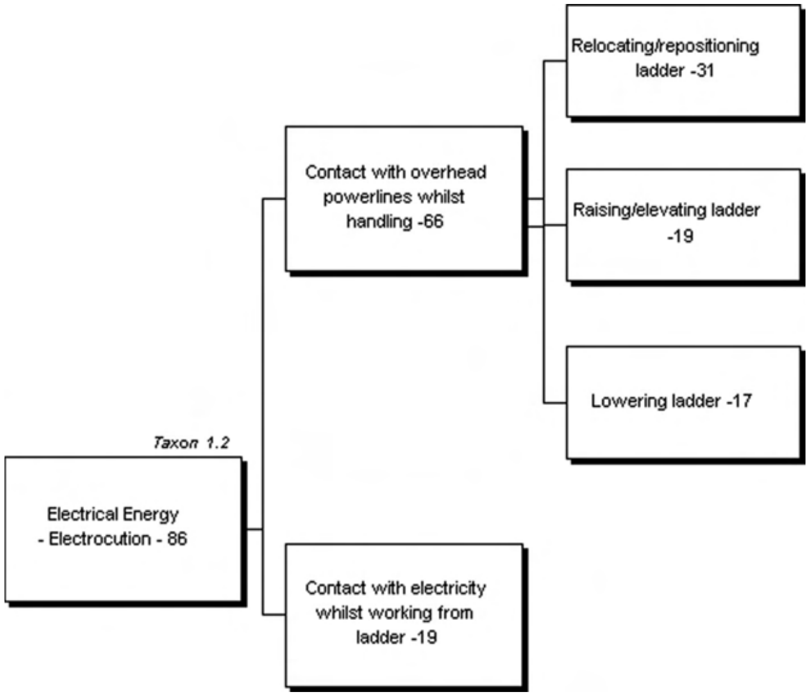

Figure 5. Taxon 1.2 electrical energy/electrocution.

(e) Overhead power lines were not de-energized or insulated (e.g. with rubber line sheaths);
(f) Portable ladder was conductive (e.g. aluminium extension ladder);
(g) Electricity faults to earth through the ladder and person.

2. Person fell with ladder due to sliding of support – 42 (15% of the problem, with the majority associated with outward sliding of the ladder feet, followed by lateral sliding of the top support).
   Common causative factors include:
   a) Person was standing/working on a portable ladder;
   b) The ladder was placed at too shallow an angle (less than 70°);
   c) The ladder was not secured (at the top or bottom);
   d) Friction required by ladder supports was greater than the friction available;
   e) The ladder slipped and the person fell;
   f) The person was not otherwise supported (e.g. fall arrest system).
3. Person fell during transition onto/off ladders (e.g. from roofs) – 40 fatalities (14%).
   Common factors include:
   a) Person transitioning to and from the ladder at a height;
   b) The ladder was not extended sufficiently above the top support point;
   c) The ladder was not secured (at the top or bottom support);
   d) The person was not otherwise supported (e.g. fall arrest system).
4. Person fell from ladder after overbalancing/slipping – 34 fatalities (12%).
   Common factors include:
   a) The person's hand or foot slipped on the ladder rung (i.e. friction required exceeds friction available at the rung);

b) The person was carrying an item and had only one hand available for ladder climbing;
c) The person was not otherwise supported (e.g. a fall arrest system).

5. Person fell from top of stepladder – eight fatalities (3%).
Common factors include:
a) Ladder incorporates a top step, which can be stood upon;
b) Person working from top step (e.g. using both hands overhead);
c) Person becoming unstable and falling to ground.

The challenge in preventing future ladder fatalities is to focus on these key areas and provide equipment that accommodates predictable and undesirable human behaviour. For example, fatalities relating to electrocution after ladder contact with overhead power lines can be prevented by using non-conductive ladders or ladders with insulated segments. Training and procedural controls, such as warning people to 'watch for wires' or 'look up and live', are necessary, but are limited, as they do not manage the damaging energy involved (in this case electricity) nor the propensity for human error to lead to release of this energy. This problem is analogous to crane-related fatalities, where 30–40% result from contact with overhead power lines without there being an insulated link in the system or other effective control employed (Shepherd *et al.* 2000).

Increasingly, there is acceptance of the principle of 'error tolerance' in design, but there remains a need to understand human information detection, processing and execution mechanisms and the way in which these highly complex systems can fail. This is particularly the case for situations where consequences can be severe (e.g. potential for fatality).

5. Recommendations

A number of portable ladder design changes can be proposed, which are focused on controlling the major areas of risk identified previously:

1. Electrocution of person whilst handling or working from ladder – 86 fatalities (31%):
a) Portable ladders to incorporate insulated segments;
b) Provision of non-conductive portable ladders preferably reinforced plastic, which meet the requirements of ANSI A14.5 (American National Standards Institute 1992).
2. Person fell with ladder due to sliding of support – 42 fatalities (15%):
a) Provide measures to facilitate accurate placement of ladder at 70–75°, such as:
(i) Provide a decal on portable ladders illustrating the procedure to obtain an approximate 70° angle of inclination, as per figure 6, which is from ANSI A14.5 (American National Standards Institute 1992), and is based on recommendations outlined by Irvine (1978);
(ii) Provide feedback to operator as to the incline of the ladder (e.g. 'bubble' level or' hanging' arrow as per figure 7).
b) Provide methods to secure the ladder, which are fixed to the ladder (e.g. lashing, straps, ladder stay, or builders hook);
c) Maximize traction at the ladder feet. Ladders can slip outwards on smooth, hard surfaces (e.g. concrete), as well as loose soft surfaces (soil, mud, snow). The management of these problems requires different design solutions:
(i) For smooth hard surfaces ladder feet should be flexible rubber with serrations and incorporate an attitude pad such that contact area is maximized (as per figure 7);

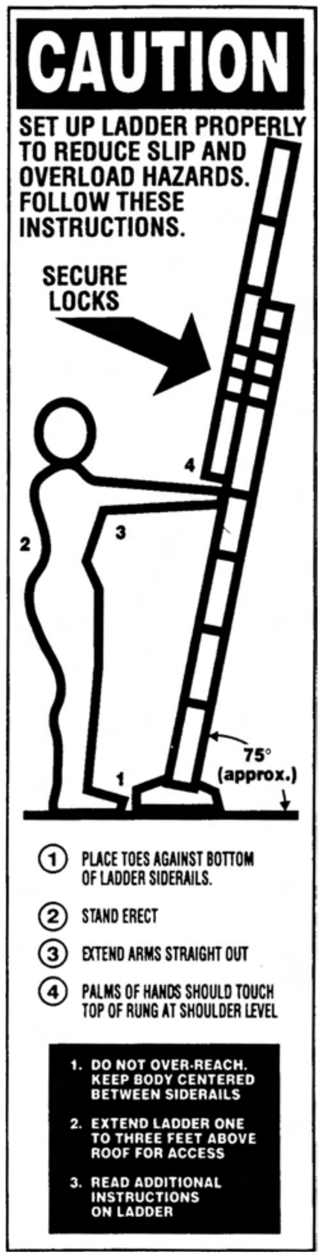

Figure 6. Warning decals for use of ladders illustrating the procedure to obtain an approximate 75° angle of inclination.

(ii) For soft surfaces, a tapered footing is required to anchor the feet (as per figure 7).

It would be desirable if ladders incorporated both designs, such that the appropriate footing could be chosen (e.g. rotate to desired feet design and lock into place).

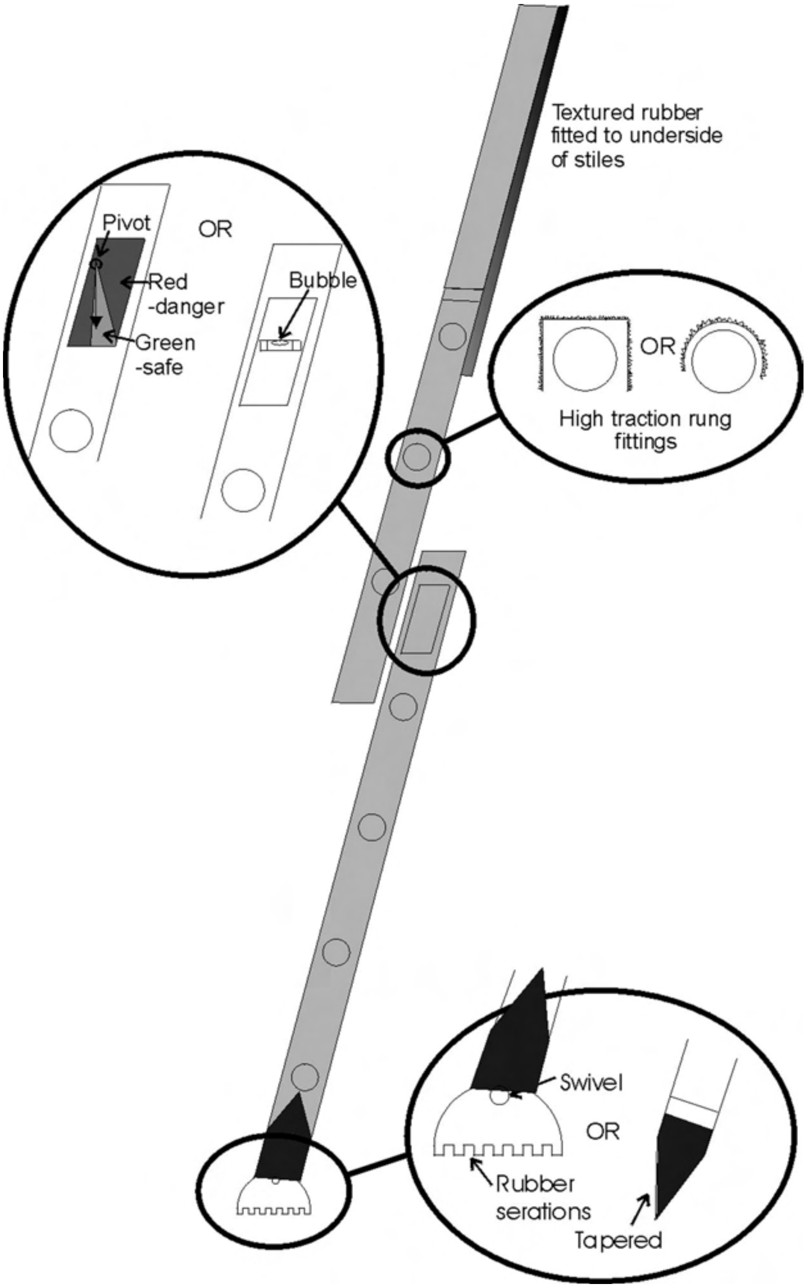

Figure 7. Side view of some proposed design improvements to traditional portable extension ladders (stylized and not to scale).

3. Person fell from ladder after overbalancing/slipping – 34 fatalities (12%):
   a) Ladder rungs to incorporate a slip resistive surface, which can accommodate predictable contaminants such as water, mud, etc. (as per figure 7);
   b) Future consideration to developing a design for barriers/cages to prevent persons working off the side of portable ladders.

4. Person fell during transition onto/off ladders (e.g. onto/off roofs) – 40 fatalities (14%):
   a) Delineate of the top 1m section of ladders, to help emphasis the need to position the ladder at least 1 m above top support;
   b) Implement splayed base for improved stability (see figure 8);
   c) Securing ladder as before.

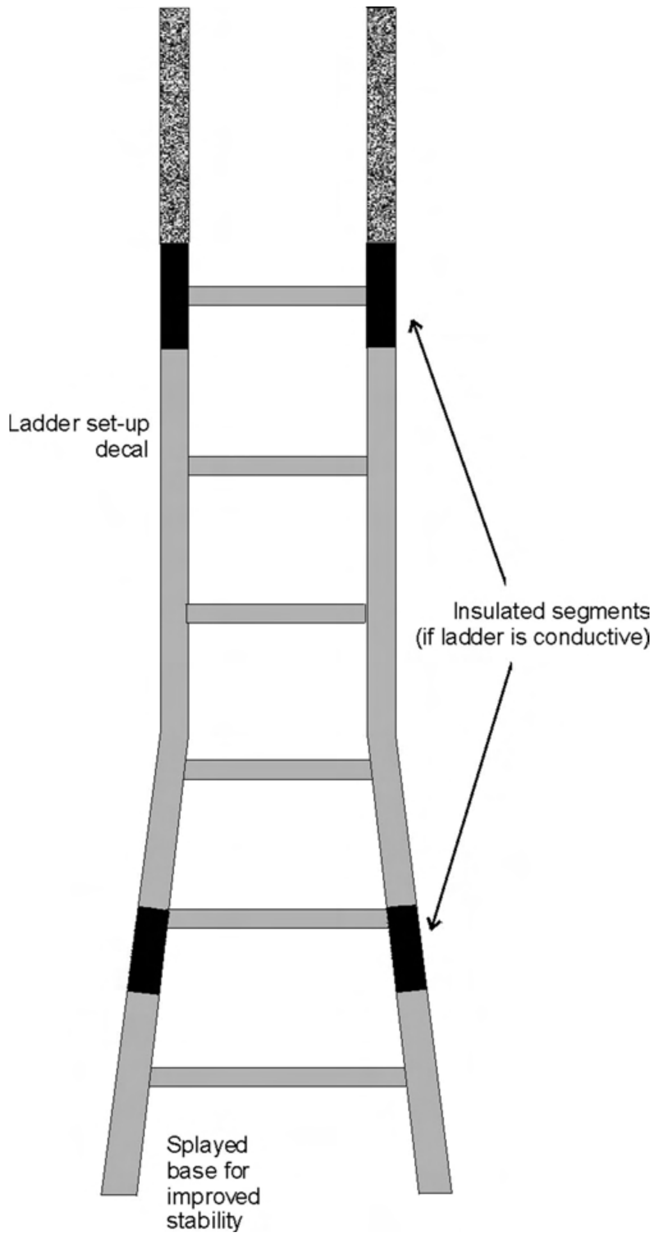

Figure 8. Front view of some proposed design improvements to traditional portable extension ladders (stylized and not to scale).

5. Person fell from top of stepladder – eight fatalities (3%);
   a) Remove top step or ensure it cannot be stood upon and install a top handhold and handrails.

6. Conclusion

A taxonomic classification of 277 ladder fatalities was prepared based on descriptive data supplied by OSHA. It was found that strong patterns emerged and that the taxonomic structure (capturing energy type and mechanism) provided detailed insight into the causative sequence leading to injury. These combined features helped elucidate injury prevention and control strategies focused on the key energy types involved and the interactions that led to release and transfer of that energy. Design changes are proposed to help address the dominant incident types identified.

In terms of applying the findings, it is important to note that the case studies analysed in this study represent a sample of fatal occupational injuries. The elucidation of patterns of fatalities is considered a necessary first step for injury prevention and control; however, it cannot be assumed that similar patterns will emerge from studies of non-fatal ladder incidents or non-occupational ladder incidents. Further work is required to provide similar insight into these areas.

As with all classification systems, valid outcomes depend on the availability of quality of descriptive injury data. This work revealed that OSHA reports based on fatality/catastrophe inspections represent an accessible and high quality dataset. In particular, it was found that each of the 277 OSHA fatality reports pertaining to ladders contained sufficient detail to allow accurate classification by an expert against the taxonomy.

A key methodological limitation is the current need to manually process injury cases. The time-intensive nature of the manual coding process is exacerbated by the need to classify large numbers of cases to yield detailed patterns. The process is also inflexible, in that if a new taxonomy or new dataset is selected, the process must be repeated. To overcome these limitations, computer-based automation of the classification process should be pursued (for example, by applying expert systems technology and knowledge acquisition techniques).

Acknowledgements

The authors would like to thank OSHA's Office of Information Management for supplying the ladder fatality data and the International Society for Fall Protection (ISFP) for supporting the project.

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APPENDIX V:

Injury Knowledge Manager – User Manual

USER MANUAL FOR INJURY KNOWLEDGE MANAGER

This document outlines how to use the Injury Knowledge Manager software tool.

The main window of the system is the *Display Case Window*. It allows the user to analyse and classify each case in the database. The user is also allowed to add/remove classification categories which are displayed on the left hand side of the window.

1. How to Display and Edit the Classification Category Tree

The classification categories (rule conclusions) are displayed in a tree structure within the left hand side panel. The *Root* category is just a default to denote the root of the tree structure. New classifications can be added by selecting a category and then clicking on the *Insert* button. Initially, select the *Root* category and then click *Insert*.

If you wish to add a sub-category to one you have created, e.g. add *Falls of people* as a sub-category to the *Gravitational Energy* category, then select the *Gravitational Energy* node and click *Insert.*

Steps to **insert** a new classification:

1. Select the node in the tree to which you add the classification, e.g. select the *Root* node.
2. Click the *Insert* button. The *Add Category* window will then appear, and the user can add details about the new classification. Once done, the name of the new classification will be displayed in the tree, attached to the selected node.

Steps to **remove** a classification:

1. Select the node in the tree which you want to remove.
2. Click the *Remove* button. The tree will be redisplayed with the remaining nodes.

Note – the Root node *cannot* be removed.

Steps to **edit** a classification:

1. Select the node in the tree you wish to edit .
2. Click the *Edit* button. The *Edit Category* window will appear, containing the name and description of the node. Makes the necessary changes and click *OK* once finished. The edited name will be displayed in the tree.

The classification categories can be read and saved by using the buttons below. This allows the user to input them once only.

- *Open button* – reads a file containing all the classification categories and then displays them.
- *Save button* – saves all the classification categories to a file.

The *Show Rules* button will open a window which displays the last 10 rules for the current case.

File Menu – contains the following options:

- Read Cases – read in saved cases from a file.
- Save Cases – saves cases to a file.
- Read Rules – reads in saved rules from a file.
- Save Rules – saves rules to a file.
- Exit – exits the system.

2. How to Analyse and Classify Cases

The right-hand side panel is used for case analysis. It contains the following features:

- *Case* box – displays current case number.
- *Class* box – displays the system's classification of this case (i.e. energy category). Default value is *No Classification*. It also lists all parent classifications, thus showing the user the branch of the classification tree.
- *Case text* box – contains the actual case text.
- *Prev* button – causes previous case to be displayed.
- *Next* button – causes next case to be displayed.

- *Save Case b*utton – the current case can be edited and then saved by clicking this button.

Note - cases are shown in a circular fashion, e.g. if the user is at case 1, and the *Prev* button is clicked, then the last case in the database is displayed.

3. How to Change the Classification for a Case

If you disagree with the classification chosen by the system and wish to change it:

1. Select the correct classification category from the category tree on the left side of the window.
2. Click the *Change* button – this will take you to the *Make a new rule* window.

Note - if the user forgets step 1 above, then the wrong classification may be given to the case in the *Create Rule* window.

The *Target Class* box displays the correct classification category for this case.

The current case is displayed in a box on the left hand side.

Sometimes, a rule will fire, but the conclusion it gives is still incorrect. In this case, the original case which led to the last rule firing is shown in the box on the right hand side. In addition, the last 10 rules which have fired will be displayed in the *Original Rule* box at the bottom of the window. This is to provide reference data for the user so that they can decide what unique conditions to pick for the new rule, in order for the system to correctly classify the current case.

4. How to Generate New Rules

The *New rule* box at the bottom of the *Make a new rule* window is used to store the conditions for the new rule. Choose conditions by studying the current case and deciding what words, phrases led you to choose the correct classification. Each condition must be separated by a comma. You can choose a condition in the following ways:

- Type words directly into the *New rule* box. Each word, phrase must be separated by a comma, e.g. *cord, electric shock* – this means we have 2 conditions, the case must contain the word *cord* and the phrase *electric shock*.
- Select the text directly from the case and then click the *Grab* button to place the selected text in the *New Rule* box.
- If you want words or phrases to appear in a certain order, use the ‘<’ operator, e.g. *cord< electric shock* – means that we have 1 condition, the word *cord* must appear before the phrase *electric shock* in the case.

Grab button – select condition from current case and click this button to make it appear in the *New rule* box.

Clear button – click this to remove all conditions from the *New Rule* box.

Test button – performs tests as follows:

- Tests if new rule applies to current case. If it does, it asks the user if they want to keep this rule.
- If the rule doesn’t apply to current case, it gives an error message to the user. The new rule text box is cleared and the user is asked to input new rule condition(s).
- The system performs this test only if there is an original case displayed and the new rule is valid for the current case. It tests the new rule against the original case. If the new rule applies to this case as well, there could be a conflict resolution problem.

Done button – once satisfied with the new conditions, click this button so that the system can create a new rule. An error message is given if the new rule does not apply to the current case. If the rule is valid, the new classification for this case will appear in the *Class* box of the *Display Case Window*. This window will then disappear.

APPENDIX VI:

Injury Knowledge Manager – Technical Documentation

TECHNICAL DOCUMENTATION FOR INJURY KNOWLEDGE MANAGER

This document describes the various Java classes that comprise the Injury Knowledge Manager programming tool. It will also detail how these can be wrapped up in a .JAR file ready to be executed.

The system consists of code which creates the various Graphical User Interfaces (GUIs) and the back-end which contains the actual ripple-down rule (RDR) system. The flow of the code is as follows:

1. Set up the main window – called the *Display Case* window.
2. Read in all the cases from a data file and store in a database represented by a Java Vector.
3. Display the first case with the default classification in the *Display Case* window.

After these steps, it is up to the user how they proceed.

There are 3 GUIs:

- *Display Case* – the main GUI, which displays the classification categories and the current case with its conclusion (i.e. classification).
- *Add Category* – allows the user to add a new category to the classification tree.
- *Make a new Rule* – allows the user to create a rule.

Java Classes which Create the GUI Windows

MainClass.java – the class which starts the whole system running. Calls *MainFrame.java* and sets up values on how to display the main window.

MainFrame.java – creates and runs the *Display Case* window. Performs following tasks:

- Sets up all the components of the Display Case window.
- Calls code to set up database of cases.
- Displays the first case.
- Contains all methods to deal with clicking buttons or choosing menu options. Note that when reading/saving rules or cases to a file, the *Java serializable interface* is used. This data is not saved or read as ordinary text.

AddConceptDialog.java – displays *Add Category* GUI. Performs following tasks:

- Sets up components for the Add Category window.
- Reads in new classification category name.

EditConceptDialog.java – displays *Edit Category* GUI. Performs following tasks:

- Sets up components for the Edit Category window.
- Reads in any edited classification name or description text

MakeFrame.java – displays *Make a new Rule* window. Performs following tasks:

- Sets up components for the Create Rule window.
- Displays cornerstone case and any rules fired, if required.
- Reads in conditions and conclusion to create new rule.
- Adds node containing new rule and current case to the RDR tree.

RulesTestMsg.java –

- Displays various windows giving messages as to whether or not the new rule input is valid for the current or cornerstone case.
- Creates the window for displaying last 10 rules fired for a case.

Java Classes to Simulate Database

DataCase.java - object which stores a case. Attributes are the case number, the case index number and the case text.

Database.java - contains a Vector which stores each case as a *DataCase*. Allows insertion and removal of cases.

DatabaseMan.java - Loads in data cases from text file (currently *workplace.dat*). Each case is stored in the database as a *DataCase* object. Also saves database to a specified file.

Java Classes which Implement the Category Classification tree

Concept.java –object stores the category name and its description. It is used to store the classification names displayed in the classification category tree.

ConceptTreeModel.java – implements Java TreeModel to allow classification category tree to be displayed in main window.

Java Classes which Implement the RDR system

BinNode.java
Object stores essential data for each node of the RDR Tree such as rule, conclusion, cornerstone case, pointers to the true and false branches, and pointer to its parent node.

Conclusion.java
Object which stores name and description of conclusion of a rule, e.g. a classification category. It does this by using a *Concept* object.

Rule.java
Stores conditions of rules.
Fire() method checks whether or not rule conditions appear in the current case.

InferEngine.java

Contains methods for firing rules – starts from the root node of the RDR tree and traverses until a node fires or end of tree reached. Pointers kept as to where any new nodes should be added.

TraverseTree.java, Queue.java – used to output RDR tree node values in breadth-first order.

Creating the TAR file

The code is executed by running it from a .tar file, e.g. *injuryRDR.tar*. The following files need to be placed in the .tar file:

- All Java classes
- File containing the cases.
- Images needed for the GUIs

To create a .tar file, input the following command:

tar cmvf injuryRDR.tar classfile /injuryRDR workplace.dat /images

- The Java classes are in the directory */injuryRDR*
- The images are in the directory */images*
- *workplace.dat* contains all the cases as text
- *classfile* contains the line:

Main-Class: injuryRDR.MainClass

This tells the system to start running the injuryRDR system from the *MainClass* file.

Before running the *tar* command, make sure that all files are in directories which reflect their package names, i.e. all the Java classes should be in a directory called *injuryRDR* since they belong to this package.

APPENDIX VII:

Case Study: Australian Drill and Blast Incidents, 1993-1998

(n=456)

PATTERN ANALYSIS OF DRILL AND BLAST INCIDENTS IN THE OPEN CUT MINING INDUSTRY

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KEYWORDS

Open Cut Mining, Drill and Blast, Pattern Analysis, Incidents, Accidents, Dangerous Occurrences

ABSTRACT

An analysis of 456 drill and blast incidents in the open cut mining industry is presented. The study is based on injury reports supplied by Queensland and Western Australian Departments of Minerals and Energy and reported dangerous occurrences (or near-misses/hits) supplied by the New South Wales Department of Mineral Resources.

Analysis of drill and blast incidents which resulted in injury (Qld and WA data) revealed a distinct pattern. Over 80% of occurrences result from three types of damaging energy: gravitational energy – falls of people (26%) and falls of objects (12%); human energy – lifting/pushing/pulling (25%), and; machine energy – caught in and struck by (22%).

Analysis of reported dangerous occurrences (NSW data) revealed a fundamentally different pattern. Over 80% of reports relate to two types of damaging energy: thermal energy – fires on the drill rig (42%), and; vehicle energy – minor collisions and overturns (42%).

The significant discrepancy between the pattern of injury (Queensland and WA data) and reported dangerous occurrences (NSW data) indicate that perceptions of risk do not reflect the reality of how people are injured.

INTRODUCTION

This study provides a description and analysis of 456 incidents relating to drill and blast activities in the open cut mining industry. Approximately 90% of the incidents are associated with production drilling, with the remainder associated with exploration drilling.

The objectives of this study are to:

- describe the pattern of drill and blast incidents;
- compare the pattern of actual injuries and reported dangerous occurrences;
- identify priority areas which produce the majority of damage;
- establish key focus areas for future control.

METHODOLOGY

"*The employer who wants to prevent injuries in the future, to reduce loss and damage, and to increase efficiency, must look systematically at the total pattern of accidental happenings – whether or not they caused injury or damage – and must plan a comprehensive system of prevention rather than rely on the ad hoc patching up of deficiency which injury or accidents have brought to light.*"
Robens Committee 1972

An approach was made to key government agencies within Australia to supply descriptive data regarding drill and blast incidents, with the following data being supplied:

- 214 lost-time injury reports from 1983-1998 (involving lost time of one shift or more), supplied by the *Queensland Department of Minerals and Energy;*
- 128 injury reports from 1994-1998, supplied by the *Western Australian Department of Minerals and Energy*;
- 114 reported dangerous occurrences (no injury) from 1989-1998, supplied by the *New South Wales Department of Mineral Resources*.

Sources at the United States Mine Safety and Health Administration and the South African Department of Minerals and Energy were also approached, but were unable to supply descriptive data regarding drill and blast incidents.

The incident data was then classified to elucidate patterns. A most effective way to classify incident data is according to the types of damaging energy involved. This is based on the concept that injury (or damage) results from an energy exchange which goes beyond tolerable limits of humans. In epidemiologic terms, the type of damaging energy is the "agent" involved in the injury (Gibson, 1961). Insight into the damaging energy involved allows control measures to be focussed on preventing, mitigating or otherwise managing the damaging energy exchange. A commonly used classification of damaging energy types is provided as Table 1.

RESULTS

It would be ideal to combine the Queensland, Western Australian and New South Wales drill and blast incident reports. However, the Qld and WA data cannot be validly integrated with the NSW data as the populations are significantly different (actual injuries versus reported dangerous occurrences).

Instead the Qld and WA data can be combined and compared with the NSW data as follows.

Pattern of Drill and Blast Injuries (Qld and WA data)

When assimilating the Queensland and Western Australian injury data the total number of reports becomes:

214 (Qld) + 128 (WA) = 342

The following damaging energy types were identified as being associated with the greatest number of injuries:

1. Gravitational Energy:

   – Falls of people (86 or 26% of injuries, as per **Figure 1**)

   Common fall mechanisms involve:

   - Person stepping from machine to ground, commonly involving uneven ground surfaces and high or swinging bottom steps/rungs;
   - Slips and falls on drill rigs (to the same level and to a lower level), involving contamination of underfoot surfaces and slipping whilst manually handling objects such as drill rods and drill bits.

   - Falls of objects (40 or 12% of injuries). More than half of these are associated with the person being struck by a falling drill rod (e.g. resulting from the drill rod pivoting/breaking free whilst disconnecting, or falling whilst removing and reseating the drill rod). The remainder involved persons inadvertently dropping objects including head rods, spanners, drill hammers onto feet or hands etc. There are two reported cases of injury resulting from the drill mast collapsing and falling.

2. Human Energy – lifting, pushing/pulling, impact etc (85 or 25% of injuries, as per **Figure 2**)

Common injury mechanisms involve:

- Person lifting or carrying heavy objects such as drill rods, drill cables etc;
- Person impacting their hands and fingers while working;
- Muscular strains and sprains after recovery from slips and trips.

3. Machine Energy - caught in/struck by moving parts of drill rig (75 or 25% of injuries, as per **Figure 3**)

Common injury mechanisms involve:

- Persons hand caught in rotating equipment such rotating drill rods and chain/sprocket assemblies;
- Person struck by items such as descending drill heads or stilsons wrench when attached to the drill rod.

Pattern of Reported Dangerous Occurrences (NSW data)

The following damaging energy types have been identified as being associated with the greatest number of reports of dangerous occurrences (NSW data, n=114).

1. Thermal Energy (48 or 42% of dangerous occurrence reports, as per **Figure 4**)

Most of these dangerous occurrences involve drill rig fires. Common ignition mechanisms include:

- failure of hydraulic hoses, and the subsequent spraying of fuel/oil onto hot components;
- electrical related fires resulting from short circuits due to insulation being worn, abraded or melting.

2. Vehicle Energy (48 or 42% of dangerous occurrence reports, as per **Figure 5**)

Most of these occurrences are minor collisions and near overturns, including:

- minor collisions between drill rig and utility vehicles (with one vehicle stationary);
- perceived near overturning of the drill rig during setup or operation.

DISCUSSION

Comparison of the pattern of drill and blast injuries (Qld and WA data) and reported dangerous occurrences (NSW data) reveals significant differences. **Figure 6** is a chart showing the percentage involvement of damaging energies for the two datasets.

With respect to dangerous occurrences, it is apparent that there is a high level of reporting of incidents involving thermal energy (fire) and vehicle energy (collision and overturns) but a gross under-reporting of incidents involving gravitational energy (falls of people and objects) and human energy (lifting, pushing/pulling).

In short, reports of dangerous occurrences (or near-misses/hits) do not match the pattern of actual injuries. There are likely to be a range of explanations for this, including: misperceptions of risk; the subjective and personal judgement required to define a dangerous occurrence, as well as; the tendency to report incidents which result in equipment damage and under-report incidents which do not result in personal injury.

Such comparisons give insight into the need for organisations and governments to avoid relying solely on reported dangerous occurrences when attempting to predict future high risk exposures.

Given that over 80% of the cost of workplace incidents in Australia results from 13% of permanent injury incidents (Australian Industry Commission, 1995), it is contended that there is a need to understand the pattern of permanent injury, and effectively direct resources towards these major areas of risk.

Unfortunately, State Government reporting systems for drill and blast incidents do not capture the likely severity of injury. It is therefore important to recognise that the Qld and WA injury data include temporary and permanent injury, whilst the NSW data is based on dangerous occurrences (no injury).

With these qualifications in mind, the pattern analyses of drill and blast injuries and reported dangerous occurrences highlight the following priority areas requiring control:

1. Gravitational energy:
   - Falls of people, particularly drill rig access/egress and slip and fall occurrences on/around drill rigs. Drill rig access can be optimised by removing vertical stepladders and providing formal access systems, such as hydraulically

actuated stairway access systems (available for larger rigs). Slip-resistive surfaces should be implemented to cope with the predictable range of contaminants.

- Falls of objects, particularly falls of drill rods and falls of the mast. Reliable engineering controls should be in place to prevent the problem of drill rods pivoting or breaking free and falling whilst disconnecting, removing or reseating the drill rods. As a minimum, formal inspection systems should be in place to ensure mast mounting point integrity.

2. Human energy - particularly lifting, carrying and manoeuvring heavy objects such as drill rods, drill bits and drill cables. Materials handling equipment such as hydraulic jibs and truck/utility-mounted cranes should be provided and used to lift and transport all heavy equipment.

3. Machine energy - particularly people becoming entangled in the rotating drill rod or pulled into chain/sprocket nip points. It should be ensured that there is sufficient guarding or other protection on all moving parts as is required by Australian Standard AS 4024.

4. Vehicular energy, particularly minor vehicle collisions and near overturns. Vehicles should be fitted with a roll over protective structure (ROPS) and be fitted with effective indicators of acceptable operating slopes.

5. Thermal energy (fire). It should be ensured that there is an adequate emergency response to drill rig fires including appropriate communication and fire-fighting

capacity. Components which become hotter than the auto-ignition temperature of oil should be protected from likely oil sources by a barrier.

CONCLUSIONS

This paper presents outcomes of a study of 456 Open Cut Mining drill and blast incident records held by Queensland, Western Australian and New South Wales Government Departments.

Strong patterns emerged out of the analysis of drill and blast related injuries, allowing for identification of dominant energy types and mechanisms of injury, as well as key focus areas for future control.

A key finding was that the pattern of drill and blast incidents which resulted in injury is vastly different from the pattern of reported dangerous occurrences. It appears that perceptions of risk do not match the reality of how people are injured. This work emphasises the limitations of attempting to predict future high risk exposure by relying solely on the pattern of reported incidents (which may be dominated by reports of dangerous occurrences and near-misses).

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