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An integrated industrial risk assessment methodology for accident safety, chronic health, and chemical exposure

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Abstract

Context – Industrial safety primarily uses ISO31000 risk assessment based on consequence and likelihood to anticipate and prevent accidents. The method focuses on avoiding the occurrence of temporally immediate biophysical harm. Chronic health conditions are more difficult to include, as the harm is not necessarily immediate and the consequences can remain long after the hazardous event is removed. Furthermore the consequence scales vary for the different hazards. In the case of chemical hazards, the Globally Harmonised System (GHS7) measures these by severity (dose required for death), but this metric is incompatible with the graduated harm scales used in ISO31000. Consequently it is difficult to include chemical hazards in the methods used for other workplace hazards. There is a need for a single integrated method that can accommodate all aspects of industrial safety.

Approach – The GHS7 chemical exposure scale is reworked and extended to non-death outcomes to make it compatible with the ISO31000 Risk management approach.

Originality – A set of three harmonised consequence scales are developed for safety (immediate accident consequences), health (long term & chronic ill-health), and chemical exposure (death as well as less severe outcomes). This allows a single ISO31000 compliant methodology to be used.

Keywords: health and safety; hazard; occupational health;

1 Introduction

Risks are possible future events that might happen. The term has variable usage, and can either mean the chance of an event, or the combination of consequences and the likelihood of those consequences. In industrial health and safety (H&S) it refers to possibility of harm. A common industrial approach is to use the ISO31000 risk management method (ISO 31000, 2009) which partitions risk into consequence and the likelihood of the consequence arising(SAA/SNZ HB436, 2004). The assessment process involves identifying the hazards, anticipating their potential for harm (consequence) and the likelihood of that harm arising. Those assessments are based on the existing state of the safety management system, i.e. the level of protection already in place to prevent the root cause arising or preventing it propagating to a harmful outcome. More sophisticated methods, such as bowtie analysis, are available to represent the barriers on that propagation pathway(J. Aust & Pons, 2020). However this is beyond the basic implementation of ISO31000.

In the basic risk assessment process, the combination of consequence and likelihood determines the overall risk. This may be done with either quantitative or qualitative methods. The risks may then be prioritised and treatments devised for the more significant risks. This method has widespread use, and is the basic approach to due diligence with legislative expectations for industrial safety. The method is best suited to analysing hazards that produce an immediate biomechanical injury.

The ISO31000 process is well-suited to assess those hazards that result in immediate physical harm consequences, such as accidents. There is a physical causal sequence of events, and an immediate biomechanical injury outcome. These may be termed *safety* hazards(Ji et al., 2020). The immediate biophysical nature of hazards is evident in the NZ legislative definition of notifiable injuries(NZ Govt, 2015b), which refers to amputation, head injury, eye injury, burns, lacerations, and any other injury requiring immediate hospital admission.

In contrast there are also *health* hazards for which there is no immediate biomechanical injury, but rather the consequences only become apparent later - sometimes very much later. Effects can also be cumulative. Hence the onset of symptoms may only be apparent in returement years, and difficult to attribute to an individual work episode or workplace. An example is hearing loss from noise exposure. This has negative consequences later in life, such as inability to talk with friends and family, and hence contributes to social isolation and loneliness. Quality of life metrics are good at measuring these effects, but industrial risk assessment is not.

Health hazards are difficult to detect at the workplace because their consequences are not immediately evident. Hence chronic health hazards may be overlooked in basic industrial risk assessments.This has the further difficulty that immediate treatments are not provided, and depending on the jurisdiction the worker may be disqualified for funded rehabilitation or work compensation. For example in New Zealand this disqualification applies. Furthermore, the effects of exposure may be cumulative, in complex ways that also depend on unknown characteristics of the individual person.

From the perspective of someone in industry conducting a hazard assessment for a technical system, this uncertainty is problematic. There needs to be an objective method to attribute *health* consequences to a specific operational activity. A solution exists for this part of the problem, in the form of the diminished quality of life (DQL) method(Ji et al., 2021). As the name suggests, this uses a *quality of life* score which is a concept from public health. The specific score used was the World Health Organisation Disability Assessment Schedule WHODAS(Chiu et al., 2014; Üstün, 2010), which measures loss of quality of life in terms of functional disability and social isolation. This approach is in contrast to the more technically-focused method for measuring chronic harm, which is *disability adjusted life years* (DALY) that takes death as the parameter of interest.

Chemical hazards are another type of hazard, for which rapidity of death is the conventional consequence metric. However the death metric makes it difficult to integrate chemical hazards with other types of industrial safety because the scales are so different. There is a need to harmonise the consequence scales for all these types of harm: immediate accident consequences; long term & chronic ill-health; and chemical exposure. Doing so has the potential to provide a unified and coherent approach to the hazard assessments used by industry.

This has the further potential benefit of helping industry with their legal responsibilities. Specifically, the New Zealand Health and Safety at Work Act (NZ Govt, 2015a) requires chemical hazards to be assessed, and identifies chemicals as ‘any natural or artificial substance in any form’. The breadth of this definition, plus the lack of specificity in the act about the means for this to be accomplished, is problemmatic from a practitioner perspective. This paper describes the development of a novel method to integrate chemicla hazards into basic risk assessment.

2 Chemical hazards

General context

Common chemical hazards in the workplace are poisons (herbicides, pesticides, rodent poison, disinfectants), heavy metals (lead, cadmium, mercury), reactive substances (acids, caustic, chlorine, cleaning products), solvents (paint thinners, glues), petroleum products (diesel, bitumen, petrol, lubricants), dust (asbestos, silicon), food additives. This list and the examples are not exhaustive.

Typical direct types of harm from a human perspective are toxicity, corrosion, fire, and explosion. Toxicity refers to disruption of physiological function, e.g. poisons and carcinogens. Skin damage is another important category of harm. The main routes into the human body are by ingestion (swallowing), touch, and respiratory (breathing).

There are also indirect or secondary channels of harm, whereby the substance is liberated to the environment, and people are harmed by environmental exposure. Often this secondary channel has the potential to affect many people, and the substance may be insidious and difficult for the wider public to detect. The environmental harm also extends to other life forms and ecosystems generally.

The main methods for preventing chemical harm are warning labels on the containers, safety data sheets describing the hazards for the substance, appropriate procedures for handling the substance (including PPE and cleaning), keeping an inventory of substances on site, and storage facilities (including not storing mutually reactive substances together, ventilation, and prevention of accidental environmental discharge). Disposal of residue substance and containers is also important, because this can lead to undetected environmental discharge.

Classification of chemical hazards

Much of the prevention of chemical hazards depends on the accurate identification and labelling of substances. This is facilitated by the Globally Harmonised System (GHS 7), which is a method for classifying chemical hazards(UNECE, 2017). The GHS *hazard classes* are physical, human health, and environment:

- Physical hazards, i.e. explosion, flammability, self-reactive substances, oxidising substances, corrosive substances.
- Human health hazards, such as acute toxicity (oral, dermal, inhalation), eye irritation, carcinogenicity, reproductive toxicity.
- Environmental hazards, i.e. eco-toxicity to the aquatic and terrestrial environments.

The GHS7 system is mainly used to determine labelling requirements, safety data sheets, and to provide instructions on how to store, use and dispose of the products. It is not primarily a risk assessment mechanism, at least not like the ISO31000 risk management approach.

The GHS has been progressively developed over the years, and version 7 was in place at the time of writing. Originally a European development, it has subsequently been adopted by other nations, for example New Zealand adopted the GHS7 in April 2021, which replaced the former Hazardous Substances and New Organisms (HSNO) classification system.

Health severity in the GHS

The health severity category is determined from the 'acute toxicity estimate' (ATE) as
$ATE = LD_{50}/LC_{50}$
where

LD_{50}	Lethal dose: the amount of the substance, administered in one bolus oral/dermal dose, that kills 50 percent of people (or organisms, typically a rat or rabbit). The dose is assumed to be proportional to body weight.
LC_{50}	Lethal concentration: the amount of the substance in air or water that over a 4 hour exposure will kill 50% of organisms within 14 days. The dose is measured as concentration.

Smaller ATE values are more toxic. Both LD_{50} and LC_{50} are measures of concentration, so the overall dependency of the ATE equation is approximately concentration squared. Values for ATE range from below 5 to 5000. A value of $ATE \leq 5$ is category 1, the most toxic.

The typical hazard labelling statements from GHS Table 3.1.3 are paraphrased in Table 1.

Table 1: Hazard statements on labels depend on the severity category.

Category	Category 1	Category 2	Category 3	Category 4	Category 5
"Hazard statement"	"Fatal if swallowed, contacted, or inhaled"	"Fatal if swallowed, contacted, or inhaled"	"Toxic if swallowed, contacted, or inhaled"	"Harmful if swallowed, contacted, or inhaled"	"May be harmful if swallowed, contacted, or inhaled"

Adapted from(UNECE, 2017).

Separately there is a *hazard category* which is a severity factor [1…5] with 1 the most severe. However this is incompatible with the ISO31000 risk formulation.

Other terms related to toxicity, though not used in the GHS are shown in Table 2.

Table 2: Additional terms related to toxicity

No Observed Adverse Effect Level (NOAEL)	The highest ingested exposure that is without adverse effect. Alternatively, the threshold of ingested exposure beyond which statistically significant adverse biologically events are detected.
Lowest Observed Adverse Effect Level (LOAEL)	The lowest exposure that causes an adverse change in the organism. This may also be measured in terms of concentration, hence LOAEC.

The nature of these toxicity tests is dependent on the protocols and admission criteria for the organisms(WHO, 2000). The NOAEL and LOAEL complement each other by exploring the thresholds from different directions.

Critique of the GHS

From a risk perspective, the measure of toxicity ('categories') in the GHS7 is natively unsuitable for a risk assessment scale, for several reasons.

First, it is based on the level of harm that arises immediately or shortly after exposure. It has no provision for chronic harm, cumulative effects over time, or delayed onset harm.

Also it does not experimentally measure augmented effects of mixtures of toxins, rather it treats them as independent. For example, if all the substances in a mixture are in the same severity category, then the mixture itself is deemed to be in the same category. This is not a conservative assumption.

Furthermore it only measures harm in terms of death. It ignores the fact that quality of life may be greatly reduced even if a person does not die. Hence it also ignores disability as an outcome of exposure. The GHS implicitly makes the naïve assumption that a person will either die from exposure, or not be affected at all, and if they are ill for a while they will make a full recovery. In practice there are many other outcomes possible, such as shortening of life, degradation of bodily function, or disfigurement (with loss of self-esteem).

In addition, the GHS provides no link between its categories and the type of harm that occurs to people. Harm can occur to different parts of the human body, e.g. skin, lungs, liver, etc., and the health consequences can be profoundly different, with death not necessarily being the outcome. This is related to the GHS simplistic use of death as a measure of outcome.

Consequently it is difficult to integrate the GHS with the conventional ISO31000 risk assessment process. This is problematic as the ISO31000 method underpins most industrial assessments of H&S, whereas the GHS is the basis for the toxicity information available at the workplace. There is a need to reconceptualise the chemical toxicity risks, so they can be included alongside the other risks in the workplace. This is important as chemicals are found throughout workplaces, and hence their hazards exist alongside other types of hazards.

3 Method

The objective of this work was to find a way to integrate the chemical hazards into the risk management process. In doing so, the GHS should be preserved – or at least elements of it – since it is the dominant methods for identifying hazards of common workplace chemicals, and it has the additional benefit of being explicitly stated on the containers. Hence the GHS information is accessible, via the labels, to workers in a way that is not achieved to a comparable level with machine safety. On the other hand, the ISO31000 risk assessment method is also dominant in industrial safety, in its provision of the conceptual foundations of risk being the product of consequence and likelihood, and documented in a risk register, and this also needs preservation.

The present work extends previous work (Ji et al., 2021) which provided a method for harmonising the consequence scales for short term safety accidents, and long term (including chronic) health outcomes. It used the WHODAS disability score(Chiu et al., 2014; Üstün, 2010), which measures loss of quality of life. In turn (Ji et al., 2021) was a further development of (Pons, 2019) which conceived of a method to align the hazard assessment with the categories of harm in the national legislation, with New Zealand (NZ) as the jurisdiction under examination. The latter is an important consideration for practitioners because of the need to do due diligence to the legal requirements of the jurisdiction with its definitions of serious harm. Hence the combination of (Ji et al., 2021) (Pons, 2019) already provided (i) a set of harmonised scales for short-term and long-term harm, (ii) integration into an ISO31000 compliant risk matrix, and (iii) demonstration of how to align the risk assessment consequences with definitions of harm in H&S legislation. While the latter attribute was only demonstrated for the NZ jurisdiction, it is believed to be more widely applicable because of the underlying commonality and increased convergence of H&S systems across jurisdictions.

The present paper devises a scale so that chemical hazard may be included as a third consequuence scale in the integrated hazard assessment. This scale was derived from the GHS, but required some adjustments, especially at the lower level of harm where the GHS is silent. The particular problem of the GHS is the asymmetrically bias towards death outcomes. It does not include the minor harm consequences that feature in the conventional hazard assessments, and which are so important in detecting incipient weaknesses in a safety management system. Likewise the ATE numbers themselves are not helpful in a risk assessment, even if known. To solve this it was necessary to find more descriptive words for the GHS severity categories, and then broaden to non-fatal levels of harm.

4 Results

Finding more descriptive words for the GHS severity categories

The Hodge and Sterner descriptors (Hodge & Sterner, 1949) were used to re-word the GHS severity categories. They provide six levels: extremely toxic; highly toxic; moderately toxic; slightly toxic; practically non-toxic; and relatively harmless. Each of these also has a ‘probable lethal dose for man’ in units that people can easily understand, e.g. ‘One drop is fatal’ corresponds to ‘extremely toxic‘. Elsewhere the top five levels have been mapped to GHS Categories 1-5, e.g. in the Canadian jurisdiction(CCOHS, 2021), see Table 3.

Table 3: Descriptive labels for toxicity, from (Hodge & Sterner, 1949) and(CCOHS, 2021).

Toxicity Rating	Commonly Used Term (Hodge & Sterner, 1949)	Probable Lethal Dose for an adult human (Hodge & Sterner, 1949) (CCOHS, 2021)
1	Extremely Toxic	1 grain (a taste, a drop)
2	Highly Toxic	4 ml (1 tsp)
3	Moderately Toxic	30 ml (1 fl. oz.)
4	Slightly Toxic	600 ml (1 pint)
5	Practically Non-toxic	1 litre (or 1 quart)
6	Relatively Harmless	1 litre (or 1 quart)

Even so the descriptors only address fatal outcomes. For integration with risk assessment, this needs to be broadened to non-fatal levels of harm, but it is not immediately obvious how this might be done.

Broadening to non-fatal levels of harm

From a risk perspective, there is an incongruity in the GHS notion that a substance can be considered ‘Relatively Harmless’ but still cause death if ingested in quantities of (say) a litre. These incongruities – there are several in Table 3 – appear to act against harmonisation with ISO31000.

Nonetheless this incongruity can be turned around to advantage. It is necessary to consider the existing state of the safety system. For example, one litre of toxicity level 5 substance can indeed be reasonably considered to be ‘practically non-toxic’, providing it is properly labelled, securely stored, only accessible by people with sufficient training in its proper use, stored in small quantities, and where users are provided with appropriate personal protective equipment (PPE). Hence the presence (or absence) of the safety management system (SMS) has a material effect on the overall risk. This reasoning allows ‘practically non-toxic’ to be reinterpreted as ‘unlikely to cause death when used in a competent safety system’ (our definition).

This is consistent with the ISO31000 approach, whereby the risk assessment is done with the SMS with its current controls. Thus from the ISO31000 perspective of consequence and likelihood, death is a consequence, but is unlikely given the existing state of the safety system.

Linking GHS categories to chronic harm scale

Safety systems are imperfect and do fail occasionally – this is the central insight of the barrier and bowtie methodologies(Jonas Aust & Pons, 2019). For example, even with the above safety systems, the level 5 substance might nonetheless be spilled and a worker may be subject to a partial exposure. This might not kill the person, but it could have permanent health consequences that resulted in impairment immediately or in the future, e.g. reduced lung function. This is a chronic harm outcome, and while the GHS makes no provision for it, the chronic harm scale of (Ji et al., 2021) is available – without further modification – to represent this outcome.

This reasoning allows the Category 5 toxicity to be identified as corresponding to the ‘Moderate incident/WHODAS 20 Long term impact’ point(Ji et al., 2021). The other four levels of the GHS categorisation can likewise be harmonised.

Representation of non-life-threatening toxicity

The next challenge is how to include toxicity effects that do not cause death, i.e. level 6 and beyond. The GHS only goes as far as category 5, and Hodge and Sterner only to level 6, because they were only concerned with life-threatening toxicity. However lower levels must exist, and the challenge is how to represent them.

A common such metric for industrial engineering is DALY. However this still measures outcomes in terms of death, specifically how that might be brought forward in time due to prior exposure. It does not consider the quality of a person's life while alive. The WHODAS disability metric (Chiu et al., 2014; Üstün, 2010) much better addresses the quality of life question, which it measures in terms of functional disability (the ability to perform physical tasks of daily living), and social isolation. The latter refers to the way that the disability interferes with the ability to see or listen or meet other people. Hence WHODAS is a more holistic and nuanced measure of a person's life in their retirement years.

However the WHODAS is merely a questionnaire that gives a score for level of disability. It is not a risk assessment tool, nor does it natively provide a set of categories that could be used to form an ordered scale. That functionality was instead developed by(Ji et al., 2021), and used to create a consequence scale for chronic harm. For example, "Amputation" has a WHODAS score of 30, whereas "Temporary effects to human body, healed naturally" scores 5. Previous work (Ji et al., 2021) established these chronic harm categories and correlated them with the accident/safety scale, for example "Amputation" is commensurate with "Serious harm: Notifiable injury". The latter part of that descriptor, "Notifiable injury", has a specific meaning in the NZ Health and Safety at Work Act(NZ Govt, 2015a), hence this also illustrates how the consequence scale may be harmonised to a specific legislative framework(Pons, 2019).

Regarding non-fatal chemical toxicity, the solution is to represent them as levels 6-8, based on parallels with the WHODAS-derived scale(Ji et al., 2021), which does extend down to such levels. This is justified as the WHODAS represents a measure of disability(Ji et al., 2021). Thus level chemical level 6 is made equivalent to 'Permanent but not debilitating injury' on the chronic harm scale. Then levels 7 and 8 follow likewise.

Finally, it is necessary to provide descriptive text for the newly created levels 6-8. Here it is useful to co-opt the LOAEL and NOAEL concepts for levels 7 and 8 respectively. This completes the development of the Chemical toxicity consequence scale. The results are summarised in Table 4 (column D). The last step to make a workable risk assessment tool is to assign a quantitative score to the consequence scale. For this the scale of (Ji et al., 2021) is adopted in its entirety, see Table 4 (column E).

Table 4: Proposed Harmonised consequence scale for chemical hazards.

A	B	C	D	E
GHS toxicity category and hazard statement (UNECE, 2017)	**Commonly Used Term (Hodge & Sterner, 1949)**	**Probable Lethal Dose for an adult human (Hodge & Sterner, 1949) (CCOHS, 2021)**	**Loss of health consequence scale for chemical hazards: Description**	**Loss of health consequence scale for chemical hazards: Score (Ji et al., 2021)**
1 "Fatal if swallowed, contacted, or inhaled"	Extremely Toxic	1 grain (a taste, a drop)	Extremely toxic. Fatal if swallowed, contacted, or inhaled. One drop is fatal	**500**
2 "Fatal if swallowed, contacted, or inhaled"	Highly Toxic	4 ml (1 tsp)	Highly toxic. Fatal if swallowed, contacted, or inhaled. One teaspoon is fatal	**100**
3 "Toxic if swallowed, contacted, or inhaled"	Moderately Toxic	30 ml (1 fl. oz.)	Moderately toxic. Toxic if swallowed, contacted, or inhaled. One tablespoon is fatal	**60**
4 "Harmful if swallowed, contacted, or inhaled"	Slightly Toxic	600 ml (1 pint)	Slightly toxic. Harmful if swallowed, contacted, or inhaled. Two cups are fatal	**30**
5 "May be harmful if swallowed, contacted, or inhaled"	Practically Non-toxic	1 litre (or 1 quart)	Practically non-toxic. May be harmful if swallowed, contacted, or inhaled. One litre is fatal	**20**
-NONE-	Relatively Harmless	1 litre (or 1 quart)	Relatively harmless. Permanent but not debilitating injury. May cause death for sensitive individuals	**10**
-NONE-	-NONE-	-NOT APPLICABLE-	Temporary harm with no permanent loss of ability or quality of life	**5**
-NONE-	-NONE-	-NOT APPLICABLE-	No adverse effects expected, exposure is below NOAEL	**2**

Integrated risk matrix

Taking all these steps together gives a third parallel consequence scale for the risk matrix, as shown in Figure 1. The Chemical toxicity scale runs from 1-8, with the descriptors as shown in the bottom row of that figure. Nonetheless it is scored 500-2 for compatibility with the other scales. The Safety scale is for accidents that result in immediately injury, and the Health scale is for long-term and chronic health.

The integrated methodology may then be used in the normal way provided by ISO31000, that is hazards are identified, their consequences C estimated and the likelihood L of those consequences arising (assuming an existing level of protection from the safety management systems), and the risk computed as $R = C * L$.

Likelihood of the consequence arising

Description	Probability, events per annum	Qualitative likelihood	Likelihood score								
Annual occurrence	***1.00***	***Almost certain***	***10***	5000	1000	600	300	200	100	50	20
Has occurred several times in your career	***0.6***	***Likely***	***6***	3000	600	360	180	120	60	30	12
Might occur once in your career	***0.4***	***Possible***	***4***	2000	400	240	120	80	40	20	8
Event does occur somewhere from time to time	***0.2***	***Unlikely***	***2***	1000	200	120	60	40	20	10	4
Heard of something like this happening elsewhere	***0.1***	***Rare***	***1***	500	100	60	30	20	10	5	2
Theoretically possible but not expected to occur	***0.01***	***Almost incredible***	***0.1***	50	10	6	3	2	1	0.5	0.2

Severity of Adverse health consequences

Loss of health	500	100	60	30	20	10	5	2
Safety consequence	Catastrophe: multiple deaths occur, would have negative impacts to next generation	Death: People loss of life	Serious harm: Notifiable injurles. Permanent and serious harm	Serious harm: Notifiable injurles. Incident results in serious harm	Moderate incident: Incident occurs and exposure to moderate harm	Minor harm: Incident occurs and minor harm	Minor harm: Incident without harm or with tiny impacts.	No harm: Hazard could be sufficiently managed by the current preventions.
Health consequence	Health disaster: Multiple people affected with high WHODAS scores	WHODAS up to 100 Death or paralysis.	WHODAS up to 60 Half-body, or leg paralysis	WHODAS up to 30 Amputation.	WHODAS Up to 20 Long term impact e.g. hearing loss	WHODAS up to 10 Permanent but not debilitating musculoskeletal injury	WHODAS Up to 5 Temporary effects to human body, healed naturally.	WHODAS up to 2 No harm to human body.
Chemical Toxicity per GHS 7	GHS Category 1: Extremely toxic. Fatal if swallowed, contacted, or inhaled. One drop is fatal	GHS Category 2: Highly toxic. Fatal if swallowed, contacted, or inhaled. One teaspoon is fatal	GHS Category 3: Moderately toxic. Toxic if swallowed, contacted, or inhaled. One tablespoon is fatal	GHS Category 4: Slightly toxic. Harmful if swallowed, contacted, or inhaled. Two cups are fatal	GHS Category 5: Practically non-toxic. May be harmful if swallowed, contacted, or inhaled. One litre is fatal	Level 6: Relatively harmless. Permanent but not debilitating injury. May cause death for sensitive individuals.	Level 7: Temporary harm with no permanent loss of ability or quality of life. Exposure is below LOAEL.	Level 8: No adverse effects expected. Exposure is below NOAEL.

Risk appetite response scale	
1000+	Cessation, immediate intervention required
120+ to 1000	Unacceptable risk. Cease operations until risk is under control
60+ to 120	Urgent treatment required. Operations proceed with caution and ongoing monitoring of risk.
10+ to 60	Implement treatment in a reasonable time period. Continue operations with caution and monitoring
0-10	No special treatment required. Continue the operations with on-going monitoring of the efficacy of existing preventions.

This Chemical Toxicity scale assumes an existing safety system comprising substances that are properly labelled, securely stored, only accessible by people with sufficient training, and appropriate personal protective equipment is provided. If the safety system is not strong, then consider increasing the likelihood of the consequences arising.

Figure 1: Integrated risk assessment methodology for accident safety, chronic health, and chemical hazards.

This risk matrix has several deliberately designed attributes. The consequence scale is non-linear, and this is deliberately to emphasise that the loss of many lives in a catastrophe is a much worse outcome than the death of a single worker (where many other scales stop). In contrast the linear consequence scales (e.g. 8..1), as commonly used in industry, under-represent severe outcomes such as multiple deaths. Also, the likelihood scale is also non-linear for reasons given in(Ji et al., 2021). Second, the consequence and likelihood scales, when multiplied, give numbers that can be consistently interpreted: the rank order of the product is preserved. Furthermore, the quantitative and qualitative methods become consistent in that they give the same risk outcome.

The figure also includes a risk appetite response from(Pons, 2019), with grey to green colours and quantitative risk thresholds. If necessary this can also be linked to the level of organisation decision-making (board, executives, managers, supervisors, workers), see (Pons, 2019) for details, thereby creating a systematic reporting framework for a safety management system. The risk appetite therefore indicates the organisational response to risks, and the colours and thresholds can be adjusted as appropriate. This is a potentially valuable attribute of the method, because it makes the communication responsibilities explicit.

In turn this type of communication is important for due diligence from the perspective of H&S legislation. In the specific case of New Zealand there is a requirement that board and executives keep themselves informed about the hazards in their operations. For reasons of practicality they cannot be informed about *every* hazard, and therefore there is value in the safety management system having a method whereby it is clear to all staff which hazards have to be escalated to higher managers, and which can be dealt with at lower levels.

Treatments

To further integrate these different classes of hazards, it is necessary to ensure that their treatments are included in the process. The conventional H&S approach to treatments is the hierarchy of hazard control. This emphasises the treatments of isolation, minimisation, and PPE. Depending on the context there can be additional elements (such as administrative controls), and sub categories. For example minimisation is often described as including isolation and engineering controls. These hierarchies also depend on the jurisdiction, being written into regulation. For the case of NZ the regulation (NZ Govt, 2015a) calls for either elimination or minimisation, without further details.

Regarding hazard control for chemical substances, the concept of the hierarchy of hazard control is well-established in the practitioner literature. However, it is difficult to find a comprehensive set of such controls especially one that is also accommodates non-chemical hazards. We suggest a generalised hierarchy of hazard control as represented per Figure 2.

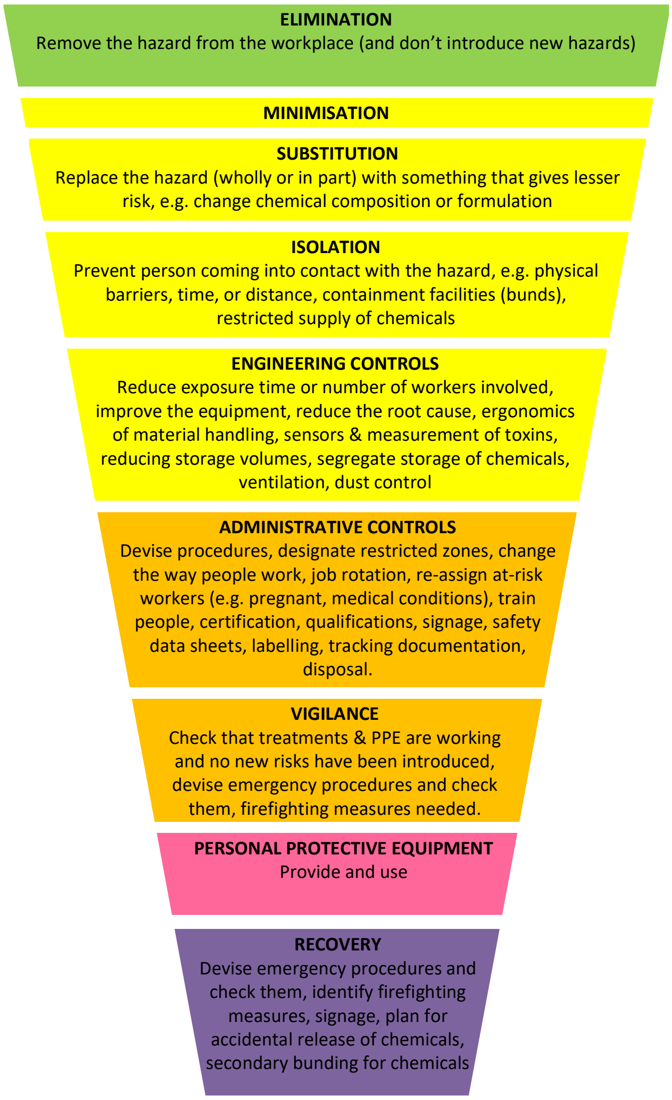

Figure 2: Proposed hierarchy of hazard control to include machine and chemical safety.

This hierarchy also includes a recovery component. This is to address a limitation of the conventional hierarchy being primarily focused on *prevention* of risk, ignoring *residual risk* (that treatments are not fully effective) or the need for *recovery mechanisms (or barriers)* to prevent further loss of control after the hazard manifests.

The hierarchy of hazard control has the benefit of providing a systematic way to think about treatments. In its pyramidal representation it conveys the notion that first efforts ought to be directed to elimination or minimisation of hazards, and that PPE should be merely the last line of defence rather than the only defence.

5 Discussion

Previous work (Ji et al., 2021) showed the addition of a 'health' scale was sufficient to elicit a greater awareness of chronic health in the hazard assessment process. This is consistent with the idea that the framework within which risk-assessors work constrains how they approach the problem. Thus it is hoped that the integration of the chemical toxicity scale into the conventional hazard assessment process will raise awareness of this class of risk.

Implications for practitioners

The intended use is that a person assessing a complex set of hazards would use all three consequence scales where necessary. For example, if the product under examination was a motor driven portable construction compactor, then the risks of impact damage to feet could be assessed under 'safety' consequences, the noise and vibration under 'health' consequences, and the inhalation of exhaust gases under 'chemical toxicity'.

Limitations

The arguments presented here for the development of the chemical hazard scale follow a philosophical logic, and are somewhat subjective. Nonetheless this is invariably how consequence scales are determined.

Conclusions

Chemical hazards are measured by severity, the dose required for death, in the Globally Harmonised System (GHS 7), but this metric is incompatible with the more graduated harm scales used for industrial safety. Reworking the chemical exposure scale makes it compatible with the ISO31000 Risk management approach. Thus a unified set of three consequence scales are provided for safety (immediate accident consequences), health (long term & chronic ill-health), and chemical exposure.

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