Research report

Risk and control velocity

The missing element of time in risk management

A research report presented in partial fulfilment of
Master of Health (Workplace Health and Safety)

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Word count (excluding bibliography): 20,120

Abstract

Risk management and risk techniques have not included the impact of time in risk assessment (risk velocity and control velocity. The current study creates definitions for risk and control velocity that can be applied by risk and health and safety professionals. RV is situated in risk techniques, including bowtie analysis, failure modes effects and criticality analysis, and latent failure. Control velocity is tested against existing engineering concepts such as mean time to fail, mean time between failures, and operating time to fail, and applied to the hierarchy of risk control used in health and safety risk management. The definitions are tested with real-world case studies to identify how risk and control velocity can be used to strengthen risk assessment and control.

Keywords

Risk velocity; control velocity; risk techniques; risk management; bowtie analysis; failure modes and effects analysis (FMEA); mean time to failure (MTTF); operating time to failure (OTTF); hierarchy of control; health and safety

Acknowledgements

It takes a village to raise a child, they say – and that goes for research as well! I owe thanks to a lot of people for supporting me and encouraging me along the way, some of whom are mentioned here.

Thanks to the Government Health and Safety Lead for the 2018 Public Sector Research Scholarship, the Health and Safety Association of New Zealand for the 2019-2020 Applied Research Scholarship, and Ministry of Primary Industries for personal study funding.

Thanks to colleagues at Inland Revenue and MPI that encouraged me, let me bend their ears into pretzels about velocity, and challenged me to think more deeply. Particularly at IR: Elizabeth Sartorelli and Michael Hurle; at MPI: Jeanette McKeogh, Michelle Ellis, Chris O'Flaherty, Rob Jenkins, Grant Boston, and Fiona Hennessey. Particular thanks to Jeanette for letting me use work time for research-related meetings and being an all-around lovely boss; and for Grant and Fiona for inspiring me to consider new case studies to test my thinking. Thanks also to Jesse Drake for allowing me to present an early version of this work in an MPI Science Network seminar.

Professor Melissa Tedone and Dr Rosie Grayburn of the Poison Book Project invited me to be part of their international bibliotoxicology working group, after I enquired if I could use their work as a case study, which has been an honour and a delight.

My friends, especially Jill, Pamela, Fiona, Elizabeth, Daisy, Frances, Coley, Sara, members of Papatūānuku's Daughters and the Grove of the Summer Stars, and sensei and friends at KKA Karate Academy, for keeping me balanced, grounded and exercised!

The lovely (and in some cases long-suffering!) people who reviewed and offered comment on this research: Dad, Bruce, Grant, Jesse, and Rob.

Dr Chris Peace, thanks for all the inspiration and encouragement, helping me get my first paper published, and being an amazing mentor and friend for more than 15 years now. I never had any doubt about who I wanted to supervise my risk research!

My wonderful family: my fabulous and funny teenager Ash; Dad, Julie and Tony, and Bruce. You've all stood by me in what's been a very challenging few years (including concussion!), and I couldn't have done this without you. Storm, for snuggles, purrs and cuddles whenever I needed them (and sometimes when I didn't – trying to type with you wrapped around my arm has been challenging!).

And Mum, I'm sorry you didn't see it finished, but I finally did it.

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1.1 Abbreviations and glossary

The following abbreviations and common names are used throughout this research.

COSO2016	*Enterprise Risk Management: aligning risk with strategy and performance* (COSO, 2016, p. 27)
CV	Control velocity
ERM	Enterprise risk management
FENZ	Fire and Emergency New Zealand
FMEA	Failure modes and effects analysis (IEC60812:2008)
FMECA	Failure modes, effects and criticality analysis (IEC60812:2008)
FME[C]A	Failure modes, effects [and criticality] analysis (IEC60812:2008): the FMEA technique with or without the criticality analysis
GRWM Regulations	The Health and Safety at Work (General Risk and Workplace Management) Regulations 2016, New Zealand
HSE	Health and Safety Executive (UK)
HSRM	Health and safety risk management
HSWA	Health and Safety at Work Act 2015
MBIE	Ministry of Business, Innovation and Employment (New Zealand government agency)
MPI	Ministry for Primary Industries (New Zealand government agency)
MTBF	Mean time between failures (IEC60050-192:2015)
MTTF	Mean time to failure (IEC60050-192:2015)
OTTF	Operating time to failure (IEC60050-192:2015)
RV	Risk velocity
RV TTC	Risk velocity time to cause
RV TTI	Risk velocity time to impact
RV TTO	Risk velocity time to outcome
RV TTR	Risk velocity time to recover
WorkSafe NZ	WorkSafe New Zealand (New Zealand government agency)

2 Introduction

2.1 Context

I have been working as a health and safety professional since 2003 and been involved with hundreds of risk assessments across a wide range of industries and situations, using a variety of risk techniques. The aim is always the reduction of uncertainty and white spaces (Cherry, 2010) in order to assist organisations to reach their objectives, with all workers going home safe and healthy at the end of the day.

Three key international Standards (IEC31010:2019; ISO31000:2018; ISO45001:2018) describe risk in terms of uncertainty that is often measured or estimated using likelihood and consequence (see section 3.1 *Risk* below). Over my career, I realised that there was a missing element to risk assessment as outlined in the Standards. I could not differentiate risk assessments by time before organisational objectives were impacted, or illness or injury occurred (for health and safety risks).

ISO31000:2018 includes identification of the business context, with consideration of the external context of organisational operations, and notes that there are 'time-related factors' (ISO31000:2019, p. 11); when the organisational context is volatile, risks may express differently. The Standard does not clarify what those time factors are, or how the context is affected by time.

I began to research and consider speed or time related to risk from a pragmatist perspective, seeking to understand whether this would clarify the risk landscape of the organisations I worked with. My initial scan of the literature identified the term risk velocity (RV). RV is an emerging concept in enterprise risk management (ERM) (Davis & Lukomnik, 2010; Ramamoorti, Baskin, Epstein, & Wanserski, 2017; Tattam & Esteban, 2013) that was first identified in an insurance practitioner publication (Mandel, 2009). It has not been discussed widely in peer-reviewed risk management journals, although a very brief definition was provided in COSO2016. The only extensive development of RV I identified was in a thesis (Chaparro, 2013), and this was not presented in a form that could be applied by practitioners.

One risk technique I use frequently with organisations is bowtie analysis. Bowtie analysis, a combination of fault tree analysis (FTA) and event tree analysis (ETA), discussed further below, is both relatively simple to use and a powerful method for visualising how a risk could affect organisational objectives. As I considered how speed or time could affect risk, I also wondered whether speed and time could be incorporated into this widely used risk technique.

2.2 White spaces

Cherry (2010) describes research as searching amongst the absences: looking at the white spaces of the boundaries of our knowledge, and using research and practice to reduce uncertainty, especially where data is limited or ambiguous. She identifies four areas where research could lean into white spaces and impact on practice:

1. Identification of white spaces and the dynamics and issues in those areas
2. Offering and modelling strategies and tools that could help practitioners reduce uncertainty
3. Exploration of developing practice in areas of uncertainty
4. Revealing how decision-making is done in conditions of uncertainty.

Risk management is defined in ISO31000:2018 as the “effect of uncertainty on objectives”; risk management therefore naturally works around the white spaces of what is known and what is not. Risk management is also concerned with business decision-making at an enterprise level (Fraser & Simkins, 2016) and within the organisation.

Cherry concludes by identifying core skills needed by researchers are similar to core skills required by master practitioners working with complex practice, and she questions ‘what can researchers learn from master practitioners?’ (Cherry, 2010, p. 16). The current research is my investigation into how the concept of velocity illumines white spaces in risk and control management, and tests it with a number of case studies that apply my theoretical work.

2.3 Rationale and significance

Risk velocity (RV) considers the speed of the likelihood of effect of exposure to a risk (consequences) and/or the speed of the effect of exposure; changes in velocity may change the risk exposure outcome, the way the risk needs to be managed, or both. It is the missing element of standard risk management techniques that has not received the attention it deserves. RV is significant for all areas of risk management.

ISO31000:2018 and COSO2016, two widely-used international frameworks for risk management (Dali et al., 2012), are of little help to risk practitioners seeking information on RV. ISO31000:2018 does not mention RV at all; COSO2016 mentions RV briefly and does not show how it could be applied in ERM or other risk disciplines such as health and safety risk management (HSRM). Peace (2019), in his recent thesis on risk assessment techniques, devotes a short section to it and includes it briefly in his Risk Canvas. Aven and Thekdi (2021), in their otherwise-comprehensive textbook *Risk Science: an introduction*, do not mention it at all.

A systematic search of Google Scholar, JSTOR and ProQuest on the search parameters *"risk velocity" AND "health and safety"* confirmed this concept has not been significantly researched or applied within HSRM. My initial findings paper (Parkin, 2021a) appears to be the first time that RV has been applied to specific health and safety risk exposures, outside of the brief mention in the Risk Canvas (Peace, 2019).

Use of RV in financial risk management was briefly surveyed for this research report to identify any developments of the concept that could apply more widely in ERM or HSRM. No significant developments were identified, and the search parameters were therefore excluded.

My research defines RV and identifies how it fits within accepted risk assessment methods. I present a full definition of RV and link it to known risk techniques, including failure modes effects [and criticality] analysis (FME[C]A) used in process engineering (Gilchrist, 1993) and bowtie analysis (de Ruijter & Guldenmund, 2016). The term FME[C]A is applied throughout this research to refer to both FMEA and FMECA, as the risk assessment process is similar whether or not assessment of criticality is included. I apply RV to the accident theory modalities of latent failure (Reason, 1990) and drift into failure (Dekker, 2010).

The inclusion of RV in risk techniques gives risk management practitioners, health and safety professionals, and organisational governance improved processes for reducing uncertainty and the white spaces of the unknown areas of risk assessment (Cherry, 2010).

My research identifies that there is a parallel concept of control velocity (CV), and explores the relationship between this and engineering concepts such as mean time to failure (Gaver, 1963), mean time between failures (Griffin, 1960), and operating time to failure (IEC60050-192:2015). The concept of CV, the speed of degradation of risk controls, has not been previously described in either ERM or HSRM literature. I will discuss types of control failure, ranging from chronic (such as corrosion) to acute failure (such as major rupture), as this has significant relevance to control selection for health and safety risks.

Latent failure (Reason, 1990) and RV appear to have a natural relationship. My research investigates the linkage between latent failures and RV, and identifies whether the concept as originally stated by Reason (1990) is enhanced by the application of RV.

My research also applies CV to the hierarchy of health and safety risk control set out in the Health and Safety at Work (General Risk and Workplace Management) Regulations 2016 (GRWM Regulations) and identifies whether considering time in risk controls significantly reduces white spaces (Cherry, 2010).

I take all of these areas and apply them to four wide-ranging case studies, in order to pragmatically test the developed theory through practical application. The research is completed by identifying how RV and CV can be integrated into other kinds of risk management, and other disciplines such as business continuity and emergency management, asset management, and long-term enterprise risk management.

2.4 Aims and objectives

This research aims to:

1. Identify and provide working definitions of risk velocity and control velocity
2. Situate risk and control velocity in the context of risk techniques
3. Link control velocity to the health and safety hierarchy of risk control
4. Test the effectiveness and relevance of risk and control velocity definitions through case studies.

This research is intended to assist health and safety and risk management professionals who require resources to expand their application of risk techniques to include speed and time.

2.5 Research design approach and methodology

2.5.1 A pragmatic approach

In their paper *A manifesto for Reality-based Safety Science*, Rae, Provan, Aboelssaad, and Alexander (2020) identified that most research published as "safety science" is neither used nor even read by health and safety professionals. Similar disquiet has been identified in other management and leadership disciplines (for example, Hall & Hess, 1978; Toffel, 2016; Vermeulen, 2005).

My belief is that research conducted for a practical subject such as HSRM and ERM should be able to be read, understood and practically applied by practitioners working in the field, without requiring significant degrees of modification to be useful. This stems from my career where academic research and professional practice have intertwined, with my research informing my practice, and practice directly informing my research. This kind of reflexive practice is pragmatic by its very nature (Farjoun, Ansell, & Boin, 2015).[1]

Wein (2009, p. 808) summarises my position:

> My rule of thumb for working on a problem was whether the answers to the following four questions were yes, no, no, and yes: Is the problem very important (i.e., could it directly or indirectly lead to catastrophic consequences)? Has the problem been sufficiently addressed in the academic literature? Has the problem been satisfactorily addressed by policy makers? Would the problem be fun (i.e., sufficiently challenging) to work on?

When organisations do not perceive how time or speed influences risk (RV), it could lead to catastrophic consequences. The problem has been insufficiently addressed in literature, as discussed in section 2.3 *Rationale and significance* above, and has also not been considered by practitioners. The final question posed by Wein (2009) was proven in the research itself, in the creation of a simple framework that could be applied by practitioners.

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[1] Reflexive practice is also a requirement of my professional bodies, through the "continuing professional development" process and requirement.

My research is conducted from a pragmatist perspective. The pragmatic approach allows theoretical ideation to be tested by case studies, and acknowledges that 'all research is cumulative and yet incomplete and that preliminary judgments must be made with the evidence at hand' (Mills, Durepos, & Wiebe, 2010, p. 724). Pragmatism offers a middle way between rationalism and structuralism. It provides a perspective that is not bound to rigid theoretical foundations, and is a flexible ontology that is valuable to real-world problem-solving (Farjoun et al., 2015).

Structure and process are closely intertwined in a pragmatist worldview (Daft & Weick, 1984; Dewey, 1929). In this research, the risk techniques provide structure, and RV is the process that weaves through it; the case studies provide what Daft and Weick (1984) call enactment, where the experimental theories are tested.

The development of theoretical models in this research builds on earlier conceptualising of risk velocity (for example, Chaparro, 2013; Davis & Lukomnik, 2010; Mandel, 2009; Ramamoorti et al., 2017; Ramamoorti, Wanserski, & Stover, 2019; Tattam & Esteban, 2013). The four case studies in section 6 pragmatically contextualise and test those models.

My aim is to create a potential framework for RV and CV that could be practically utilised by health and safety professionals and risk practitioners (Johnson & Onwuegbuzie, 2004). I draw on my work experience to identify whether the framework is feasible for application by health and safety and risk professionals (Toffel, 2016).

2.5.2 Structure of research report

As this research report is concerned with pragmatic theoretical ideation, it is not presented in the classic experimental research format of Results, Discussion and Conclusion. There is no Results section, as the theories were not field-tested during this research. Instead, the research is presented in five main sections:

- Section 3: *Definitions* of the terms used in this research
- Section 4: *Discussion*, clarifying the definitions of risk and control velocity and identifying whether they can be applied to risk techniques
- Section 5: *Application,* showing the utility of the definitions and their application to risk techniques

- Section 6: *Case studies* that test concepts developed in the Discussion and Application through real-world examples
- Section 7: *Conclusion*, with identification of opportunities for future research.

2.5.3 Relationship of risk velocity to other risk assessment methodology

RV forms part of the wider activity of risk assessment. Risk assessment in general is a pragmatic and hermeneutical approach, as it seeks to take into account the context of the organisation or activity (ISO31000:2018) and apply that context to the "text" of the work itself (Howell, 2013).

Risk assessment in general is also time-bound, in that a risk assessment exists as a point-in-time assessment; any change in circumstances may change the risk assessment (COSO2016; ISO31000:2018; Peace, 2019). However, RV is a specific form of hermeneutical phenomenology because it argues that risk (the meaning) is always linked directly with time. Application of velocity turns risk into a temporal construct, creating a discussion that sites the reduction of uncertainty (risk management) more deeply into the temporal context of an organisation. This is discussed further in section 3.1.1 *The uncertainty definition* below.

2.5.4 Research methods, data analysis, and procedure

My literature reviews were carried out through a variety of search engines and parameters to develop a comprehensive understanding of literature around RV and CV, including JSTOR, Google Scholar, and others.

The literature is used for theoretical concept development and application to case studies, using information that is freely available in the public domain or is contained in peer-reviewed literature, wherever possible. Case studies are intended to test concept applicability for real-world use by risk managers and health and safety professionals (Rae et al., 2020).

2.6 Treaty of Waitangi and Vision Mātauranga

There are three key principles to honouring Te Tiriti o Waitangi in this research: participation, protection, and partnership (M. L. Hudson & Russell, 2009; Wickham, 2022, pers. com). My research does not seek to apply Māori traditional knowledge (Mātauranga

Māori) in a risk context; although I consider areas where Mātauranga Māori illustrates risk situations. For example, section 6.1 *Case study: Whakaari* below applies RV and CV to the eruption of the Whakaari volcano on 9 December 2019 that killed or seriously injured 47 people. Within that case study, I note that Mātauranga Māori understood and explained Whakaari's unpredictable nature (Hamilton & Baumgart, 1959; Kilgour et al., 2021).

I also honour the intention of Te Tiriti o Waitangi through choosing case studies and examples that are primarily based in Aotearoa New Zealand, although the principles of velocity are applicable universally.

My colleagues (well-versed in both academic research paradigms and kaupapa Māori) identified that the key elements to consider are how the research protects the mana of the Treaty principles, and how tikanga and the whakapapa of research and reflection is respected through the research process. I discussed my research with tangata whenua to ensure that it reflects manaakitanga and whakaute (respect) for kaupapa Māori throughout.

2.7 Ethics

This research did not require primary data gathering, so there are no ethical implications around informed consent and management of primary data sources.

All case study information is available in the public domain. The sole exception are two photographs used in section 6.4 *Case study: Work at height (WAH)* below taken by myself in 2010, which are used to illustrate a well-known risk in HSRM.

Where this research addressed situations where people have been injured or have died as a result of a risk exposure (such as the 9 December 2019 Whakaari disaster), I treat this information with manaakitanga to those affected. Personal stories are not required to illustrate RV or CV.

2.8 Rigour and validity strategy

I will use published, peer-reviewed research in English wherever possible. Grey literature, defined by Adams, Smart, and Huff (2017, p. 433) as 'the diverse and heterogeneous body of material available outside, and not subject to, traditional academic peer-review processes', is used where, for example:

- There is limited published peer-reviewed research, for example in bibliotoxicology (an emerging research field) and/or there is a need for contemporaneous information that has not yet been peer-reviewed
- It illuminates issues or provides additional context, for example narrative that can be used to show the effectiveness of RV or CV

When utilising grey literature, I will identify whether the source is credible and the information or research gathered is likely to be trustworthy (Adams et al., 2017). I cite my sources to confirm that the grey literature is reliable; where it is a less-reliable source (for example, media reports) this will be identified in the text.

2.8.1 Management of bias

I will note potential areas of bias, including confirmation bias, search parameter biases, heuristic biases, and anchoring bias (Tversky & Kahneman, 1974). As this is a pragmatic approach to research, there is a risk of confirmation bias being present in the application of velocity to case studies: there is a risk I will see what I want to see (Klayman, 1995). This is managed by considering alternative hypotheses as part of the research, and testing ideas with others during the research process.

Selection of sources in English also introduces possible bias, as non-English perspectives of risk management are by nature excluded.

2.9 Research questions

The research questions are:

1. How should risk velocity be defined?
2. Can risk and control velocity be applied in risk techniques?

3 Definitions

3.1 Risk

Aven, Renn, and Rosa (2011) identify eleven definitions of risk, grouped into three broad areas (Table 1); all three of these areas are used in this research. Two of these areas are discussed in the current definition; probability and expected values is discussed in the definition in section 3.7 *Failure modes effects [and criticality] analysis (FME[C]A)* below.

Table 1: Broad risk definitions

Broad risk definition area	Examples of use
Probability and expected values	FME[C]A (IEC60812:2008)
Events or consequences	ISO45001
Management of uncertainty	COSO2016 and ISO31000:2018

(Source: Author)

3.1.1 The uncertainty definition

Two of the major international frameworks for risk management identify risk as a form of uncertainty that affects the objectives of a business, therefore identifying that risk management is about decision-making in the white spaces (Cherry, 2010):

- In ISO31000:2018, 3.1, risk is defined as the 'effect of uncertainty on objectives'
- In COSO2016, risk is defined as 'The possibility that events will occur and affect the achievement of strategy and business objectives' (COSO2016, p. 9), and 'involves uncertainty and affects an organization's ability to achieve its strategy and business objectives' (COSO2016, p. 3)

Uncertainty means that '[w]e do not have the knowledge needed to determine if the event will occur or not, when it will occur and what the consequences (outcome) will be' (Aven et al., 2011, p. 1076). This kind of uncertainty is described in IEC31010:2019 as epistemic uncertainty. Epistemic uncertainty implies time: it is either something that is unknown in the future, or something that is already present but unknown (latent) in the organisation or the situation. However, none of the key Standards (COSO2016; IEC31010:2019; ISO31000:2018) identify time or speed as part of epistemic uncertainty.

It is noted that risks can have positive (opportunities) or negative effects on an objective (ISO31000:2018).

3.1.2 Likelihood and consequence

ISO45001:2019 (p. 5) defines risk as both the 'effect of uncertainty' without the link to business objectives, and a combination of the consequence of an event and likelihood of that event occurring. Aven et al. (2011) link severity with the idea that the consequences affect something that is valued by people.

Likelihood is defined in ISO31000:2018 (s. 3.7) as the 'chance of something happening…. whether defined, measured or determined objectively or subjectively, qualitatively or quantitatively, and described using general terms or mathematically (such as a probability or a frequency over a given time period)'.

This definition introduces probability and frequency, which are loosely connected with RV. Many organisations have included either a quantitative probability calculation (which may or may not reflect the complexity of the risk), or an estimated probability (often in a form such as "event could occur within 1-2 years") in their definitions of likelihood (Peace, 2019).

ISO31000:2018 (s. 3.6) defines consequence as the 'outcome of an event, affecting objectives'; COSO2016 does not define it.

For the purposes of this research, the uncertainty definition of risk from ISO31000:2018 is adopted.

3.2 Risk velocity (RV)

There is no agreed definition of RV in the literature, and various definitions have been offered (Chaparro, 2013; Mandel, 2009; Ramamoorti et al., 2017; Ramamoorti et al., 2019; Samson, 2020; Sobel, 2010; Tattam & Esteban, 2013; Wieczorek-Kosmala, 2019). All the definitions of RV found in the literature contain speed or time as an element that should be factored into risk techniques.

For the purposes of this research, risk velocity is defined as the directional effect of time or speed on uncertainty (either incoming or outgoing from a top event). This is further developed in section 4.1 *Clarifying the definition of risk velocity* below.

3.3 Control

Control is widely used in risk literature, but there is a lack of definition of what comprises a control in many of the key risk sources (IEC61025:2008; IEC62052:2010; ISO31000:2018).

A control is defined in ISO31000:2018 (p. 2) as 'measure that maintains and/or modifies risk,' with the clarifying note that controls 'include, but are not limited to, any process, policy, device, practice, or other conditions and/or actions.'

The international food safety standard, *Codex Alimentarius*, defines a control measure as 'Any action and activity that can be used to prevent or eliminate a food safety hazard or reduce it to an acceptable level' (Codex Alimentarius Commission, 2011, p. 15).

Reason (1990, p. 199ff) uses the term defences interchangeably with controls. Bowtie analysis refers to controls as barriers, defined as 'those parts of a system that prevent deviations from occurring' (de Ruijter & Guldenmund, 2016, p. 212).

For the purposes of this research, the definition in ISO31000:2018 is adopted.

3.4 Control velocity and reliability engineering

Control velocity applies the concept of time or speed to the life of a control, which links controls to reliability engineering. There has been extensive research in reliability engineering around mean time to failure (Gaver, 1963; Lienig & Bruemmer, 2017; Massoumnia, Verghese, & Willsky, 1989), mean time between failures (Lienig & Bruemmer, 2017; Ryu & Chang, 2005; Torell & Avelar, 2004), and operating time to failure (IEC60050-192:2015; Lienig & Bruemmer, 2017) but this does not appear to have been widely applied to HSRM or ERM.

3.4.1 Mean time to failure (MTTF)

MTTF is an engineering reliability measure first identified as part of the Minuteman Missile programme (Griffin, 1960) that identifies the statistical mean length of time a system or system component is expected to function before it fails, sometimes described colloquially as "average life expectancy" (Lienig & Bruemmer, 2017). MTTF is replaced by Mean Operating Time to First Failure or MOTTFF (IEC60050-192:2015), clarifying that it is the mean time before the system or component fails for the first time that is measured. Ryu and

Chang (2005) identify MTTF as the nominal statistical life of a system or component. MTTF is applied to this research when considering controls and their durability.

For the purposes of this research, MTTF is defined as the mean length of time a system or system component is expected to operate before it fails.

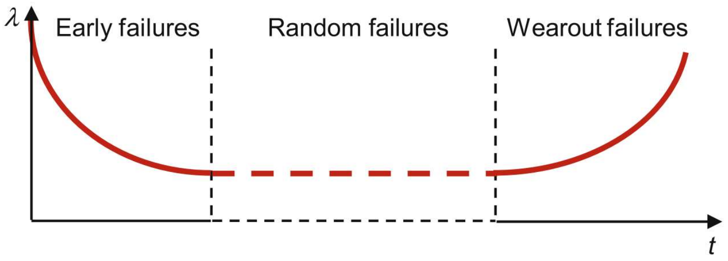
3.4.2 Mean time between failures (MTBF)

MTBF is an engineering reliability measure that identifies the statistical mean length of time a system or system component is predicted to operate between each breakdown, failure or stoppage, during normal operations, usually represented in units of hours (Lienig & Bruemmer, 2017; Ryu & Chang, 2005; Torell & Avelar, 2004).

The bathtub curve (Figure 1) depicts the changing numbers of failures over the lifecycle of a system or component, with more failures at the beginning of life due to unidentified manufacturing weaknesses, environmental stress, or manufacturing flaws; the lowest number of failures during the main operating period; and a rising number of failures as the system or component ages and starts to wear out (Lienig & Bruemmer, 2017; Ryu & Chang, 2005).

Figure 1: Failure rates showing bathtub curve (Lienig & Bruemmer, 2017, p. 52, Figure 4.4)

Fig. 4.4 Typical plot of the failure rate $\lambda(t)$ over time t (bathtub curve) with decreasing, constant, and increasing failure rate sections



(Source: Lienig and Bruemmer (2017))

MTBF is calculated during the random failure period, when the number of failures during any given operating period are at their least. MTBF of a system is dependent on the interaction of the individual MTBFs of each individual component (Lienig & Bruemmer, 2017).

For the purposes of this research, MTBF is defined as the mean length of time between failures of a given system or component during its random failure period (where this is identified).

3.4.3 Operating time to failure (OTTF)

IEC60050-192:2015 defines operating time to failure as ‘operating time accumulated from the first use, or from restoration, until failure’ (192-05-01). This concept has been applied in reliability engineering but does not appear to have been used within ERM or HSRM.

For the purposes of this research, OTTF is defined as the time that a given control takes to fail, which may be acute or chronic (Table 2):

Table 2: Operating time to fail types compared with IEC60050-192:2015 Annex A

Operating time to fail types	IEC60050-192:2015 term
Chronic	Wear-out failure Ageing failure
Acute	No equivalence Called “sudden failure” in IEC60050-192:1990

(Source: IEC60050:192:2015 and author)

For example, process piping could fail two ways: corrosion develops and the piping begins to leak (chronic), or it could fail catastrophically in an explosion or significant major rupture (acute). Catastrophic failure was called “sudden failure” in IEC60050-192:1990, but this was omitted from IEC60050-192:2015 and there is no equivalent term identified in Annex A of that Standard.

3.4.4 Control Velocity (CV)

For the purposes of this research, CV is defined as the length of time that a risk control is expected to be in service, or when a failure of control is expected. It may be related to the level of risk control applied to a health and safety risk, and therefore relate to the requirements for monitoring the control and its outcomes.

3.5 Latent failure

Reason (1990, p. 173) defined latent errors as situations where ‘adverse consequences may lie dormant within the system for a long time, only becoming evident when they combine with other factors to breach the system’s defences.’ He later called these errors latent conditions or latent failures (Reason, 1998).

Latent failure is well-recognised in HSRM. The concept of "hidden risk" within a tight-coupled human-system interface (Perrow, 1999; Rasmussen, 1997) has assisted organisations to look more widely and deeply at their health and safety risk exposures for more than 30 years (Edkins & Pollock, 1996; Pasman, Rogers, & Mannan, 2018).

For the purposes of this research, latent failure is defined as system or process defects created by inadequate design, installation, maintenance, management, or operations, that may cause adverse outcomes such as unexpected failures or additional uncertainty in operations.

3.6 Drift into failure

Dekker (2010) identified that most accident models are linear and deterministic, and introduced complexity theory into accident causation. He defines drift into failure as 'a gradual, incremental decline into disaster driven by environmental pressure, unruly technology and social processes that normalize growing risk' (Dekker, 2010, p. xii). Drift into failure is similar to an electrical engineering term: "drift fail". A drift fail is 'a slow change in attributes …. [that] causes output voltage shifts, such as change in gain amplification, in analog components' (Lienig & Bruemmer, 2017, p. 71).

Dekker's definition is adopted for the purposes of this research.

3.7 Failure modes effects [and criticality] analysis (FME[C]A)

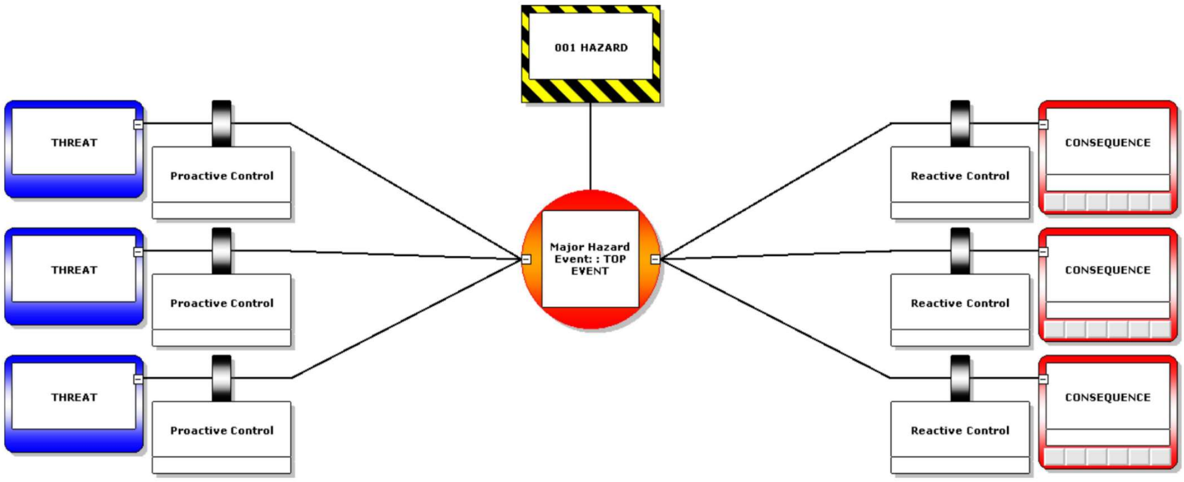
FME[C]A is a technique developed out of fault detection and quality management (Polajnar, Leber, & Buchmeister, 1970) that identifies how system components fail, and what dependencies failures (or risks/uncertainties) may create. FME[C]A is relevant to this research as it introduces an element of time or speed into the risk, alongside likelihood/probability and consequence. It is a risk technique that assists in identifying latent failures (Reason, 1990) in a system, described as "failure modes" in IEC60812:2008.

FME[C]A is defined in this research as a risk technique that identifies potential latent failures designed into a system, and their causes and effects on risk velocity and control velocity.

3.8 Bowtie analysis

Bowtie analysis (de Ruijter & Guldenmund, 2016; Hollnagel, 2008; P. Hudson, 2014; Salter, 2005; Saud, Israni, & Goddard, 2014) shown in Figure 2 is a risk technique that visually identifies the relationship between threats, consequences, the top event (cause) and controls (proactive or preventative, and reactive or recovery). It was developed in the oil and gas industry in the early 1990s following the Piper Alpha North Sea platform disaster (de Ruijter & Guldenmund, 2016) as a combination of earlier models (fault tree analysis and event tree analysis). Bowtie analysis was rapidly adopted more widely as a simple visualisation of a risk uncertainty (de Ruijter & Guldenmund, 2016; Peace, 2019; Salter, 2005).

Figure 2: Standard bowtie analysis diagram (Saud et al., 2014, p. 27, figure 2)



(Source: Saud et al. (2014) and BowtieXP computer program, Wolters Kluwer)

There is no accepted standard definition of bowtie analysis, but it is formally described in ISO31010:2019.

For the purposes of this research, bowtie analysis is defined as a risk technique that combines a fault tree with an event tree and shows the relationship between threats, consequences, the top event, and controls, influenced by both risk and control velocity.

3.9 Precautionary principle

The precautionary principle originated in environmental management. It was first noted in German environmental law in the 1970s-1980s (Aven & Thekdi, 2021), with a well-known codification made by the United Nations General Assembly (1992) in the *Rio Declaration on Environment and Development*.

The precautionary principle identifies that, where uncertainty exists, for example regarding significant environmental impact, a precautionary approach should be taken if there is insufficient information to take a probability-based risk management approach (Aven, 2011; Aven et al., 2011; Aven & Thekdi, 2021; Rausand, 2020). There is ongoing discussion in the literature about the implications of this principle for risk management, and several definitions are proposed (for example, Aven, 2011; Aven & Thekdi, 2021; Golrang, 2020; O'Riordan & Cameron, 2013; Rausand, 2020).

Aven and Thekdi (2021, p. 217) summarise the definition for the precautionary principle as:

- An ethical principle expressing that if the consequences of an activity could be serious and subject to scientific uncertainties, then precautionary measures should be taken, or the activity should not be carried out.
- A principle expressing that regularity actions may be taken in situations where potentially hazardous agents might induce harm to humans or the environment, even if conclusive evidence about the potential harmful effect is not (yet) available.

This definition is adopted for this research.

3.10Bibliotoxicology

One of the case studies of this research considers the emerging research field of bibliotoxicology. Antiquarian book conservators have identified that transition and heavy metals have not only been used in art (Finlay, 2002) and museum specimen conservation (Muir, Lovell, & Peace, 1981), but also in book bindings, book end papers, and book illustrations (Clark & Mirabaud, 2006; Delbey et al., 2019; Tedone, 2020; Tedone & Grayburn, 2020, 2022). There is little research in this area: the potential scale of contaminated books, and their potential health impacts on those conserving, reading, storing and handling them, is not yet understood.

Bibliotoxicology is defined for this research as the identification and risk management of books that are physically contaminated with hazardous substances toxic to humans, and that pose a potential health risk to humans handling or working with the contaminated items.

4 Discussion

4.1 Clarifying the definition of risk velocity

4.1.1 Velocity in classical physics

The classic physics definition of velocity is distance divided by time (Equation 1):

Equation 1: Velocity

$$Velocity = \frac{Distance}{Time}$$

In physics, velocity is a directional vector, indicated diagrammatically by an arrow. Velocity always has a straight-line direction, identified from the outside of the object. Risk velocity has direction as well: both towards and away from the risk exposure or top event (Figure 4 below).

4.1.2 Parts of risk velocity in the literature

Definitions in the literature indicate that velocity should be taken into account in several parts of risk management activity, as summarised briefly in my initial findings paper (Parkin, 2021a).

Sobel (2010) divided risk velocity (RV) into speed of onset of a risk, speed of impact of the risk on business activities, and speed of reaction (how quickly a business reacted to a risk event). Tattam and Esteban (2013) identified time to cause (TTC) and time to impact (TTI), where TTC represented the time that the risk was expected to express, and TTI was the 'time taken for a risk to move from the initial causes through to experiencing the impacts' (Tattam & Esteban, 2013, p. 147). IEC31010:2019 (p. 27) identifies the 'time horizon' of a risk as short, medium, long, or any but does not clarify which part of risk techniques are affected by the time horizon.

Chaparro (2013) also divided RV into TTC and TTI and added time to recover (TTR), thereby including the length of time for recovery from the risk exposure and creating a clear link with business continuity management and response. This concept was later described in IEC31010:2019 as increasing adverse effects of a failure (or risk exposure) over time. RV is therefore implied in the Standard but not named or defined.

4.1.3 Risk velocity in financial risk management

A small but growing literature exists around the application of RV to financial risk and stock market projection and prediction (for example, AlAli, 2020; Grimwade, 2019; Ramamoorti et al., 2019; Rothschild, 2006).

In general, this is a “simple” RV identifying whether the risk is fast or slow (without further differentiation) to reduce uncertainty. This literature was briefly surveyed and identified as outside the scope of this risk report. However, future development of RV may benefit from further consideration of this literature to identify if there are any additional elements that could be included.

4.2 Control velocity (CV)

Definitions for CV for either enterprise risk management (ERM) or health and safety risk management (HSRM) were not identified in the literature search. However, there has been significant work in engineering about control efficacy and reliability. Mean time to failure (MTTF), mean time between failures (MTBF), and operating time to failure (OTTF) can all be applied to controls, and these definitions can be grouped together under the heading of CV.

4.3 Risk techniques

IEC31010:2019 is a key summary of 41 risk techniques, but nowhere in this Standard are RV, CV, MTTF, MTBF, or OTTF mentioned. However, all of the risk techniques have a “time horizon” allocated in Table A.2 that describes whether the risk technique is considered appropriate for short, medium, long term, or all time periods. This implies some form of RV is included in each technique, but not identified. The potential relationship with RV and CV is identified in Table 4 below, with time horizon excluded.

Of the risk techniques listed in IEC31010:2019, four are relevant for incorporation of RV and/or CV (Table 3 below):

Table 3: Summary of Standards applicable to risk techniques

Name	**Abbreviation**	**Applicable Standards**
Event tree analysis	ETA	IEC31010:2019 IEC62052:2010
Fault tree analysis	FTA	IEC31010:2019 IEC61025:2008
Bowtie analysis		IEC31010:2019
Failure modes and effects analysis Failure modes, effects and criticality analysis	FMEA FMECA	IEC31010:2019 IEC60812:2008

(Source: author)

FTA and ETA are combined into bowtie analysis (de Ruijter & Guldenmund, 2016), all three of which are separately discussed in IEC31010:2019. FTA and ETA will be briefly discussed, with further analysis used for bowtie analysis. Both FTA and ETA as described in their individual Standards use Boolean conditional logic gates and probability analysis, which is not usually incorporated into bowtie analysis (IEC31010:2019).

The fourth technique is FME[C]A, used in engineering to analyse a system or process to identify failure potential (it is called FMECA when the criticality of those failures is also calculated). It is discussed briefly in IEC31010:2019 and extensively in its own Standard, IEC60812:2008.

4.3.1 Fault tree analysis (FTA)

FTA is a type of dependability analysis used to identify causes or initiating events that lead to a top event, with AND/OR Boolean logic gates for each cause identified. IEC31010:2019 (p. 64) identifies top events in FTA as ‘undesirable’; however, IEC61025:2008 identifies that the technique can also be used to create success trees where the outcome/top event is a success rather than failure.

FTA is applied from the top event, with all the potential causes/primary events cascaded from it as deductions. When it is combined with ETA, the FTA is turned on its side so the top event becomes the centre of the bowtie analysis (Figure 2 above).

RV may be implied in classic FTA analysis as defined in IEC61025:2008 as failure rates or failure frequencies. CV may also be implied by the incorporation of MTTF or MTBF to identify what are referred to as ‘primary event probabilities’ (IEC:61925:2008 p. 11), as shown in Table 4 below. However, there is no clear application of time or speed within FTA that provides an equivalence to the definitions of RV and CV created in this research, and evidence that RV has been applied within the literature is extremely scarce.

4.3.2 Event tree analysis (ETA)

This risk technique is described in IEC62052:2010, and identifies the top or initiating event, consequences or events, and controls/mitigating factors. It can be combined with FTA to create a bowtie analysis technique, with each top event of an FTA forming the "node" for the beginning of the ETA. IEC62052:2010 identifies that ETA is not suitable for application to failures that are dependent or conditional on one another. ETA may be combined with FME[C]A for identification of severity of outcomes, which may become the initiating events used in ETA.

Speed or time-dependent events are specifically excluded from ETA analysis (IEC62052:2010, s.5), which means that RV has been excluded from the historical use of this technique both in the Standard and in dependent literature.

CV may be implied, as mitigating factors/controls are organised in order of time intervention (IEC62052:2010, s.8.2.3) and the logic order they would occur (Table 4 below); however, this implication does not appear to be borne out in the literature.

4.3.3 Bowtie analysis

The bowtie analysis model (Figure 2 above) clearly shows dependencies between threats, controls, the top event, and consequences. Boolean AND/OR gates are not usually employed (IEC31010:2019). It is accepted that bowtie analysis is a simplified version of a combined FTA and ETA (IEC31010:2019, p. 60), with the top event in the centre of the bowtie being the top event of the fault tree and the initiating event/node of the event tree.

There is an implication of time or speed in the time horizon for the technique noted in IEC31010:2019 (Table 4 below), but this has not been explored in the Standard or the literature.

4.3.4 Failure modes, effects [and criticality] analysis (FME[C]A)

FMEA is used to identify the effects of potential failures within a system (comprising any combination of software, hardware, people, or processes), and how those effects can be mitigated. FMECA is used when a calculation of the criticality of failure is included in the analysis, known as the risk priority number (RPN). Again, there is a time horizon applied in IEC31010:2019.

RPN may imply RV. RPN is defined as ‘a subjective measure of the severity of the effect and an estimate of the expected probability of its occurrence for a predetermined time period assumed for analysis’ (IEC60812:2008, p. 15). The inclusion of a time period for the analysis of the potential for faults implies that the time period for fault detection is part of the analysis (Equation 2, expanded from IEC60812:2008, p. 15):

Equation 2: Risk Priority Number (RPN)

$$RPN = Severity \times Probability\ of\ occurrence \times Detection$$

This inclusion of time implies that the RPN includes RV, although this is not identified as such in IEC60812:2008 and does not appear to have been described in FME[C]A literature.

IEC60812:2008 identifies that RPN is applied together with the identified severity of the failure mode in order to prioritise identified failures for treatment: failures with the same or similar RPN are checked for severity, with higher-severity failures prioritised for mitigation. There is also a dependency on detection probability; low detection ability is scored with a higher RPN, and therefore increased attention needs to be paid to mitigating the effect of and potential for the failure. The detection probability may imply CV, as time is an implied element of failure detection.

RV may contribute to FME[C]A by providing a group of standard descriptors for velocity (Table 9 below), which may assist in the description of RPN and identification of its effects.

4.4 Velocity and risk techniques

RV has been neglected in existing research into risk techniques and their application, as shown in Table 4 below. The relevant literature in their applicable Standards has not applied RV or CV, even where they are implied by time horizons, speed or time in the Standard text.

Table 4: Summary of risk techniques and their relationship to risk velocity and control velocity

Risk technique	RV	Implied by	CV	Implied by
Fault tree analysis (FTA)	Implied	Failure rates Failure frequencies	Implied	MTTF MTBF
Event tree analysis (ETA)	Clearly excluded		Implied	Time interventions
Bowtie analysis	Not mentioned		Not mentioned	
Failure modes and effects analysis (FMEA)	Implied	Risk priority number RPN	Implied	Detection

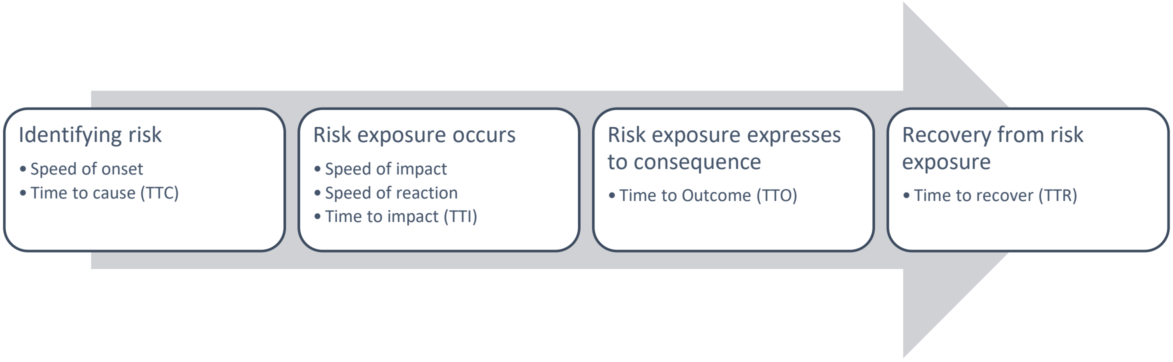
(Source: author)

4.4.1 The missing part of risk velocity

A missing element from the parts of RV outlined in the literature summarised above has been identified during this research, shown most clearly in the bowtie analysis (combined FTA/ETA): the velocity from a risk exposure or top event to each possible consequence of the exposure (Figure 2 above, Figure 4 below). I call this Time to Outcome (RV TTO).

All four parts of RV are shown in Figure 3, including the new measure RV TTO:

Figure 3: Summary of risk velocity actions



(Source: author)

I use the following definitions of the parts of RV (Table 5 below), linked with the parts of a risk bowtie analysis (Figure 2 above) throughout this research.

Table 5: Definitions of the parts of risk velocity, including new measure RV TTO

Part of risk velocity	Abbreviation	Definition	Direction
Time to Cause	RV TTC	The time between the identification of an area of uncertainty (risk), and when that risk is close enough to cause initial threats	Before risk exposure
Time to Impact	RV TTI	The time taken for an identified risk uncertainty to fully express in a top event	Before risk exposure
Time to Outcome	RV TTO	The length of time from the impact/top event to each individual consequence	After risk exposure
Time to Recover	RV TTR	The time taken from the impact of a risk exposure to return to normal operations or health of business, process or person	After risk exposure

(Source: author)

4.4.2 Risk velocity and bowtie analysis[2]

The introduction of RV and CV into the bowtie analysis technique makes a significant contribution to risk modelling by assisting those using the visual methodology of a bowtie analysis to identify the speed that each part of the uncertainty may appear (Figure 4 below) or controls may fail (Figure 5 below). This may significantly impact on the choice of controls (barriers) employed to reduce uncertainty.

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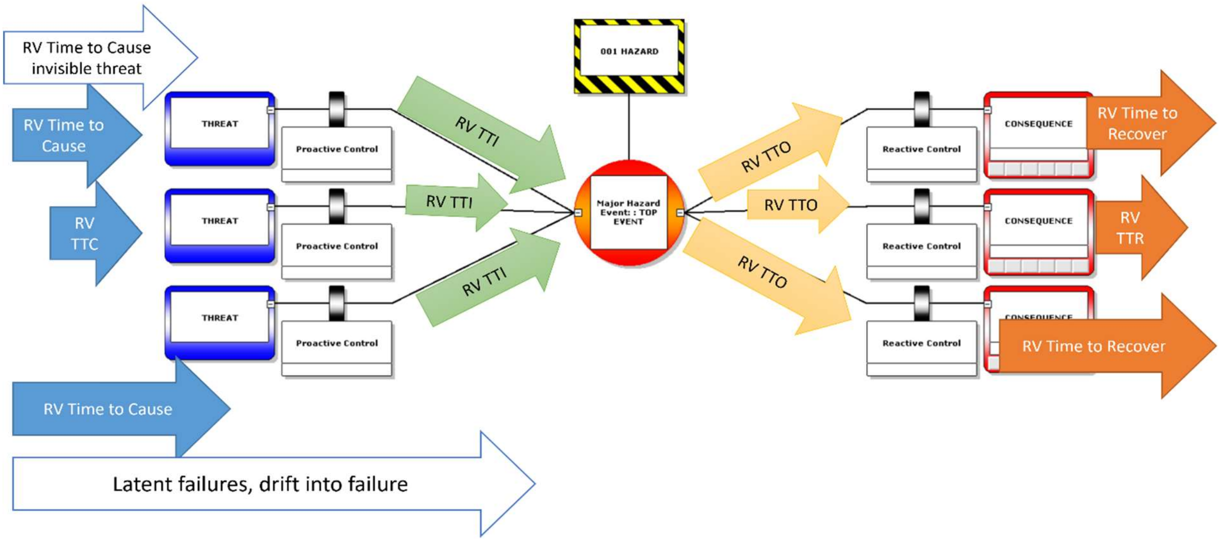
[2] As ETA and FTA combine to comprise bowtie analysis, they will not be discussed as separate techniques.

Figure 4: Inclusion of risk velocity in classic bowtie analysis diagram adapted from Saud et al. (2014)



(Source: Saud et al. (2014), BowtieXP, and author

RV Time to Cause (RV TTC) is shown at the left-hand of the bowtie analysis diagram, where threats (uncertainties or risk exposures) are pictured. Each of the identified threats has an RV TTC that indicates how quickly each individual threat could eventuate. This can be indicated in the diagram by the length of the arrow leading to the threat (similar to physics vectors, Equation 1 above). Where there is an “invisible threat” that has not been identified in the risk landscape (e.g., the advent of a pandemic creating mass business disruption) an “invisible arrow” can be shown to assist practitioners to consider unidentified threats.

Generally, the threat lines between threats and the top event are generated by a bowtie analysis modelling program. However, using the length of the threat line to indicate the velocity of the threat provides an immediate visual cue as to the velocity of the exposure, as with physics vectors. RV Time to Impact (RV TTI) is indicated along each threat line. Each threat will take a different length of time to eventuate, so this can be shown by the length of the arrow.

Following the top event there are consequence lines leading to each potential consequence. Again, the length of each vector should indicate the velocity. I have called this RV Time to Outcome (RV TTO) and defined it in Table 5 above. RV TTO has not been previously identified in the RV literature.

Each potential consequence has its own RV Time to Recover (RV TTR), again indicated by the length of the arrow leading away from the consequences, that identifies to practitioners how long it could take to recover from each consequence. In some cases, there may be more than one RV TTR for a given consequence.

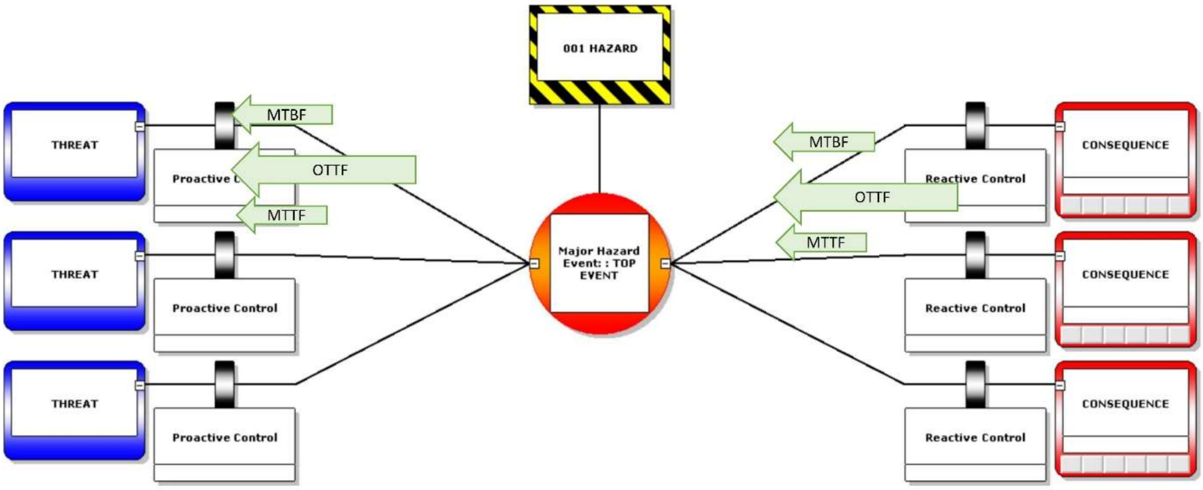
Use of RV combined with the bowtie analysis technique (ETA and FTA) may reduce uncertainty by visually representing where time needs to be taken into consideration in managing the risk. Examples of application are shown in Figure 8 in section 6.2 *Case study: Bibliotoxicology,* and in Figure 12 in section 6.4 *Case study: Work at height (WAH)*.

4.4.3 Control velocity and bowtie analysis

Similar to the application of RV above, CV may be applied to bowtie analysis (FTA/ETA), providing clarity on control reliability. The standard bowtie analysis diagram (Figure 2 above) identifies what controls are in place but does not reduce uncertainty by representing control reliability.

Representing CV measures MTBF, MTTF and OTTF by differing-length vectors (similar to RV) for each control in a bowtie analysis (Figure 5) provides improved clarity on the effectiveness of that control, thus reducing uncertainty.

Figure 5: Control velocity applied to bowtie analysis, adapted from Saud et al. (2014)



(Source: Saud et al. (2014), BowtieXP, and author)

MTTF for each control identifies the mean length of time that the control is likely to operate for before it fails. MTBF for each control identifies the mean length of time between failures of a control in its random failure period (the bottom of the bathtub graph, Figure 1 above). OTTF identifies how long that control will take to fail, once failure starts (which could be acute or chronic).

In engineering, each failure time is precisely calculated using probability statistics. Where quantitative data is available, it should be used to reduce uncertainty as much as possible; however, where quantitative data is not available, the qualitative descriptors in Table 9 below (or another set of clearly-defined qualitative descriptors appropriate to the control) could be used.

Examples of application are provided in Figure 9 in section 6.2 *Case study: Bibliotoxicology*, and Figure 13 in section 6.4 *Case study: Work at height (WAH).*

4.4.4 Velocity and failure modes and effects [criticality] analysis

FME[C]A relates to both velocity and the bowtie analysis discussed above by including identification of 'how and when the failure can be detected' (IEC31010:2019, p. 49). Control detection requires a control such as an alarm, monitoring, or audit process. Strong detective controls may increase certainty around system failure rates (discussed in section 3.4 *Control velocity and reliability engineering* above) and assist in identifying the individual elements of RV for a risk event (Grimwade, 2019).

For example, process piping requires detective controls such as pressure release valves and integrated alarm systems. The number of times that a pressure valve releases, or an alarm deploys in a particular section of plant, can assist to identify the MTTF and MTBF of that plant. Equally, an alarm or valve series in multiple sections of process piping can assist in understanding the RV TTC and RV TTI of a failure event such as an overpressure, by studying the speed that the detective controls identified the overpressure moving through the various parts of the plant. A similar process applies to detective controls in a financial or ERM system. FME[C]A thus relates to the FTA side of a bowtie analysis.

Detective controls applied through FME[C]A may also be of use in the ETA side of the bowtie analysis to assist in identifying RV TTO. In the process piping example above, detective controls used in FME[C]A may also be able to pinpoint whether the event could be acute or chronic.

An FME[C]A analysis is unlikely to be able to assist in identifying RV TTR.

4.5 Velocity, latent failure and drift into failure

Latent failure is widely used In health and safety literature, popularised by Reason (1990) and his Swiss Cheese model of accident causation where "holes" in the barriers or controls allow threats through (P. Hudson, 2014; Larouzee & Le Coze, 2020, pp. 188-189; Reason, 1998; Shorrock, 2020; Stapleton, 2006).

RV has an implied relationship with latent failure, as RV is frequently a hidden element of risk exposures (as discussed above). The word latent itself indicates a time element to the failure. The latency could be found in two of the three CV areas (Table 6):

Table 6: Potential control velocity of latent failures

Potential velocity of latent failures	**How velocity relates to latent failure**
CV mean time to failure	MTTF is the length of time that a system or process is likely to work for before it fails. This implies latent failure as there will be parts of the system that fail earlier due to design decisions and individual component failures, which may cause weaknesses in the entire system.
CV operating time to failure	OTTF is the time that a failure takes to occur and can be either acute or chronic. Latent failure is also implied here, as either type of failure speed may be caused by inherent issues in the design.

(Source: author)

Drift into failure (Dekker, 2010; McGregor, 2008) identifies that the latent failures may be caused by a series of decisions or actions that were logical for the organisation or situation at a point in time, but have the long-term effect of eroding barriers or controls. This may not be identifiable until after something has gone wrong (McGregor, 2008).

For example, a large multi-site manufacturing company planned to upgrade their forklifts.[3] There were two types under consideration: one with the traditional three pedals (from left to right: inching pedal, brake and accelerator), the other had two (left to right: fixed footrest

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[3] This example is based on a real situation investigated by the author.

for left foot; inching pedal, and brake/accelerator on one rocking pedal operated with the right foot), as shown in Table 7:

Table 7: Forklift pedals, showing the correct foot to operate each pedal

Foot placement	Three pedal forklift model	Two pedal forklift model
Footrest		Left foot
Inching pedal	Left foot	Right foot
Brake	Right foot	
Accelerator	Right foot	
Brake/accelerator combined		Right foot

(Source: author)

The company selected the model with two pedals for financial and contractual reasons and instructed all sites to upgrade. Site operators at all sites were trained when the new forklifts arrived.

Approximately a year later, Forklift A came unexpectedly into the path of Forklift B. Driver A braked hard, rocking the brake/accelerator pedal to the left and Forklift A stopped rapidly in under a metre. Driver B also attempted to brake hard but reacted as though they were driving a three-pedal forklift or a passenger car, depressing Forklift B’s inching brake very hard with their right foot. Forklift B skidded around 8m and t-boned Forklift A, with forks jammed into the side battery cowling. Fortunately, both forklift operators had their loads at carry height, and no-one was injured. However, had Driver B had their load elevated, Driver A would have been seriously injured or killed.

All three areas of latent failures, drift into failure and velocity are present in this example. Latent failure and drift into failure are summarised in Table 8 below:

Table 8: Latent failure and drift into failure in forklift example

Failure type	Explanation
Latent failure	The company-wide decision to change the model of forklift from three- to two-pedal design, with minimal input from site-based forklift operators.
Drift into failure	Introduction of the two-pedal forklift Creeping familiarity with the forklifts by operators Driver B reacting according to their long-standing training for the three-pedal design (and for a passenger car) in a high-stress situation

(Source: author)

RV describes both of these situations (Table 9 below): RV TTC is medium fast (a year of operation), RV TTI is extremely fast, RV TTO is also extremely fast, and in this case, RV TTR was very fast because fixing the cowling on damaged Forklift A took about a month. However, had the collision caused more serious damage to Forklift A, or serious injury to Driver A, RV TTR could have been significantly longer (Table 10 below).

In this case, two controls failed: forklift selection and operator training. Forklift selection has a medium slow-slow MTTF, and an acute OTTF of extremely fast. Training MTTF is medium fast, with OTTF extremely fast (see section 5.2 *Control velocity and the hierarchy of control* below).

5 Application

5.1 Simplifying velocity for use: qualitative descriptors

Chaparro (2013) provided a non-linear set of five descriptors for risk velocity (RV) that I have adapted for consistency and ease of use, creating eight qualitative descriptors in Table 9 that can be applied to RV or control velocity (CV). An earlier version containing six descriptors was initially applied to section 6.2 *Case study: Bibliotoxicology* below, a scenario with very long RV time to cause (TTC), and found to be inadequate to describe RV of many years. I therefore took a pragmatic approach and adapted the descriptors partway through this research.

The qualitative descriptors are provided in order to reduce the possibility of the kind of confusion identified by Duchesne and Lawless (2000) in their analysis of the variability of scales for FME[C]A, and are applied throughout sections 5 *Application* and 6 *Case studies*.

Table 9 also fulfils part of the requirements of the *Reality-based Safety Science manifesto* of Rae et al. (2020) by providing a simple process that could assist health and safety and risk practitioners to more easily apply the concepts of velocity to their risks.

Table 9: Qualitative descriptors for velocity with indicator colours

Qualitative description	Definition
Extremely fast	Instantaneous, little or no warning, or very rapid onset, days
Very fast	Onset occurs in a matter of days to a month
Fast	Onset occurs from 1-6 months
Medium fast	Onset occurs from 6-12 months
Medium slow	Occurs over 1-5 years
Slow	Onset over 5-15 years
Very slow	Onset 15-50 years
Extremely slow	50 years or more

(Source: author)

The indicative colour scale can be used to assist with visual representation of velocity, as shown in the case studies below.

For RV time to recover (TTR), the colour scale is reversed, with the more desirable shorter times to recover indicated with green and less-desirable longer recovery marked in red (Table 10 below):

Table 10: Qualitative descriptors for risk velocity time to recover (RV TTR), with indicator colours

Qualitative description	Definition
Extremely slow	Recovery 50 years or more
Very slow	Recovery 15-50 years
Slow	Recovery over 5-15 years
Medium slow	Recovery occurs over 1-5 years
Medium fast	Recovery occurs from 6-12 months
Fast	Recovery occurs from 1-6 months
Very fast	Recovery occurs in a matter of days to a month
Extremely fast	Instantaneous or very rapid recovery, days

(Source: author)

5.1.1 *Caveat for qualitative descriptors*

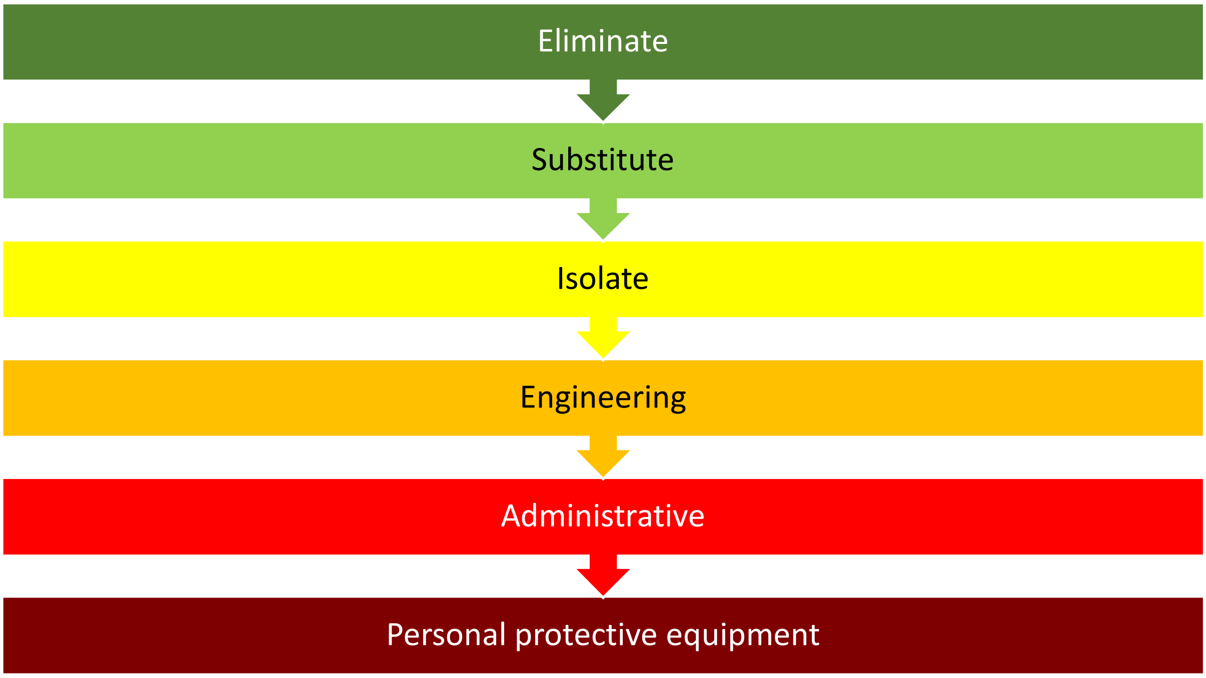
The qualitative descriptors in Table 9 and Table 10 may not be suitable in all circumstances. Further research applying velocity to very long-term events, such as section 6.2 *Case study: Bibliotoxicology* below, may require individual definitions and qualitative descriptors to be developed as part of that work.

5.2 Control velocity and the hierarchy of control

The New Zealand legislative hierarchy of health and safety risk management (HSRM) identifies a descending level of control effectiveness in the Health and Safety at Work (General Risk and Workplace Management) Regulations (GRWM Regulations), Regulation 6 (Figure 6 below). Each type of control has a varying effectiveness to reduce uncertainty, based on the seminal work on energy damage and countermeasures by Haddon (1973).

The application of CV to HSRM provides additional clarity to control effectiveness. The location of the control on the hierarchy does not necessarily equate to its velocity. Where quantitative information is available for each control's CV (mean time to fail, MTTF; mean time between failures, MTBF; and operating time to fail, OTTF), it can be used to provide additional precision; otherwise, the qualitative descriptors in Table 9 above can be used.

Figure 6: Hierarchy of health and safety risk controls from most to least effective



(Source: Health and Safety at Work (General Risk and Workplace Management) Regulations 2016, author)

5.2.1 Elimination controls

An elimination control has removed the risk to health and safety entirely. There are two types of elimination control: physical changes and administrative elimination.

A physical elimination control has no CV, as there is no continuing risk exposure: the risk has been permanently removed for all time. However, if an elimination is an administrative decision (for example, a go/no go decision point as discussed in section 6.1 *Case study: Whakaari* below), an extremely fast OTTF is appropriate as there is a possibility that the control could be affected by human error (Reason, 1990).

5.2.2 Substitution controls

Substitution controls remove one sort of risk and replace it with another, less harmful one; for example, a hazardous substance is removed and another, less harmful substance is substituted in its place. CV is identified for the substituted control (the control that is put in place following the substitution) and therefore is not discussed further here (Haddon, 1973). It is noted that CV could be used as one of the ways that the most appropriate choice of substitution control could be chosen.

5.2.3 Isolation controls

Isolation controls remove a person from a health and safety risk exposure using time, distance, or shielding (Haddon, 1973; Kim, 2018; Mukherji, Gupta, & Agarwal, 2020). Developed primarily in radiation safety, these three processes are also applicable for HSRM isolation controls in other contexts. For example, in a busy distribution centre, pedestrians can be isolated from mobile plant such as forklifts, elevating lift trucks, and reach trucks using all three of these methods. However, CV may vary depending on the way that these controls have been applied (Table 11 below).

Wherever possible, quantitative data on failure rates should be obtained and used for isolation controls; where this is not possible, indicative data from accident statistics across an industry could be used. The qualitative descriptors from Table 9 above have been used in Table 11 below, using an example of exposure of pedestrians to mobile plant in a distribution centre.

Table 11: Example isolation controls (mobile plant) compared with control velocity using qualitative descriptors

Isolation method	Application		MTTF	MTBF	OTTF
Time	Pedestrians and mobile plant are not in the same work area at the same time	Permanent isolation by time: pedestrians permanently excluded from the area when mobile plant is operating	Medium slow-slow, as site design may change	Medium slow-slow, as site design may change	Medium slow-slow, as site design may change
		Temporary isolation by time, where pedestrians and operating mobile plant share the area and there are quick changes between use	Fast- Medium fast, due to risk of human error (Reason, 1990)	Extremely fast	Extremely fast: if control fails, it will be instantaneous
Distance	Pedestrians are at a physical distance from mobile plant operating areas	Permanent isolation by distance: pedestrians are permanently excluded from the area where mobile plant is operating	Medium slow-slow, as site design may change	Medium slow-slow, as site design may change	Medium slow-slow, as site design may change
		Temporary isolation by distance: pedestrians keep their distance from operating mobile plant	Fast	Fast	Extremely fast: if control fails, it will be instantaneous
Shielding	Pedestrians are working behind physical barriers to prevent mobile plant incursions	Permanent isolation by shielding: there is a permanent, fixed physical barrier preventing pedestrians and operating mobile plant coming in contact	Medium slow-slow, as site design may change	Medium slow-slow, as site design may change	Medium slow-slow, as site design may change
		Temporary isolation by shielding: there is a temporary visual indicator (e.g., cones or painted safe walking markings) indicating pedestrians and mobile plant operating zones	Fast	Very fast	Extremely fast: if control fails it will be instantaneous

(Source: author)

5.2.4 Engineering controls

Engineering controls are fixed, physical controls, and can be expected to have medium slow to very slow CV (it is not expected that a physical, fixed control would fail in under a year). Quantitative data on MTTF and MTBF may be available for physical engineering controls such as machinery guarding, and where this is available it should be used, even if combined with the qualitative descriptors in Table 9 (or similar) to assist with practitioner application of CV.

OTTF could be expected to have two values for acute and chronic failures, of extremely fast and slow-very slow respectively. In some cases, chronic OTTF may even be extremely slow.

5.2.5 Administrative controls

Administrative controls include policies, processes, safe operating procedures, training, and signage that rely on a worker to comply (Barnes, 2011). The velocity of administrative controls varies, and the examples are provided in this research are not exhaustive.

The length of time a policy or process remains current for would equate to its MTTF (for example, two years or medium-slow).

Knowledge retention and effective application of both skills- and knowledge-based training decreases over time (Alliger, Tannenbaum, Bennett Jr, Traver, & Shotland, 1997; Häggström & Edlund, 2022; Sanli & Carnahan, 2018), with both knowledge and skills declining in the year following training (Sanli & Carnahan, 2018). A MTTF for training as a control would therefore be medium fast. Training associated with policies and procedures would also have a medium fast MTTF.

However, failure to follow or utilise training and procedures is instantaneous, therefore OTTF for training and procedures would be extremely fast.

5.2.6 Personal protective equipment (PPE)

PPE is the lowest level of the hierarchy of control from the GRWM Regulations shown in Figure 6 above. However, this does not mean that PPE has an extremely fast CV, as it depends on the expected life of the PPE item in question.

Figure 7: GNS scientist sampling high temperature fumarole on Whakaari (GNS Science, n.d.)

For example, in Figure 7, the scientist sampling fumaroles at Whakaari is wearing a supplied-air respirator. AS/NZS1716:2012 identifies that a respirator should last for a minimum of five years of operational use; MTTF is therefore medium slow. MTBF would need to be identified from the specific testing data of the PPE manufacturer.

OTTF for PPE is likely to have three values (Table 12):

Table 12: Operating time to failure for personal protective equipment, using respirator as an example

OTTF for PPE	Quantitative	Example qualitative descriptor from Table 9 above
OTTF chronic	As defined by manufacturer	Medium slow-slow
OTTF acute	As defined by manufacturer	Very fast-extremely fast
OTTF operator failure (where operator fails to use PPE, or uses it incorrectly)		Extremely fast

(Source: author)

5.2.7 *Summary: CV and hierarchy of control*

The discussion above has shown that CV could provide health and safety practitioners with a more robust understanding of control effectiveness, with varying velocities for each type of control in the hierarchy. This degree of granularity can be used to more effectively map controls and their projected ability to act as barriers to a risk, for example in a control register or heat map such as Table 13. Where a combination velocity such as slow-very slow is identified, the colour for the more extreme of the two velocities is used.

Table 13: Example hierarchy of control with control velocities using qualitative descriptors

Hierarchy of control	Mean time to failure	Mean time between failure	Operating time to failure
Eliminate (permanent removal)	None	None	None
Eliminate (administrative decision)			Extremely fast
Substitution	(measured against substituted control)		
Isolation (time, permanent)	Medium Slow	Medium Slow	Medium Slow
Isolation (time, temporary)	Medium fast	Very fast	Extremely fast
Isolation (distance, permanent)	Medium Slow	Medium Slow	Medium Slow
Isolation (distance, temporary)	Fast-medium fast	Extremely fast	Extremely fast
Isolation (shielding, permanent)	Medium Slow	Medium Slow	Medium slow
Isolation (shielding, temporary)	Fast-medium fast	Very fast	Extremely fast
Engineering	Slow	Slow	Chronic: slow-very slow
			Acute: Extremely fast
Administrative	Medium fast		Extremely fast
PPE	Slow-very slow		Chronic: Medium slow-slow
			Acute: Very fast-extremely fast
			Operator failure: Extremely fast

(Source: author)

Used in combination with the bowtie analysis risk technique (Figure 5 above), the use of CV vectors provides a clear visual representation of the effectiveness of each individual control in the bowtie analysis. Examples of how this could be applied are shown in section 6.2 *Case study: Bibliotoxicology,* Figure 8 and Figure 9, and in section 6.4 *Case study: Work at height (WAH)*, Figure 12 and Figure 13.

6 Case studies

In section 4 *Discussion* above, I clarified the definition of RV, finding three parts of RV in the literature and identifying a fourth part (RV TTO) that is not discussed elsewhere. I identified the relationship between velocity and three key failure measurements in engineering: MTTF, MTBF, and OTTF that makes up CV. RV and CV was applied to risk techniques, including bowtie and FME[C]A.

In section 5 *Application*, I showed how CV relates to the hierarchy of risk control in HSRM and provided simple qualitative descriptors to assist practitioners to identify RV and CV for their risks.

In this section, I apply RV and CV to four case studies to pragmatically test the validity of the velocity concept and theoretical work above for effective practical application to real-world examples. All information in the four case studies is in the public domain, with the exception of two images used to illustrate section 6.4 *Case study: Work at height (WAH)* that I took in 2010.

Presentation of an early version of this research to the Ministry for Primary Industries' Science Network Seminar led to the recommendation from colleagues that I use the Lake Ōhau wildfire as a case study of a situation with layered velocities (*6.3 Case study: Lake Ōhau wildfire*).

6.1 Case study: Whakaari

Te Puia Whakaari, the dramatic volcano (Kilgour et al., 2021), has long been recognised as New Zealand's most active volcano. Mātauranga Māori recorded that it was an active volcano through a number of legends of Ngāti Tūwharetoa and Ngāti Awa iwi (Hamilton & Baumgart, 1959; Kilgour et al., 2021; King, Goff, & Skipper, 2007; Orbell, 1973; Pacey, 2014), that recognise that it is prone to rapid eruptions with little warning beforehand.

The eruption of the Whakaari volcano on 9 December 2019 killed 22 and seriously injured 25 people who were visiting the volcano as tourists or tour guides. A series of Volcanic Activity Bulletins issued by GNS Science (GNS) from October-December 2019 (GNS Science, 2019a, 2019b, 2019c, 2019d) had previously identified that volcanic activity was increasing. On 3 December 2019, GNS noted that,

> 'The monitoring observations bear some similarities with those seen during the 2011-2016 period when Whakaari/White Island was more active …. [and] the volcano may be entering a period where eruptive activity is more likely than normal.'
>
> (GNS Science, 2019c)

On 9 December 2019, Whakaari was at Volcanic Alert Level 2 (VAL2), the highest level used in New Zealand for non-eruptive activity (GNS Science, 2014).

6.1.1 Risk velocity and Whakaari

The gaps between eruptive periods at Whakaari are generally several years (Kilgour et al., 2021), meaning the RV TTC (from risk horizon to threats) is very slow to extremely slow.

In 2018, GNS scientists published a method for establishing whether it was safe to carry out scientific observations on active volcanoes in 'a state of detectable unrest or erupting' (Deligne, Jolly, Taig, & Webb, 2018, p. 2) known as VoLREst (Volcanic Life Risk Estimator). VoLREst 'outputs a quantitative estimate of the hourly risk of fatality at different distances from a vent area' (Deligne et al., 2018, p. 2). They considered risk exposures on active volcanoes that do not have detectable physical changes that could warn of imminent eruptive activity – in other words, extremely fast RV TTI (movement from threat to top event).

The VoLREst calculation for different Volcanic Alert Levels (VALs) takes time into account (a form of RV TTI), with VAL2 defaulted at 4 weeks for the purposes of the model (Deligne et al., 2018), or very fast RV TTI. It is noted that the VAL system available to the public does not include the time definitions included in VoLREst (Deligne et al., 2018; GNS Science, 2014).

VoLREst also calculates hourly fatality risk, which is used to manage scientists' overall exposure to high-risk fieldwork in any given year, which appears to be a form of application of RV TTI. VoLREst does not appear to include consideration of RV TTO or RV TTR. It is also noted that,

> Results [of VoLREst analyses] to date are only used internally [within GNS Science] and at present are not used to support Civil Defence and Emergency Management, Department of Conservation, or concessionaires (e.g., [companies who employ] tour guides, [companies who employ] ski field operators) evacuation or access decisions. This has led to situations where the public has access to a volcanic area but GNS Science staff are not permitted to go; when this has happened GNS Science publicly stated that staff are not visiting the area….
>
> (Deligne et al., 2018, pp. 15-16)

RV TTO was extremely fast, as the movement from the top event (eruption) to consequences was instantaneous in this and other instances of eruptive activity at Whakaari. RV TTR for the Whakaari disaster is slow to very slow (where recovery is possible). There are multiple consequences, both for the people who were injured and killed and for the concessionaires, all of which have slow-very slow RV TTR (Table 10).

It is unknown whether RV was included in the risk techniques used by the concessionaires; however, given the lack of literature and general knowledge on RV (as noted above), it seems unlikely.

6.1.2 Control velocity and Whakaari

Control velocity applies to a number of potential controls for the events of 9 December 2019, but the key CV to be considered applies to the administrative elimination control of a go/no go decision. A go/no go decision point may have identified whether it was safe for concessionaires and tourists to visit the volcano at any given time on any given day, informed by the VAL.

MTBF and MTTF for Whakaari (and volcanoes in general) cannot be identified due to their unpredictability. OTTF to decide not to visit Whakaari is extremely fast, as the volcano can erupt with little to no warning.

However, given the heightened VAL2 and repeated warnings from GNS Science about potential eruptive activity (GNS Science, 2019a, 2019b, 2019c, 2019d), it seems reasonable to suggest that applying the precautionary principle to the go/no go decision could have been considered, given the extremely fast OTTF of the control. However, information published in the media following the disaster suggests that visitors may not have been provided with sufficient information to make an informed personal go/no go decision (Radio NZ, 2019; Stuff, 2019a), and an administrative elimination go/no go control does not appear to have been applied by concessionaires.

It is noted that a risk can be both positive and negative: in the case of the visit to the volcano on 9 December 2019, it is likely that the opportunity of visiting an active volcano (for visitors) and the commercial opportunities of taking a paying tour group[4] (for concessionaires) outweighed the perceived risks of volcanic eruption and the risk and control velocity of the activity.

6.1.3 Velocity and Whakaari: summary and discussion

The overall velocities for the Whakaari eruption of 9 December 2019 are summarised in Table 14:

Table 14: Summary velocities for Whakaari using qualitative descriptors

Velocity	**Qualitative descriptor**
RV Time to cause	Extremely slow-very slow
RV Time to impact	Extremely fast-very fast
RV Time to outcome	Extremely fast
RV Time to recover	Very slow
CV Operating time to fail	Extremely fast

(Source: author)

Would consideration of RV and CV have impacted on the uncertainty of whether a trip should have been taken to Whakaari on 9 December 2019?

Had the VoLREst analysis been made available to concessionaires, or had each concessionaire included RV and CV in their own risk assessment, particularly RV TTI, RV TTO, and OTTF (all extremely fast), it may have contributed to identifying that Whakaari was entering an unpredictable phase and a go/no go decision not to visit the volcano may have been made. Use of RV and CV may have reduced uncertainty and identified the risk of significant volcanic eruption and resultant serious injuries and fatalities more clearly.

Recent research has created a machine-learning data model that was able to predict eruptions at Whakaari in five of seven eruptive events since 2012 using real-time tremor data from the volcano’s sensors (Dempsey, Cronin, Mei, & Kempa-Liehr, 2020); crucially, this model would have provided up to 17 hours’ advance warning of the eruption on 9 December 2019, allowing an informed go/no go decision for an extremely fast OTTF.[5]

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[4] The costs of a tour on Whakaari in 2019 were reported in an online Stuff article in 2019: ‘The adult price of the "Walking on a Live Volcano" tour was $229, with children aged 15 and under charged $130 [per person]’ (Stuff, 2019b).

[5] Dempsey et al. (2020) note that the data-driven model can only identify eruptive precursors similar to what has been included before, which is why one eruptive period was not identified by the model.

Unfortunately, this data model was not available at the time, and it is still in the experimental stage and not yet ready for operational deployment. Dempsey et al. (2020, p. 5) also note that,

> This forecasting approach does not resolve the problem of who decides when to publicize warnings…. Ultimately, tour operators, government regulators, and the public all bear some responsibility for adjusting their actions in response to new information about the volcano state. These issues must be urgently addressed if automatic forecasting is to meet societal expectations of volcano warnings and prevent future tragedies.

6.2 Case study: Bibliotoxicology

This case study was presented at the Inaugural Bibliotoxicology Working Group Symposium (Parkin, 2022).

As identified in section 3 *Definitions* above, book conservators have recently identified antique and historic books contaminated with transition and heavy metals. Tedone and Grayburn (2022) are initially focusing on Victorian cloth bindings published in the 1800s contaminated with friable copper acetoarsenite[6] pigment, known variously as Emerald Green, Schweinfurt Green, Vienna Green, King's Green, and Paris Green when sold as a pesticide (Tedone & Grayburn, 2020, 2022), and chrome yellow. Over 10% of the green Victorian-era cloth-case bindings analysed in their study of two significant American rare book collections[7] were contaminated with arsenic.

Delbey et al. (2019) identified that there was contamination in end-papers and in-book art that included a much wider range of toxic substances in hand-bound books published in the 1700s, which was confirmed by similar testing carried out by Melbourne Museum in Australia, reported in a trade publication (Museums Victoria, n.d.). Delbey et al. (2019), in a small-sample study of 16th and 17th century hand-bound books, identified the presence of arsenic trisulphide[8] known as orpiment, and organic indigo (mixed together to make a green pigment); and salts of copper, antimony, barium, gold, lead, chromium and mercury, all of which have been used in painting and art for centuries, and in some cases, millennia (Finlay, 2002).

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[6] $Cu(C_2H_3O_2)_2 3Cu(AsO_2)_2$

[7] Collections tested are housed at the Winterthur Library (Delaware) and The Library Company of Philadelphia.

[8] As_sS_3

At this stage, the degree of contamination in the world's libraries, private and public book collections, and second-hand book trade is not known, nor has the complete time period when heavy and transition metals may have been used to decorate books been identified. For the purposes of this discussion, the work of the Poison Book Project at Winterthur Library is discussed. The qualitative descriptors developed in Table 9 above will be tested for suitability against this risk.

6.2.1 Risk velocity and bibliotoxicology

There is a significant literature on arsenicosis due to both the very lengthy history of this poison, and the effects of drinking groundwater contaminated with heavy metals and arsenic, particularly in Bangladesh and India. There is also a significant literature surrounding the use of Emerald Green during the Victorian era for non-book uses, including in paint, wallpaper, clothing and fabric, and toys (for example, Tedone & Grayburn, 2020; Tedone & Grayburn, 2022; Whorton, 2010).

Tedone and Grayburn (2022, p. 4) quote an 1883 account of a child poisoning themselves after using an arsenical book cover as a watercolour paint palette and accidentally ingesting some of the dissolved arsenic; this was not an isolated incident, with a large number of arsenic poisonings recorded during this time (Whorton, 2010).

Given this extensive literature of the knowledge of the risk of exposure to arsenic, the Poison Book Project has employed the precautionary principle: this exposure risk is now identified and therefore there is a responsibility to manage the risk to reduce exposure to workers handling the books, and members of the public who wish to read them.

The cloth-bound books contaminated with friable Emerald Green were created predominantly between 1840-1860, with a very few in the early 1870s (Tedone & Grayburn, 2020, 2022). The qualitative descriptor of RV TTC presented in Table 9 above has extremely slow defined as 50 or more years; this may not provide enough granularity for an RV TTC that is around 150-180 years. Another descriptor may be required for risk exposures with time periods measured in decades or centuries.

RV TTI is medium slow-slow, as it has taken some time before the impact of having books contaminated with Emerald Green or other hazardous substances has been realised in the wider book conservation field; other areas such as general lending libraries and the second-hand trade are unlikely to have understood the risk of contaminated books. There is a risk that unidentified arsenical books may be unwittingly taken into homes, stored and transported, for example in backpacks and handbags, and shed friable arsenic material, thus spreading contamination.

PubChem identifies that Emerald Green[9] includes six Globally Harmonised System (GHS) Danger warnings, including acute toxicity, carcinogenic, reproductive toxicity, specific organ damage through single exposure, and prolonged exposure; seven GHS Warnings, including noting that it is absorbed through the skin; and 22 GHS Precautionary markers. PubChem states, ‘the probable oral lethal dose for humans is 5-50 mg/kg, or between 7 drops and 1 teaspoonful for a 150-lb [68kg] person’ (National Center for Biotechnology Information, 2022, 9.1.4 Health Hazards).

Tedone and Grayburn (2022, p. 7) carried out “pick-up tests” with dry cotton pads and cotton swabs wiped over the spines and covers of books suspected of contamination, and observed that, ‘The pick-up tests resulted in a significant, measurable amount of arsenic offset from the dry bookcloth.’ Destructive sampling from the first book identified with Emerald Green pigment (*Rustic Adornments for Homes of Taste*, Hibberd, 1857) identified an average of 1.42mg/cm^2 of arsenic (Brower, 2022). RV TTO for acute exposure is extremely fast, with adverse effects showing in approximately 30 minutes to a few hours.

Chronic RV TTO to Emerald Green is dependent on exposure. ‘Latency for skin cancer associated with ingestion of arsenic may be 3 to 4 decades’ (Agency for Toxic Substances and Disease Registry, 2010); neuropathy is several years, and other chronic effects also are slow-very slow. Whether there would be enough absorption to cause chronic ill-health effects for people that regularly handle arsenical books is yet to be determined.

RV TTR (Table 10) is likely to be medium slow-slow (if recovery is possible at all). Stenehjem et al. (2007) described a person who suffered acute poisoning with arsenic suffering after-effects five years after the event. It is difficult to identify RV TTR for chronic exposure to arsenic; even in literature reviews such as Guha Mazumder and Dasgupta (2011), the focus

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[9] PubChem lists copper acetoarsenite as Paris Green.

is on the effects of exposure rather than recovery time. In terms of the exposure from Emerald Green books, the level of chronic exposure has not been identified.

A summary of RV for arsenical books is in Table 15.

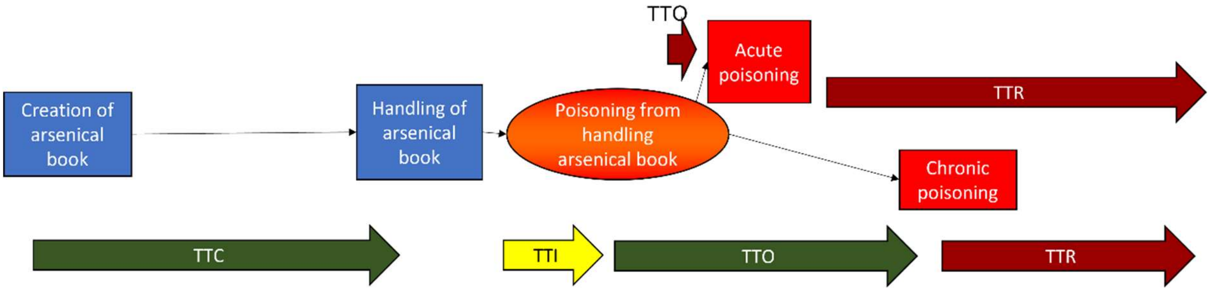
Table 15: Summary risk velocities for exposure to arsenical books using qualitative descriptors

Velocity	Qualitative descriptor
RV Time to cause	Extremely slow
RV Time to impact	Medium slow-slow
RV Time to outcome (acute)	Extremely fast
RV Time to outcome (chronic)	Extremely slow
RV Time to recover (suggested only)	Medium slow-slow

(Source: author)

This is shown graphically in the simplified bowtie analysis in Figure 8.

Figure 8: Example bowtie analysis for bibliotoxicology, showing risk velocity



(Source: author)

6.2.2 Control velocity and bibliotoxicology

A number of controls have been instituted in Winterthur Library (Tedone & Grayburn, 2022) to manage the risks of exposure to arsenical books (Table 16 below). An example CV is assigned to each control, with a brief explanation. An example of how this could be shown in a bowtie analysis follows (Figure 9 below).

Table 16: Controls for arsenical books showing hierarchy with control velocity qualitative descriptors

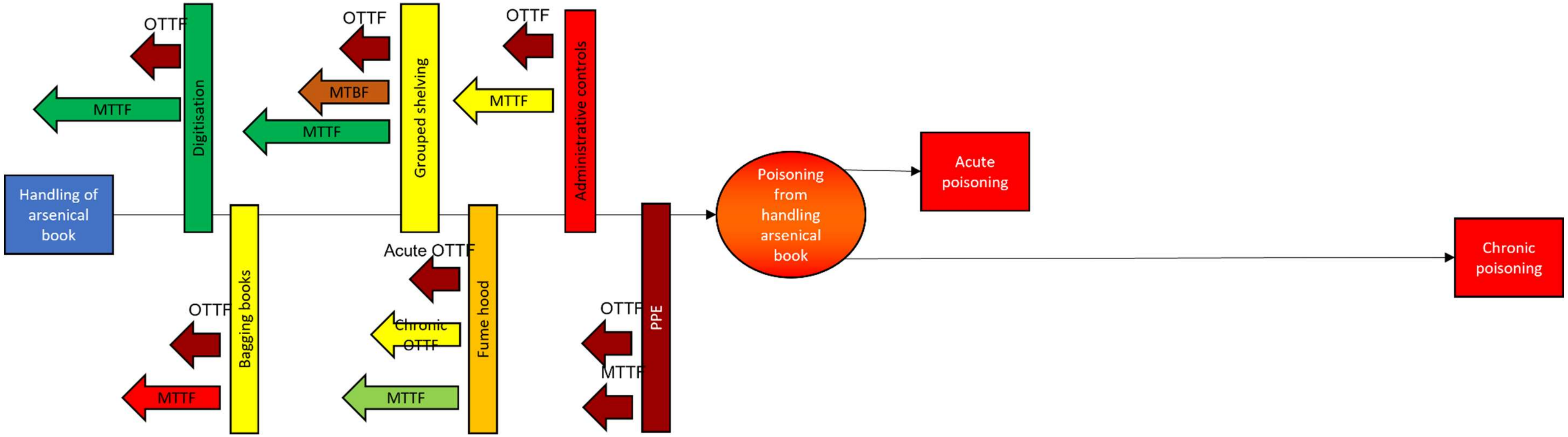
Hierarchy of control	**Control used for arsenical books**	**Mean time to failure**	**Mean time between failures**	**Operating time to failure**
Eliminate	Digitisation of arsenical books to significantly reduce the need for handling or circulation	Slow-very slow	Unknown	Extremely fast, as a person may still request access to the actual book
Substitution	*Not used*			
Isolation	Containing arsenical books in individual, resealable polyethylene bags	Fast-medium fast, estimate of life of polyethylene bag before tearing in handling	Unknown	Extremely fast
	Shelving all identified arsenical books together in the Rare Books vault, where access to the collection is tightly controlled	Slow-very slow	Fast, as shelving mistakes can be made	Extremely fast, as a book shelved in the regular collection breaches this control immediately
Engineering	Handling of arsenical books for conservation under a fume hood	Slow – fume hood useful life is approximately 10 years (LabTech Supply, n.d.)	Unknown	Acute: Extremely fast, if fume hood is rapidly breached or breaks down
				Chronic: Medium slow-slow, as extraction may become less efficient over time
	Handling of arsenical books for conservation in 'a ductless particulate hood with a combination HEPA/charcoal filter' (Tedone & Grayburn, 2022, pp. 9-10) where a fume hood is not available	Slow – fume hood useful life is approximately 10 years (LabTech Supply, n.d.)	Unknown	Acute: Extremely fast, if fume hood is rapidly breached or breaks down
				Chronic: medium slow-slow, if extraction becomes less efficient over time

Hierarchy of control	Control used for arsenical books	Mean time to failure	Mean time between failures	Operating time to failure
Administrative	Individual warning labels for each arsenical book (on its polyethylene bag)	Medium fast, assuming the labels are plasticated rather than paper or cardboard	Unknown	Extremely fast, if person fails to take note of label and still handles book
	Labelling the shelves where arsenical books are stored	Medium slow, as shelf labels are likely to last for more than a year	Unknown	Extremely fast, if person fails to take note of label and still handles book (taking it out of its individual bag)
	Inclusion of arsenical books in the emergency management plan	Medium slow, as policies and procedures have limited effective life	Unknown	Extremely fast, as retention of knowledge of the plan decreases quickly (Sanli & Carnahan, 2018)
	Handling of arsenical books restricted to on-site viewing in the Rare Books reading room, supervised by trained staff	Medium slow, as policies and procedures have limited effective life	Unknown	Extremely fast, due to potential for human error (Reason, 1990)
	Arsenical books placed on surfaces that can be easily wiped down, including use of a polyethylene cover over book wedges and cushions used for supporting rare and fragile books	Medium slow, as policies and procedures have limited effective life	Unknown	Extremely fast, due to potential for human error (Reason, 1990)
	Staff trained in safe handling of arsenical books	Medium slow, as policies and procedures have limited effective life	Unknown	Extremely fast, as retention of training decreases quickly (Sanli & Carnahan, 2018)
	Clear written procedures for handling arsenical books	Medium slow, as policies and procedures have limited effective life	Unknown	Extremely fast, due to potential for human error (Reason, 1990)

Hierarchy of control	Control used for arsenical books	Mean time to failure	Mean time between failures	Operating time to failure
Personal Protective Equipment	Use of nitrile gloves for handling arsenical books	Extremely fast, as nitrile gloves are one-off use	Unknown	Extremely fast, due to potential for human error (Reason, 1990)
	Use of a 'respirator with organic solvent and particulate filters [by conservators] should be considered only as a last resort' (Tedone & Grayburn, 2022, p. 10)	Fast, as useful life is 6 months (Standards New Zealand, 2012)	Unknown	Extremely fast, due to potential for human error (Reason, 1990)

(Source: author)

Figure 9: Example bowtie analysis for bibliotoxicology in bowtie analysis, showing control velocity



(Source: author)

6.2.3 Velocity and bibliotoxicology: summary and discussion

Application of the qualitative descriptors in Table 9 and Table 10 above to bibliotoxicology has shown that it is difficult to indicate both velocity that is very fast or extremely fast with one that is extremely slow, and still achieve useful granularity for the practitioner. For extremely long-term velocities such as this, the caveat to the qualitative descriptors identified in this research in section 5.1.1 holds true: a timescale may need to be developed that is specific to the situation and is clearly defined (example of usage in Table 16 above).

However, applying velocity to both the risk and the current controls to this emerging risk field shows that consideration of time for both the risk exposure and the controls reduces uncertainty, particularly as the hierarchy of control effectiveness does not match CV.

It is also noted that it is relatively easy to apply MTTF and OTTF to most controls by reviewing relevant literature and identifying a qualitative measure; it is much more difficult to identify MTBF unless there is known engineering data, and it is difficult to estimate qualitatively. The MTBF measure is of value if the information can be obtained; however, using CV with only MTTF and OTTF alone significantly reduces uncertainty.

Incorporation of velocity into the bowtie analysis risk technique was tested and shown to be effective during this case study. Due to the complexity of the controls, the bowtie analysis was split to show RV and CV separately (Figure 8 and Figure 9 respectively); however, it would be possible to provide a single bowtie analysis with all velocities shown.

Issues are raised for records retention and management for slow risk and control velocities. Records retention requirements vary according to jurisdiction; however, an extremely slow RV or CV of 50 years or more (or in the case of bibliotoxicology, between 150-180 years) is likely to create a significant challenge for retention of knowledge and information regarding management and control of the risk.

6.3 Case study: Lake Ōhau wildfire

Between 4-13 October 2020, a wildfire rapidly burned through the remote Lake Ōhau area near Twizel in the South Island, destroying 48 homes, seriously damaging six more in Lake Ōhau Village, and burning over 5000 hectares of private and public land. It is one of the most significant wildfires in New Zealand's recent history (FENZ, 2021a, 2021b).

*6.3.1 Risk velocity and the Lake **Ō**hau wildfire*

A velocity overview of the wildfire considers:

- The weather
- The available fuel and fire behaviour
- The burning of the village
- Established ignition source
- Recovery

This is not an exhaustive analysis of the wildfire, or of the wildfire preconditions such as fuel loading; it is an example of how velocity could assist in both planning and response.

There are two parts to the RV TTC for weather related to the event. The first is the longer-term (chronic) weather leading into the spring of 2020, and the second is the immediate (acute) weather conditions on 4 October 2020.

The winter prior to the fire in October 2020 was New Zealand's warmest on record, and a La Niña Watch had been in place since August 2020 (NIWA, 2021). Investigators noted that,

> Despite significant rainfall [in the month] leading up to the fire, there was little change to the degree of curing in the grass fuels. Warm weather and frosts assist with reducing the moisture content of grass fuels.
>
> (FENZ, 2021a, p. 16)

The RV TTC for this longer-term weather pattern is medium fast-fast.

The immediate weather preceding the fire had an extremely fast RV TTC. Media reported that a severe wind warning was in place (OneNews, 2020). This extreme wind was distorted by the topography of the area (mountains, gullies, Ōhau Lake and valley), creating swirling that was difficult to predict.

Considering both the chronic and acute weather conditions for RV allows identification of how longer-term weather patterns may influence potential fire conditions. Application of climate change information is outside the scope of this research report; however, it is noted that there is concern that climate change is increasing dryness of fuels and therefore wildfire risk (Ellis, Bowman, Jain, Flannigan, & Williamson, 2022). Short-term weather conditions such as severe wind watches and warnings may act as indicators of increased acute risk.

The fuel dryness had an RV TTC of medium fast. The types of fuels present (wilding conifer, tussock grass, pastureland, and conservation estate) provided large amounts of “fine fuel”, small organic fuel materials that ignite easily and burn quickly when dry (FENZ, 2021a).

New Zealand has pine and conifer varieties that have been cultivated for plantation forestry projects or used for ornamental, windbreak or carbon sequestration purposes (Edwards, Stahlmann-Brown, & Thomas, 2020). However, because conifers have wind-blown seeds, many of these species have established widespread “wilding” populations as invasive pest species. The growth of trees takes several years, with a slow-very slow RV TTC for the presence of the wilding conifers. Wilding conifers significantly increased the fuel load of the area (FENZ, 2021a).

The combination of gale-force winds and extremely dry fuel caused the wildfire to “crown” through the wilding conifers and other tree areas:

> …meaning [that] it burned through the tops of the trees, creating an ember storm. Areas of wilding [conifer] increased the intensity of the fire. This is due to the small lower branches which naturally die off as the trees grow, leaving at least two metres of dry dead branches available to burn from the ground upwards.
>
> (FENZ, 2021b, p. 4)

The “crowning” of the wildfire in the wilding conifer, combined with high winds, created the extremely fast RV TTO of the wildfire. Once the fire reached the trees, it created an “ember storm,” where burning embers were blown a significant distance ahead of the main wildfire front, spreading it even more quickly (FENZ, 2021a).

Ōhau Village subdivision was established in 1986, prior to the introduction of New Zealand’s nationwide Building Act 1991 and Building Code 1992 (Buckett, 2014). Buildings were therefore subject to earlier local council fire safety requirements. It is unclear whether wildfire planning was included in the subdivision requirements for the Village.

There are two RVs that can be applied to the burning of the Village: an acute, extremely fast RV TTO when the wildfire front and ember storm swept through, and chronic RV TTC of slow-very slow related to the age of the buildings and materials. Investigation of the fire loading of the various built structures is outside the scope of this research report; however, each of the materials will have its own RV.

The ignition of the wildfire was established as accidental, through an electrical phase-to-earth fault on an 11kV power line on Pole 35693 (FENZ, 2021a), estimated by investigators to have occurred any time between weeks previously and the night of the wildfire (very fast-extremely fast RV TTI).

RV TTR for the wildfire is slow to very slow. Media reporting in 2021 identified that residents were rebuilding and replanting (Otago Daily Times, 2021); however, restoration of the area will be slow to very slow (for landscape regeneration) and medium slow (for rebuild).

The RV for the Lake Ōhau wildfire is summarised in Table 17:

Table 17: Summary risk velocities Lake Ōhau wildfire using qualitative descriptors

Risk velocity	**Threat**	**Descriptors**
RV Time to cause (chronic)	Weather	Medium fast-fast
RV Time to cause (acute)	Weather	Extremely fast
RV Time to cause	Fine fuel	Medium fast
RV Time to cause (chronic)	Wilding conifer fuel	Slow-very slow
RV Time to cause	Village construction	Slow-very slow
RV Time to impact	Power pole fault	Very fast-extremely fast
RV Time to outcome	Wildfire speed	Extremely fast
RV Time to outcome	Village burning	Extremely fast
RV Time to outcome	Wildfire ignition	Extremely fast
RV Time to recover	Landscape regeneration	Slow-very slow
RV Time to recover	Rebuild	Medium slow

(Source: author)

6.3.2 Control velocity and the Lake Ōhau wildfire

CV can be identified in a number of controls for the wildfire risk. The following is an illustrative rather than exhaustive discussion on how CV can contribute to controls.

Network Waitaki own the 11kV lines. Several of the poles and parts of the line near the Village were identified as areas of interest by the investigators, with failure of the arms of

Pole 35693 identified as the most likely cause of ignition (FENZ, 2021a). The maintenance record for Pole 35693 is not identified in the investigation report. However, another pole nearby on the same line was last serviced prior to the wildfire in 2017, with a 'nominal remaining life of 25 years' (FENZ, 2021a, p. 61): very slow MTTF. Network Waitaki (2020) identified that their regular inspection of lines was every five years (MTTF medium slow), or as required following 'extreme weather events' (p. 93). If Pole 35693 was also inspected around the same time, it would be well within inspection timeframes.[10] Maintenance was carried out as required following inspections.

In Network Waitaki's *Asset Management Plan*, the following life expectancies or projected equipment failures (MTTF) are stated for equipment implicated in the Lake Ōhau wildfire (Table 18):

Table 18: Asset management plan (Network Waitaki, 2020, p. 86, Table 18)

Equipment implicated in Lake Ōhau wildfire	Asset management plan life expectancy in years (MTTF)
XLPE cables installed <1985	45
XLPE cables installed >1985	50
PILC cables	70
Concrete pole	60

(Source: Network Waitaki (2020))

The investigation report (FENZ, 2021a) does not identify the type of cable at Pole 35693, so the shortest MTTF of very slow is applied. It can be inferred that the OTTF of the equipment is extremely fast (acute failure), or medium fast-medium slow for chronic failure (FENZ, 2021a).

CV OTTF for the quantity of wilding conifer removed from the Ōhau basin is not publicly available, although there has been a significant effort in the area as part of the national control strategy (MPI, 2014).

Media reporting identified that the emergency plan for the village was last updated in 2016, four years before the wildfire (Newsroom, 2021). Analysis in section *5.2.5 Administrative*

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[10] Following the Lake Ōhau wildfire, Network Waitaki increased its line inspection frequency in the Mackenzie Basin from five years to annually (Network Waitaki, 2021).

controls above identifies that this kind of control has a medium fast CV MTTF and extremely fast OTTF, so the emergency plan would have been well overdue for review and update.

It is also noted in the FENZ *Operational Review* of the wildfire that,

> A copy of the plan was put in every home, but knowledge of the plan was mostly only fully understood by the permanent residents. With many of the properties being used as holiday rentals, a significant number of people staying in the village at any given time would not be aware of the plan, and/or what action to take if they heard the siren. (FENZ, 2021c, p. 18)

FENZ also identified that 'the tactical fire plan for Lake Ōhau Alpine village was not available on the fire appliances that would normally respond to a [village] fire' (FENZ, 2021c, p. 20), a latent failure with extremely fast OTTF.

Control velocities are summarised in Table 19:

Table 19: Summary velocities for controls for Lake Ōhau fire using qualitative descriptors

Control velocity	Control	Descriptor
Mean time to failure	Inspection	Medium slow
Mean time to failure	11 kV equipment	Very slow
Operating time to failure (acute)	11 kV equipment failure	Extremely fast
Operating time to failure (chronic)	11 kV equipment failure	Medium fast-medium slow
Mean time to failure	Emergency plan	Medium fast
Operating time to failure	Emergency plan	Extremely fast
Operating time to failure	Emergency plan not on fire appliances	Extremely fast

(Source: author)

6.3.3 Velocity and the Lake Ōhau wildfire: summary and discussion

The application of velocity may assist in reducing uncertainty in wildfire planning, particularly where there is knowledge of potential fuel load. Uncertainties such as weather and ignition sources can be accommodated in planning or desktop simulations. There is evidence in the FENZ *Operational Review* that Lake Ōhau residents were regularly informed of significant wildfire risks and weather that could increase risk (FENZ, 2021c).

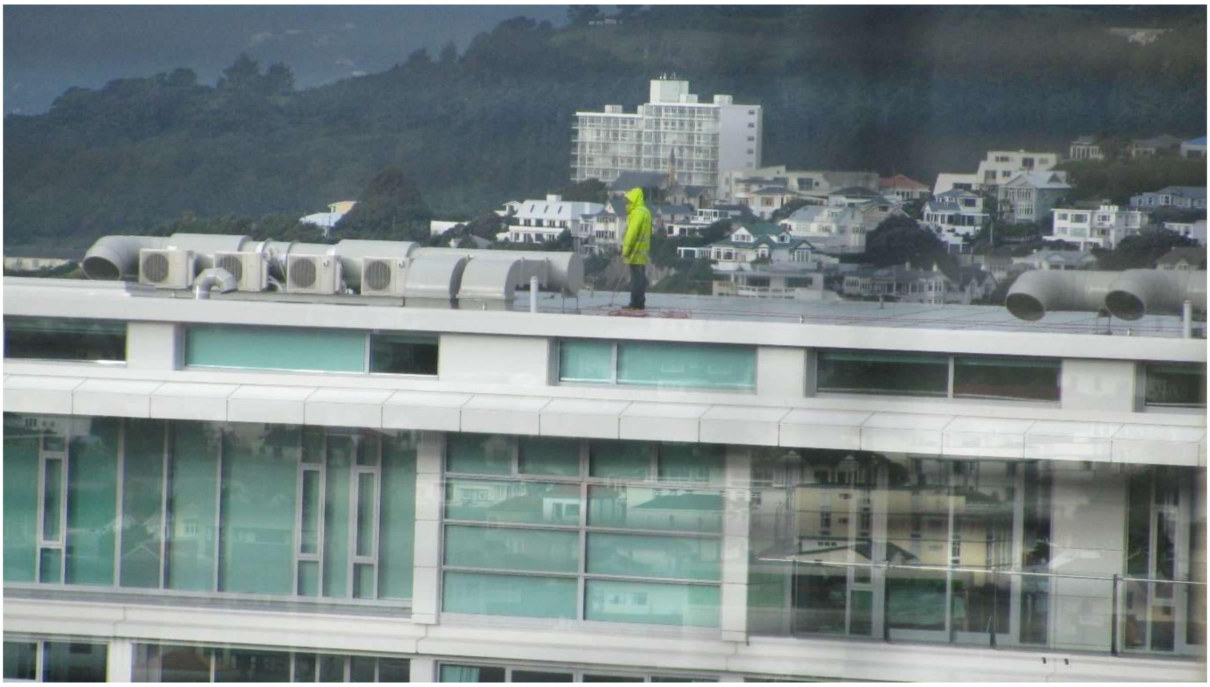
Velocity could also reduce uncertainty for organisations such as Network Waitaki who are managing large asset portfolios, by assisting them to prioritise the areas that require more frequent or targeted maintenance or management. This is further considered in section 6.5 *The implications of velocity for other management activities* below.

6.4 Case study: Work at height (WAH)

Velocity is not only useful for reviewing situations after they have occurred, as shown in the previous case studies on Whakaari, bibliotoxicology and the Lake Ōhau wildfire; it can also be included in routine risk assessment and management activity.

WAH is a situation encountered regularly in HSRM. Figure 10 and Figure 11 show a worker accessing the rooftop services area of the roof of the Chews Lane Apartments in Wellington (completed 2009) 70m above ground, with a southerly storm clearly visible (Figure 11). The worker is not harnessed to a fixed anchor point and there is no parapet or other fixed barrier to prevent falling.

Figure 10: Worker accessing service areas of Chews Lane Apartments



(Source: author)

Figure 11: Worker bringing a ladder to access service areas at Chews Lane Apartments

(Source: author)

6.4.1 Risk velocity and work at height

The RV TTC of WAH risk is related to building and access design decisions, often made decades earlier. In the Chews Lane images above, the worker was accessing the area around a year after the building opened; however, the risk of falling from height will remain as a latent failure for the life of the building, unless it is modified to include barriers. RV TTC is therefore medium slow-extremely slow, depending on the life of the asset.

Chappell (2014) identifies that a southerly weather change in Wellington can occur in around an hour. As discussed above in section 6.3 *Case study: Lake Ōhau wildfire*, RV TTI for acute weather is extremely fast and should be included in planning as part of service and maintenance contracts, if the area to be accessed is outside.

RV TTI and RV TTO are both extremely fast once the worker falls for whatever reason, including slippery surfaces, trips, or loss of balance.

However, a fall from height is not the only possible outcome. The worker could also drop unsecured equipment: RV TTI for unsecured equipment is also extremely fast. There are several possible outcomes from dropping an item, including:

- Injury to or death of another person below hit by the dropped object
- Damage to the dropped object
- Damage to items impacted by the dropped object

All of these have extremely fast RV TTO.

In the case of Chews Lane, the most likely outcome for worker fall (due to the height of the building) is a fatality; therefore, there is no possible RV TTR (Haddon, 1973).

For a dropped object, each of the possible scenarios has a different RV TTR. Assuming the item dropped is something like a hammer or other tool, RV TTR for injury of the person hit by the dropped tool ranges between fast-medium slow, depending on the person's injuries. The item would likely be smashed from a fall if it hit the ground (no recovery). Estimation of RV TTR if the item hit a car parked below is extremely difficult as it depends on the amount of damage sustained, and to which part of the vehicle: a broken windscreen might have extremely fast to very fast RV TTR, whereas a hammer smashing through the bonnet and damaging the engine block may have a much longer RV TTR (or not be recoverable at all). This is therefore not listed in Table 20 below.

There would also be business impacts from the requirements of investigation by WorkSafe NZ,[11] and the Police and the Coroner for fatal accidents. RV TTR for the investigation phase is medium slow-slow, aligning with the statutory length of time for WorkSafe NZ to investigate and lay charges. There may be other impacts on the business, including reputational risk, that will have RV TTR.

Consideration of these velocities can assist in reducing uncertainty in risk management planning. The velocities are summarised in Table 20 below and shown in the bowtie analysis in Figure 12 below.

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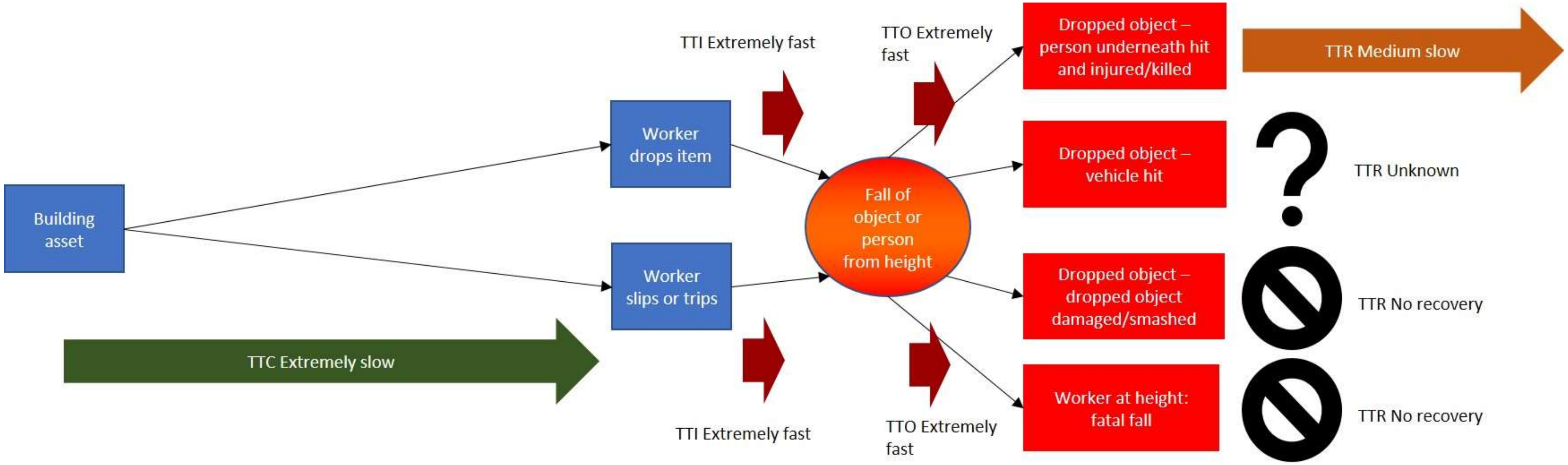
[11] Objects dropped from height are also notifiable to WorkSafe under HSWA as a "notifiable incident" (s.24).

Table 20: Summary risk velocities for work at height using qualitative descriptors

Risk velocity	Threat	Descriptors
RV Time to cause	Design decisions	Medium slow-very slow
RV Time to impact	Weather	Extremely fast
RV Time to impact	Fall from height	Extremely fast
RV Time to impact	Dropped item	Extremely fast
RV Time to outcome	Dropped item hits person below	Extremely fast
RV Time to outcome	Dropped item is damaged	Extremely fast
RV Time to outcome	Items hit by falling object	Extremely fast
RV Time to recover	Fatal fall	Non recoverable
RV Time to recover	Dropped object injury	Fast-medium slow
RV Time to recover	Dropped object smashed	Non recoverable
RV Time to recover	Investigation	Medium slow-slow

(Source: author)

Figure 12: Example bowtie analysis for work at height, showing risk velocity



(Source: author)

6.4.2 Control velocity and work at height

Unlike other jurisdictions such as the UK, New Zealand does not have Regulations for management and control of WAH. Updated guidelines were released by MBIE (2019, originally released 2012) and published on WorkSafe NZ's website; however, the website identifies that the guidelines have not been updated to include changes introduced by the Health and Safety at Work Act 2015 (HSWA 2015). This means that, although there is a 2019 publication date, the guidance may not have been substantially reviewed or updated since 2012. Dropping objects from height is controlled under Regulation 25 of the GRWM Regulations, but this Regulation does not extend to preventing or managing falls of people working at height. Best practice guidance for management of WAH is therefore sought from other jurisdictions.

The UK Health and Safety Executive (HSE) is recognised worldwide as a source of best practice guidance by health and safety risk management (HSRM) practitioners. Their guide *HSG33 Health and Safety in Roof Work* (HSE, 2020) identifies a number of controls for management of exposure to WAH. The following have been identified as relevant to the Chews Lane example, and example CV applied to the control (Table 21 below). This list is not exhaustive.

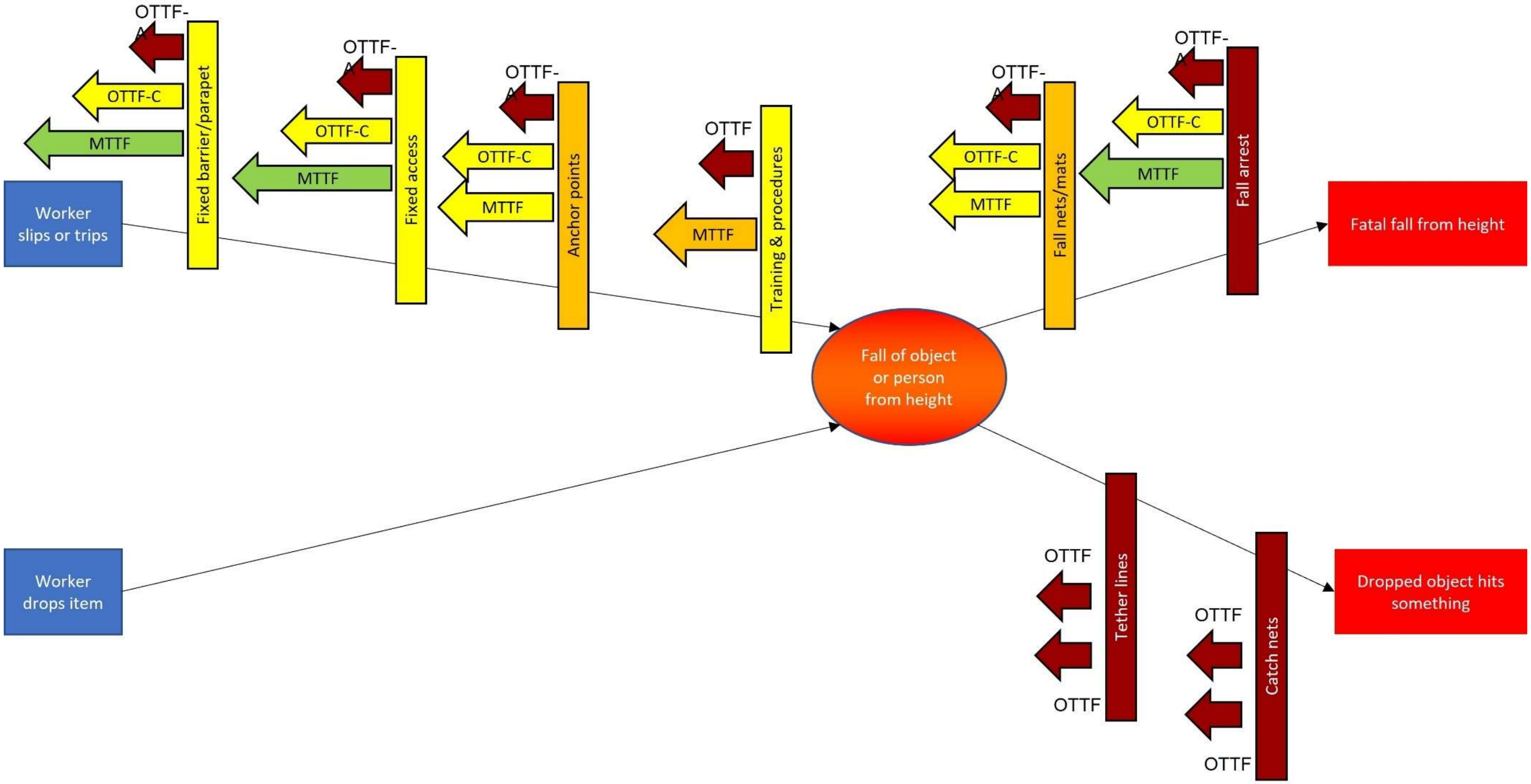
An example of how the controls could be mapped in a bowtie analysis is shown in Figure 13 below.

Table 21: Controls for work at height relevant to Chews Lane example (HSE, 2020)

Hierarchy of control	**Control used for work at height**	**Mean time to failure**	**Mean time between failures**	**Operating time to failure**
Isolate	Prevent fall by erecting permanent, fixed parapet (included in design of asset, valid for life of asset)	Slow-very slow		Acute: Very fast-extremely fast Chronic: Medium slow-slow
	Permanent, fixed safe access to roof, e.g., internal stairway	Slow-very slow		Acute: Very fast-extremely fast Chronic: Medium slow-slow
Engineering controls	Securing equipment using tether lines to prevent dropping	Very fast-extremely fast		Extremely fast
	Catch nets for dropped equipment	Very fast-extremely fast		Extremely fast
	Fixed roof anchor points: life expectancy depends on design and placement of the anchor points (Standards New Zealand, 2013). This is an estimate only.	Medium slow-slow		Acute: Extremely fast Chronic: medium slow-slow
	Fall nets or mats to catch a falling person	Very fast-extremely fast		Acute: extremely fast Chronic: medium slow-slow
Administrative	Workers trained for work at height	Medium fast		Extremely fast
	Work at height procedures, including Permit to Work	Medium fast		Extremely fast
	Work at height suspended rescue procedures	Medium fast		Extremely fast
Personal protective equipment	Work at height fall arrest harness, arrestor and line: life expectancy is a minimum of 10 years (Standards New Zealand, 2020).	Slow		Acute: Extremely fast Chronic: medium slow-slow

(Source: author)

Figure 13: Work at height example controls, using qualitative descriptors



(Source: author)

6.4.3 Velocity and work at height: summary and discussion

This case study shows that velocity can be simply applied to risks and uncertainties faced in safety management, as well as disaster management and investigation (Whakaari and Lake Ōhau wildfire) and health risks (bibliotoxicology). Consideration of RV provides the practitioner with granularity and a significantly clearer picture of the effects of the risk, reducing white spaces and uncertainty (Cherry, 2010).

Again, Table 21 above shows that it is relatively simple to apply CV MTTF and OTTF to known controls with only the information that would be available to a practitioner. Application and use of MTBF requires specialist engineering knowledge that may not always be available, and in some cases this measure may not be relevant. The ability to include CV and RV in bowtie analysis (shown in Figure 12 and Figure 13) provides significantly more clarity than only likelihood and consequence.

6.5 The implications of velocity for other management activities

6.5.1 Risk velocity, FME[C]A and the adequacy of risk assessments

FME[C]A has the risk priority number (RPN) multiplied by consequence and likelihood, often shown as an addition to a 5x5 risk matrix (Peace, 2019). This research has shown that RV is not equivalent to RPN; although RPN implies a single element of time or speed, it does not include the breadth of application of the four parts of RV (Time to Cause, Time to Impact, Time to Outcome and Time to Recover). This confirms the research of Peace (2017, 2019) regarding the overall inadequacy of a risk matrix to inform decision-makers: risk velocity, shown in this research as a key element of risk, is not included in this analysis.

However, the element of detective controls, as shown in FME[C]A, is not clearly included in control velocity, and this may be an area for further research.

6.5.2 Value of qualitative descriptors

The value of the qualitative descriptors such as those in Table 9 and Table 10 above has been pragmatically shown in the case studies. The qualitative descriptors assist in differentiating risks that might otherwise be grouped together as similar and therefore potentially missed for management attention, particularly if a likelihood-consequence assessment is used for the assessment (Peace, 2017, 2019).

Consideration of RV complements both latent failure and drift into failure by reducing uncertainty around the potential speed of a risk exposure, both in planning and investigation.

Application of CV to case studies has highlighted that the most challenging of the three failure measurements to use without specific engineering or product knowledge is MTBF. However, MTTF and OTTF can be estimated by a layperson using the qualitative descriptors in Table 9, and testing in the case studies suggests that these two measures are likely to be of the most use for risk control management by practitioners.

6.5.3 Issues for record-keeping and records retention

Consideration of velocity provides practitioners with a further way of identifying which areas require the most attention, and an estimate of timeframes involved. A fast velocity risk may require immediate attention and planning. A slow velocity risk will require a different kind of planning, communication and management due to the length of time involved.

The RV of a slow velocity risk may be significantly longer than the service life of a risk management plan, or the employment timeframes of employees. Records retention requirements vary depending on the legislative framework of the risk, but the average retention requirement is 7-10 years[12] (slow RV). A challenge is therefore presented to organisations: how to manage records for risks with slow-extremely slow RV (such as hazardous substances), so that the knowledge captured by a risk velocity assessment is retained and used to reduce ongoing uncertainty. Areas where this is likely to be relevant include:

- Management of hazardous substances, as shown in section 6.2 *Case study: Bibliotoxicology* above
- Climate change
- Building and asset selection and management

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[12] Notable exceptions are the Building Act 2004, which requires records retention for the life of the building, and the GRWM Regulations 2016, which require retention of health monitoring records for 30 years, and asbestos-related records for 40 years.

6.5.4 Links with other professional disciplines

Clarity around RV TTR provides a strong link with business continuity requirements for each risk scenario. Provision of qualitative descriptors for RV TTR such as in Table 10 above will assist business continuity and emergency management professionals to focus attention on the scenarios or exposures that have the greatest potential impact on the organisation's activities.

CV provides additional clarity to asset managers, financial management accountants controlling capital and operational expenditure, and risk professionals, by identifying:

- The expected time until an asset or control fails (MTTF)
- How often that control can be expected to fail within its operating life (MTBF)
- When it fails, how quickly it will be damaged (OTTF), both acute and chronic

Even without quantitative engineering data on each of these measures, use of qualitative descriptors such as provided in Table 9 above will still allow greater understanding of the useful life of any given control and therefore better planning for maintenance and replacement.

7 Conclusion

This research stemmed in part from issues identified in my professional career, where I identified that time or speed was missing from risk techniques outlined in the Standards I was most familiar with. The lack of appreciation of the impact of time or speed meant that there were white spaces of unknowns in the risk assessments that were unable to be closed by the techniques in the Standards.

This research has shown that current risk assessment techniques have not considered velocity, save as implied as a time horizon for risks, or as the risk priority number (RPN) used in FME[C]A. Event tree analysis (ETA) has specifically excluded time, and it is only implied in fault tree analysis (FTA). Therefore, application of any of these risk assessment techniques has, by accident or design, not considered the element of time or speed as part of the risk analysis.

This research was seeking to answer two research questions:

1. How should risk velocity be defined?
2. Can risk and control velocity be applied in risk techniques?

Sections of this research have been presented at the New Zealand Institute of Safety Management (Parkin, 2021b), the Inaugural Bibliotoxicology Working Group Symposium (Parkin, 2022), and to the Ministry for Primary Industries in a Science Network seminar.

7.1 Defining risk velocity

Risk velocity has been defined in this research through consideration of the classical physics definition of velocity, the limited literature on the subject, and application to existing risk techniques.

This research proved that risk and control velocity can usefully be applied in the risk techniques discussed: ETA/FTA (encapsulated in bowtie analysis) and FME[C]A. Application of velocity to both the risk and controls or barriers reduced uncertainty.

7.1.1 The classical physics definition

The classical physics definition identified that velocity is speed in a given straight-line direction, defined as distance divided by time and indicated by a vector. Vectors, or directional arrows indicating speed, can be usefully and simply applied to existing risk techniques to visually identify risk velocity, particularly to bowtie analysis.

7.1.2 Identification of risk velocity time to outcome

Three parts of risk velocity were identified in the limited literature for risk velocity: time to cause, time to impact, and time to recover (Chaparro, 2013; Sobel, 2010; Tattam & Esteban, 2013).

My application of risk velocity to bowtie analysis identified that there is a missing element of risk velocity not identified in the literature: time to outcome (RV TTO). Time to outcome identifies the speed that a risk impact leads to consequences of the risk. RV TTO clarifies how quickly a risk exposure could express, especially when applied to the bowtie analysis risk technique.

The discovery of RV TTO will be written up as a significant contribution to the risk velocity literature from this research.

7.1.3 Identification of control velocity

Application of the concept of velocity to controls identified that three engineering failure definitions, mean time to failure (MTTF), mean time between failures (MTBF), and operating time to failure (OTTF), together add significantly to the understanding of the efficacy of controls, particularly when applied to the hierarchy of risk control (Figure 6 above) used in health and safety risk management (HSRM).

Application of these engineering definitions to control efficacy in HSRM appeared to be novel in the literature.

Application in case studies showed that understanding how long a control was likely to last before it failed, and how quickly it could fail, was extremely useful, and provided significant clarity to asset and business continuity management. MTBF is a measure that has practical application for understanding the uptime and efficiency of a process or activity but is less useful to the practitioner, as it is difficult to estimate without specific engineering data.

7.1.4 Application of risk velocity to risk assessment techniques

Visual application of risk velocity to bowtie analysis using vectors was not identified anywhere in the literature or ISO31010:2019, and will be written up as a significant contribution to the use of this risk assessment technique.

Velocity was shown to be inadequately included in the extant literature on risk assessment, including in the international Standards ISO31010:2019, ISO31000:2018, and COSO2016, limiting the ability of risk assessment to fully inform decision-making in the white spaces. Risk priority number, used in FEME[C]A, does not adequately include speed or time, as this analysis has shown that there are multiple parts of risk velocity that inform risk and control assessment. An appreciation of the different parts of risk and control velocity in risk assessment may improve decision-making, risk and control management and planning, particularly if the risk is at an extreme, either extremely fast or extremely slow to act.

7.1.5 Development of qualitative descriptors

Chaparro (2013) identified five non-consecutive descriptors for risk velocity. My initial creation of a consecutive five-point scale did not provide enough granularity for velocities with large extremes. A second attempt produced the eight-point consecutive scales in Table 9 and Table 10.

Application of the qualitative descriptors in Table 9 (for RV TTC, RV TTI, RV TTO, and CV) and Table 10 (for RV TTR) provided sufficient granularity for a practitioner to estimate useful velocities for all parts of risk and control velocity (excepting MTBF) without specific engineering data, using only information that would be readily obtained. The qualitative descriptors provide enough information to reduce white spaces for decision-makers, and therefore improve risk management overall.

However, it is noted that velocities with large extremes (both extremely fast and extremely slow) are challenging to have on the same scale, as was shown in section 6.2 *Case study: Bibliotoxicology* above. A velocity for a risk with instantaneous effects, that is also chronic over 150-180 years, may benefit from a specific scale being defined.

The qualitative descriptors will be written up as a contribution to the literature.

7.1.6 Broad application of risk and control velocity

Application of RV and CV to a range of case studies, including disasters, chronic and acute health exposures, wildfire, and work at height showed that RV is universal across many kinds of risks. Professional discussions with other risk practitioners have identified that RV may be effectively applied to other risks including biosecurity incursions, privacy breaches, information security exposures, and enterprise risks at both the macro and micro level.

Considering velocity reduces white spaces (Cherry, 2010), allows the organisation's top management to focus more clearly on which uncertainties have the most significant impact on their business objectives, and therefore plan their activities and management requirements accordingly.

7.2 Opportunities for further research

7.2.1 Synergistic effects

RV is a concept that adds significantly to risk techniques, and has been rightly identified as the missing element from most risk management activity (Davis & Lukomnik, 2010). However, RV does not currently reduce all uncertainties:

> Sometimes consequences result from exposures to multiple events or risk sources, or develop over time; for example, environmental or human health effects from the exposure to biological, chemical, physical, and psychosocial sources of risk. In combining such risks the possibility of synergistic effects should be taken into account….
>
> (IEC31010:2019, p. 19)

RV as developed in this research does not include combined velocities that create synergistic risk effects, where different risk exposures combine to form either a hybrid of the combined risks, or a new risk altogether. This is an area that would benefit from further research: combining RVs may elicit richer risk information that could reduce uncertainty yet further.

7.2.2 Consequential effects

IEC31010:2019 identifies that some risks have consequential effects, where there may be a string of consequences that are dependent on each other, or where there are knock-on effects that cause branching or multiple outcomes. RV has not been applied to consequence strings and this is an area for future research.

7.2.3 Second victims

RV may also usefully be able to be applied to situations of 'second victims' (Dekker, 2013). Second victims are particularly identified in HSRM, where people become traumatised by witnessing an accident (e.g., colleagues who see a teammate killed or seriously injured), members of helping professions such as emergency services and medical professionals who witness severe illnesses and injuries as part of their job, and family and friends of those injured or killed.

RV may be able to assist in reducing uncertainty, particularly in estimating RV TTR, as second victims are another potential outcome that has not been considered in this research.

7.2.4 Application to real-time risk management

All application of RV and CV in this research was carried out on events that have already occurred and where there is information in the public domain. The next stage of testing RV and CV would be to apply it to real-time risk management situations across a range of industries and risk types to pragmatically prove the concept, including field-testing and refining the qualitative descriptors. Additional theoretical work could be done to identify whether any issues in the application of RV in financial risk changed the theoretical development in this research.

This research has developed a four-part framework for risk velocity that provides significant clarity to risk assessments and risk understanding, with simple qualitative descriptors. However, for some kinds of risks, it may be appropriate to have a single velocity descriptor, as appears to have been done in the financial velocity literature. Further research would be required to identify the effectiveness of the qualitative descriptors for this application.

7.2.5 Further direct relationship between risk and control velocity

This research does not address the question about whether there is, or should be, a functional relationship between the velocity of a given risk, and the velocities of the controls applied to that risk. Put simply, does a fast RV TTI or RV TTO require a slower velocity control to adequately manage that risk? Future research may wish to consider whether the velocities of the controls and risks “cancel out”, and what effect this may have on the way risks and controls are managed in the future. Investigation of this area may also provide insight into the applicability of administrative controls and personal protective equipment, that are inherently weaker controls according to the hierarchy of risk control (see *5.2 Control velocity and the hierarchy of control*).

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